PONTIFICIA
ACADEMIA
SCIENTIARVM

Scripta Varia
108

The Proceedings of the Working Group 12-14 November 2005

Water
and the
Environment

Altissimu, onnipotente bon Signore,
Tue so' le laude, la gloria e l'honore et onne benedictione.
Laudato sie, mi' Signore cum tucte le Tue creature,
spetialmente messor lo frate Sole,
Laudato si', mi Signore, per sor'Acqua.
la quale è multo utile et humile et pretiosa et casta.

(San Francesco d'Assisi, Cantico delle Creature)

VATICAN CITY
2007

WATER AND THE ENVIRONMENT

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PONTIFICIAE ACADEMIAE SCIENTIARVM SCRIPTA VARIA

108

Working Group on

WATER AND THE ENVIRONMENT

12-14 November 2005

Edited by
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EX AEDIBVS ACADEMICIS IN CIVITATE VATICANA

MMVII

ISBN 978-88-7761-091-1

PONTIFICIA ACADEMIA SCIENTIARVM
VATICAN CITY

His Holiness Pope Benedict XVI

The Participants of the Working Group of 12-14 November 2005

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INTRODUCTION

MARCELO SÁNCHEZ SORONDO

The Priority of Water

For the Presocratics, water was the principle of all things, and curiously enough it is only today that we have once again become aware that the survival of humanity and of all other species on earth depends upon the fate of water. Where water is absent, life is absent. Thus water, the common symbol of life for all mankind, valued and respected in all religions and cultures, has also become a symbol of social equity. Today we can say that the problem has two main facets: the first belongs especially to the natural sciences (study the great basins, conserve them and develop them in a sustainable way with relation to the rest of the environment); the second facet pertains more to the social sciences (fair distribution of water). For these reasons, the Pontifical Academy of Sciences, which has already organised several study weeks on this topic in the past, now wants to organise a first workshop referring principally to the first aspect, with a view to a second workshop in conjunction with the Pontifical Academy of Social Sciences.

Workshop Goals

The world is keenly aware of the fundamental role that water resources play for a safe and sustainable development. Moreover, society is also conscious of the serious danger that these resources are facing because of industrial development, megacities, contamination, and many types of conflicting uses. Concepts like Integrated Water Resources Management are commonly used as 'a process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems' (Global Water Partnership TEC Background Paper No. 4).

The above coordinated development needs a solid scientific background that will allow the decision-making process to proceed with long-term goals and equitable considerations. In this scientific foundation a key role is played by the science of Hydrology and its intimate links with Ecology and also with its sister geophysical sciences like Geomorphology, Geology, Climatology and Meteorology. As Hedin *et al.* have described it (2002, Report to the U.S. National Science Foundation), 'this disciplinary convergence will over the next several decades transform our understanding of basic processes that control the stability and sustainability of natural environmental systems. The ensuing findings will have extraordinary implications for our abilities to predict and manage how humans impact the health of ecosystems across local, regional, and global scales. Such knowledge is a critical component of a safe, sustainable and prosperous future'.

The workshop is addressed to the analysis and discussion of some of the key scientific issues that arise in the formulation described above. Because of the very wide scientific scope of the problem and its associated impacts, the workshop concentrates on some aspects that have a number of connections with the decisions that society faces in relation to water and the environment. The Vatican Academy plans to sponsor a follow-up meeting in the future that will center on the social aspects of water and in particular on water distribution.

Workshop Structure

The workshop is organized around 5 main topics: Biodiversity, Global Hydrology, Climate Change, Land-Atmosphere Interactions, and River Basins. Hydrologic dynamics provides the underlying unifying theme through which all the 5 themes are studied and discussed.

A central purpose of the meeting is to analyze the feedbacks and interactions between the 5 areas described above and explore the main scientific challenges that presently exist for a sound understanding of the hydrologic dynamics underlying some of the world's most pressing environmental problems.

PROGRAMME

SATURDAY, 12 NOVEMBER

9:00 General Introduction: Prof. M. Govind Kumar Menon
The Pontifical Academy of Sciences: Welcome, and Goals

9:15 Speaker: Dr. Reza Ardakanian
The Fair Distribution of Water
Discussion

Biodiversity and Hydrologic Dynamics

10:15 Chairperson: Prof. Nicola Cabibbo
Speaker: Prof. Marino Gatto
Threatened Biodiversity: Understanding, Forecasting, Taking Action
Discussion

11:15 Coffee Break

11:45 Speaker: Prof. Ignacio Rodríguez-Iturbe
Hydrologic Fluctuations and Vegetation Dynamics
Discussion

13:00 Lunch at the Casina Pio IV

Global Hydrology and Hydrologic Dynamics

14:30 Chairperson: Prof. Ignacio Rodríguez-Iturbe
Speaker: Dr. Peter M. Cox
Global Hydrology, Climate Change and Ecosystems
Discussion

15:30 Speaker: Prof. Soroosh Sorooshian
Water Distribution and Availability: An Overview of the Hydrologic Cycle, its Connection to Climate and Impact on Water Resources Management Strategies
Discussion

16:30 Coffee Break

Climate Change and Hydrologic Dynamics

17:00 Speaker: Prof. Dr. Lennart Bengtsson
Changes in Global Rainfall and the Hydrological Cycle: Present and Future Perspectives
Discussion

18:00 Speaker: Prof. Graham Farquhar
Worldwide Changes in Evaporative Demand
Discussion

19:00 Final Discussion

19:30 Dinner at Domus Sanctae Marthae

SUNDAY, 13 NOVEMBER

9:00 Beatification at St. Peter's Basilica of the Servants of God:
Charles de Foucauld, Maria Pia Mastena,
and Maria Crocifissa Curcio

12:30 Social Lunch at the Casina Pio IV

15:00 Guided Archaeological Visit to the Vatican Necropolis

MONDAY, 14 NOVEMBER

9:00 Chairperson: Prof. Raymond Hide
Speaker: Prof. Ulrike Lohmann
Impact of Aerosols on the Hydrologic Cycle
Discussion

Land-Atmosphere Interactions

10:00 Speaker: Prof. Gabriel Katul
Bringing Photosynthesis to the Atmosphere:
A Feedback on Terrestrial Water Cycling
Discussion

11:00 Coffee Break

11:30 Speaker: Prof. Daniel Rosenfeld
Precipitation Suppression by Anthropogenic Air Pollution:
Major Loss of Water Resources Where We Need Them Most
Discussion

12:30 Speaker: Dr. Carlos A. Nobre
Biosphere-Atmosphere Interactions in Amazonia
Discussion

13:30 Lunch at the Casina Pio IV

River Basins

15:00 Chairperson: Prof. Veerabhadran Ramanathan
Speaker: Prof. William Dietrich
Is There a Topographic Signature of Life on Earth?
Discussion

16:00 Speaker: Prof. Andrea Rinaldo
River Basins: Water and Complex Adaptive Systems
Discussion

17:00 Speaker: Dr. Moustafa T. Chahine
NASA's Measurements of Water from Space
Discussion

18:00 Coffee Break

18:30 Speaker: Prof. Malin Falkenmark
Heading Towards Basin-Level Hydrosolidarity –
Goal for Land/Water/Ecosystem Coordination
Discussion

19:30 Final Discussion

20:00 Dinner at Domus Sanctae Marthae

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SCIENTIFIC PAPERS

THE FAIR DISTRIBUTION OF WATER

REZA ARDAKANIAN

1. Justifications of Fair Distribution of Water in the World

1.1. *The World's Water Resources Geography*

According to estimates carried out, the entire water of the earth is around 136,000,000 cubic kilometers. Water depth would be equivalent to 2.7 kilometers if it were scattered on the ground surface of which 97% is allocated to the rivers' saline water, 2% to the giant polar glaciers and 1% to groundwater. A small portion of the water on the globe can be renewed or freshened.

500,000 cubic kilometers of the world's water is evaporated annually, of which 86% belongs to the oceans and 14% is allocated to the terrestrial surface. The same amount falls back to the earth in the form of rainfall and snow. 70,000 cubic kilometers of water is evaporated in the continents. Precipitation toward the continents is equivalent to 110,000 cubic kilometers, therefore 40,000 cubic kilometers per annum of river water is transferred to the terrestrial surface. Water per capita is approximately 7400 cubic meters considering the world's present population, which is higher than the required standard. This freshwater is not distributed homogeneously and the whole amount is not utilized. Two thirds of this water runs away as floods and 14,000 cubic kilometers form a relatively sustainable resource. The countries of the world are classified in 6 groups as far as water shortage is concerned:

Group I: According to water shortage criteria, this group consists of countries that are facing water shortage as 8% of the world's population lives in these countries. They are mainly scattered in west Asia and north Africa. These countries have to reduce their agricultural water use to compensate water required in the industrial sector and for drinking purposes.

Group II: These countries have to develop their water resources up to twice as much as there are to reasonably satisfy their future water requirements. These countries mainly exist in Africa's deserts and 7% of the world's population lives in these areas.

Group III: These countries have to increase exploitation of their water resources from 25 to 100% (48% averagely). These countries cover 16% of the world's total population and they are scattered within the developing countries.

Group IV: These countries are mainly amongst the developed countries and 16% of the world's population lives in these areas. Future water requirements in such countries are relatively low and their water resources are sufficient. This group covers the highest cereal producers, which are USA and Canada.

Group V: The countries of this category cover 12% of the world's population and do not need excessive water supply up to the year 2025. Their water requirement will still decrease because of an increase in irrigation efficiency.

Group VI: This includes India and China, both having a special situation. These countries cover 41% of the total population. Due to their high population and considerable water consumption, water resources management and development could be considered with regard to their high capacity.

1.2. *Relation between the World's Civilizations and Water Geography*

The history of human civilization indicates that initial civilizations were manifested by cities and governments based on agriculture in regions with sustainable water resources equipped with fertilized soils and an adequate amount of water. The regions with the above-mentioned specifications have been habitats of Assyria, Babylonia and Chaldea in Syria, Asia Minor and Greece. These civilizations faced risks and danger whenever there was an imbalance between natural resources and consumption ratio. Civilizations were gradually formed on the banks of the rivers Tigris and Euphrates, Nile, and Indus and modern irrigation techniques along with animal breeding resulted in additional food production.

Transportation facilities and water control within channels, to protect humans against floods, formed vast populations, which led to a new stage of civilization. A nation's development and improvement in ancient times depended on natural traditions and laws. This has a direct relation with available water, production, exploitation of agricultural lands and existing sources in the environment. This is still a must for sustainable development. Water has always been a vital substance for all developing sectors, especially in the potable and agricultural sector. This will absolutely continue in the future.

Civilizations residing near water resources and political decisions made have caused around 40% of the world's population to settle down in river basins, which are marginal water resources.

India and Bangladesh on the Ganges, Mexico and the USA on the Colorado River, Hungary on the Danube, and Thailand and Vietnam on the Mekong River all have some concerns to be considered. In Africa there are 57 river basins and streams running along the border of two neighboring countries. None of the regions like the Middle East have such severe, challenging problems related to water resources, which do effect their economic situation and political perspective.

1.3. *Water and Cultural Heartlands*

The world transition from the dipolar frame requires a new discipline of which new political approaches have been the bases. This has apparently been formed, based on economic and production technology.

Experience has made scientists believe that technology, wisdom, and economy could not be the only factors to merge homogeneous units or to separate non-homogeneous ones. Cultural aspects play a more important role in this respect. Development will not be sustainable without including cultural and environmental aspects.

What we are expecting from economic situations cannot be gained by improving technology. This has to be provided by taking into account cultural aspects of applying and producing technology.

The most important characteristics of cultural phenomena can be summarized as follows:

– Sustainable cultural phenomena play a fundamental role in creating regional characteristics;
– Cultural phenomena have to be learnt but the teaching process is time consuming and complicated;
– Cultural uniformity is not possible and cultural pluralism should be considered as one of the most important issues;
– In the new geography, determining cultural deferential impacts on various perspectives has been considered as a factor in geographical analysis;

– The geographical perspectives of the present era are usually affected by cultural specifications rather than climatic and other natural factors.

So, even those who believe in higher technology as a main factor in forming geographical perspectives do accept that those geographical areas with similar technologies and economies may differ as far as cultural aspects are concerned.

Cultural Heartlands are focal points in the world where culture is produced. High ratios of people living on the earth are affected by these focal points. Although these focal points have not remained in their initial place and have developed and expanded in other areas of the world, they are still considered the main points where culture has been formed. Generally, different cultural heartlands can be presented of which the most important ones are:

– Athens cultural heartland (Indian and European);
– Khaseb Crescent cultural heartland;
– Confucius cultural heartland;
– Micro-cultural heartlands.

These cultural points are severely affected by available natural resources in general and available water resources in particular.

1.4. *Water as a Human Right*

The United Nations has introduced water as a human right and public commodity. In November 2002, the United Nations Committee on Economic, Social and Cultural Rights offered that access to adequate amounts of clean water for personal and domestic uses is a fundamental human right of all people.[1] It has also been stated that water is not only an economic good but also a social and cultural commodity.

The Committee also emphasized that the 145 countries which have approved the International Commitment on Social, Cultural and Economic Rights will have to commit themselves to providing freshwater for all people in the society without discrimination.

The above-mentioned committee submitted a general declaration, which described the international commitments. The representative of the governmental and private sectors and independent institutes discussed and deliberated on water possession and the need to privatize this commodity in production and distribution systems, before having the declaration approved.

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[1] United Nations Department of Public Information, DPI/2293F, February 2003.

In the last version of the declaration the members came to the conclusion to omit privatization preventing political issues from getting involved. Water was finally defined as a limited natural resource and a fundamental public commodity for life and health.

– The declaration also emphasized the right of water which entitles everyone to sufficient, affordable, physically accessible, safe and acceptable water for personal and domestic uses.[2]

While water consumption is different in various cultures, supplying an adequate amount of freshwater is essential for the following purposes:

– To prevent human death caused by decrease in water volume in the body;
– To decrease risks related to water; and
– To provide required water for domestic, personal and hygienic uses.

1.5. *Food Security or Water Security?*

Food security means that all people should have physical and economic accessibility to food.[3] Food security at the macro level depends on the population and its increasing rate, food production (agricultural productivity), import and export trading, national income and the prices. Food or water security is considered one of the well-known subjects to be dealt with in the countries' strategic plans. The world's experiences have demonstrated that food security cannot be achieved by self-sufficiency at the national level. Self-sufficiency in food production in arid and semi-arid regions without promoting water productivity will endanger renewable water resources and will cause constraints for industries and other water services. Insisting on the above-mentioned issues in some countries dates back to before capitalism (tribal – agriculture). This is the reason why water security has gained the first priority. Higher production with less water is the first and simplest approach to water security policies. Laws and strategies, which are at the basis of consumption, should be based on sustainable utilization of the resources, productivity, equity and ecological conservation to achieve water security. Undoubtedly, the sustainable development of water resources is a method for promoting living conditions, therefore it is necessary to expand and fairly distribute these kinds of resources, enabling one fifth of the world's population to benefit.

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[2] United Nations Department of Public Information, DPI/2293F, February 2003.

[3] FAO, 1983.

1.6. *Water as a Tool to Control Domination*

Economic globalization has caused some challenges and changes in different parts of the world. These changes occurred at the same time as a discussion, entitled geo-economics. In geo-economics, economic and political competitions are focused on a specific country, although international and regional aspects are also considered.

In this respect, economic characteristics and their role in the international economy will be defined, therefore a new political category is being formed on the basis of some economic levels, some of which result in regional convergence (such as the European Union).

This idea has ruined the holistic approach of political boundaries and it has formed a specific policy in the new category. The union factor is no longer based on tribes, races or even languages; but it is now based on special economic indices.

In this process, common money is considered, transportation laws are excluded and a new common parliament will be thought over.

Recent experiences show that the important role of economic aspects for continuous unity in regional political units should now be transferred to cultural criteria. In other words changes occurring in bigger political units will be based on cultural indices rather than economic aspects. The main factor in demonstrating and determining domination will be related to culture.

Since water plays a key role in organizing the fair distribution of water among political units in the region, it will undoubtedly remain the most vital factor in their sustainability and solidity. It will also prevent the creation of local problems and control local authorities, which usually have the potential of increasing local conflicts. In this respect a new definition of geo-politics is presented. This concept includes three main elements as geography, domination and politics. Subjects concerning geo-politics are somehow related to these three components.

Another effective tool in controlling power is using international laws on water. At the present time, these laws play an important role in world power management also in solving different conflicts caused by common water basins between countries. They not only play an important role in prevention, but also in managing conflicts. Sustainable development has been changed into an international agreement in which water issues are included. The gaps of the international laws on water are summarized as follows:

– Water and Human Rights: Challenges between the first generation (inhabitant and political rights) of human rights and the second generation (socio-economic and cultural rights). Governments have to consider supplying freshwater for people in this respect;
– Water as a trading or social commodity: Water in nature cannot be considered a good, but when it comes under authority, it changes into a kind of commodity. According to the above-mentioned issue, water is considered a public wealth such as social goods;
– Challenges concerning the balance between water users competition: Rules and regulations mainly focus on demand management rather than resources management. Sustainability is the main key in resources management. In this respect it is essential to precisely take into account conflict management in order to reduce these kinds of problems.

1.7. *Water and Sustainable Development*

Sustainable development is a kind of development which supplies the present generation's requirements without affecting the future generations' abilities to provide for their needs. Uniformity of economic, social and environmental policies is required for sustainable development. One of the basic infrastructures of sustainable development is sustainability in water resources.

Sustainable development will appeal at the world level when the difference between rich and poor countries decreases. Water limitation and its problems concerns the water requirements of rich and poor countries together. Millions of poor people eat less, so that rich people can provide themselves with high protein foods, since water and land have not been fairly distributed at the world scale and therefore, adequate resources for producing food within the political margins do not exist. There is a limited ecological capacity and when some consume more than their share, some have to consume less. This causes social tensions and conflicts, which endanger the world's sustainable development. Until now the water resources management strategy has not been based on sustainable development. The main water resources management strategy has been based on higher equality in comparison to water availability.

2. CHALLENGES AND OBSTACLES TO THE FAIR DISTRIBUTION OF WATER IN THE WORLD

2.1. *International Laws on Water*

The United Nations' agreement on issues related to the environment is incomplete. Although this agreement is considered a guideline, it does not pay attention to development issues, therefore the following items should be included:

- Countermeasures of National and International laws and regulations;
- Challenges related to those supporting human rights and nature;
- Equity in water resources exploitation;
- Fair distribution of the resources throughout the world;
- National governship.

International laws should be considered as a global product in which technology is transformed into an effective tool for controlling legal regulations.

2.2. *Water Trading*

Increase in water demand has made the big trading companies of the world consider water as a beneficial trading good. The water industry is a profitable industry from the World Bank's point of view. Water is referred to as Blue Gold in the 21st Century. International trading agreements have been the most important tools for those trading companies active in the field of water.

Water is considered an economic commodity from their point of view, therefore laws and regulations on Oil and Gas govern water as well. Under these regulations none of the countries have permission to boycott water export without the World Trade Organization's authorization.

Hence, water is considered an economic good. In this case we may face the risk of leaving out the vital importance of water in human life, which may ruin various components including sustainability, productivity and ecosystem conservation.

The attitude toward privatization has accelerated in recent decades. Privatization has been publicized when free marketing (trading) and free investment have been proposed. According to this philosophy, management of social projects and resources is left to the private sector (modernism). This concept is quite different from religious and traditional perspectives. It is even in contradiction with the new postmodernist vision, which seeks a consistency between modernism and the positive aspects of tradition.

The pressure towards water resources privatization will increase by implementing new foreign trading laws and regulations. This process places at serious risk the lives of poor people and the environment. Water trading and privatization which both follow capitalist mechanisms are in contradiction with water human rights.

Virtual water trading should also be considered when discussing water trading. At present, around 15% of the entire countries' water requirements for crop production are via water with an external origin. The countries' and continents' shares is different and depends on available water resources and cropping patterns. Virtual water trading is one of the important processes toward globalization.

2.3. *Water in the Islamic Civilization*

Water is the principal vital element in legends and religion. Islam has referred to water and its role in human life in many situations. Different verses of the Holy Book, Quran, point out the importance of water, as follows:

> Verse No. 31-Anbia: 'We made every living thing from water'
> Verse No. 450-Noor: 'God created every living creature from water'

In most religions water is considered an important and holy substance.

In the constitutional laws of Islamic countries water is considered a public commodity, which is under the authority of the government.

According to principle No. 45 of the I.R. Iran constitutional law, water is considered a common wealth. It is under the authority of the Islamic Republic of Iran. Water is exploited according to the main laws of fair water distribution. Water conservation and supervision is left to the Ministry of Energy.

2.4. *Main Components of Water Issues in the Middle East*

Several components indicate the nature of water issues in the Middle East.

– Severe Water Shortage: The gap between demand and supply continuously increases and new resources should be provided in the region. Empowerment in water consumption and supply management is necessary. In order to achieve this goal the economic structure of the region should be altered;

– Water Reciprocal Issues: 90% of the surface water resources in the region pass through boundaries in the region;

– Political, Economic and Social Differences: Different countries in the region have various perspectives and visions on social, political and economic affairs as well as the water regime. The differences should be determined and studied, so that water-related problems could be solved in the region;
– Political Conflicts: The relation between different groups in the region varies. This may change from enmity to sustainable peace. Although the procedure is toward peace, it may change at any time;
– Defined Boundaries: In spite of efforts taken in the region, vast boundaries are still not determined by international authorities, therefore water rights are not clearly known in the boundaries of two countries. This causes local conflicts. Generally speaking, determining water crisis consequences and impacts in the Middle East is essential for national, regional and international security.

2.5. *Fair Conveyance and Distribution of Water*

New technologies in engineering works to better control the water cycle have mostly solved constraints related to non-homogeneous distribution of rainfall.

Agricultural, industrial and domestic production has increased with the contribution of large reservoirs and huge structures controlling conveyance and distribution have rapidly expanded, although this process has caused environmental destruction and higher expenses for water projects. Huge water conveyance projects are gradually being expanded in various parts of the world, such as groundwater conveyance from the southern deserts of Libya to the north and others such as transferring water from the Yangtze Kiang in the center of China to the Yellow River.

Fair water conveyance and distribution is an ensuing response to non-homogeneous distribution of rainfall, which should take into account legal, environmental, social and political considerations. It is essential to consider the cultural and social aspects of the projects when investigating water conveyance options. Undoubtedly, ignoring these kinds of considerations will result in unsuitable political and security conditions.

3. CONCLUSION

No influential law is available for utilizing international water, but legal, moral and ethical criteria for equity exist. There is a willingness to adopt water-sharing patterns in future, which will replace domination;

The attitude toward considering water as a sole economic commodity is too soon and social impacts should be taken into consideration as well;

Economic and trading tools include pricing, water marketing, standards, regulations and productivity criteria. Legal principles, privatization, training and civil cooperation are amongst the issues which still need to be investigated and analyzed;

Many governments have left the construction, operation and management phase to people (privatization), due to the high costs of water resources development plans. Although this will contribute to the financial part and the financial sustainability of the system, they will cause severe risks to the environment and to the poor;

Water is one of the elements of human needs that should be fairly distributed while respecting historical water rights;

Binding to the principle of water democracy and attracting civil cooperation is necessary; therefore, management of the most vital substance (water) in the world cannot be left solely to governmental bureaucracy or private companies;

Although water can be a lever for economic and political pressures, evidence proves that water is not used as a weapon due to religious and cultural trainings in the Islamic world. On the other hand, water can be considered a main axis for cooperation between governments (e.g. Doosti dam as a collaborative symbol between I.R. Iran and Turkmenistan);

Water crisis consequences for national, regional and international security require investigation on international financial and legal organization situations;

One of the most complicated water legal issues is a precise definition of international water resources and the level of authority of the governments on these resources;

Water and food security and food self-sufficiency are inaccessible and insistence on being food self-sufficient is due to national vulnerability. To overcome this problem, international legal consistency is required;

In contradiction to some concepts, conflicts between civilizations cannot be attributed prevalently to culture. This theory is based on materialistic achievements, while culture is a phenomenon beyond materialism. The present era is an era for dialogue among civilizations and civilization convergence. Undoubtedly fair water distribution at the international, regional and national level in countries with the same culture is much easier. Since water has played the main role in the creation of civilizations, fair water distribution and conveyance in regions with even different cultures could lead societies to get closer to one other.

All these subjects need to be explored enough through scientific discussions.

BIODIVERSITY AND HYDROLOGIC DYNAMICS

THREATENED BIODIVERSITY: UNDERSTANDING, PREDICTING, TAKING ACTION

MARINO GATTO & RENATO CASAGRANDI

1. *What is Biodiversity?*

The history of biodiversity is actually the history of life itself, which originated quite likely 3.7 billion years ago, certainly in the water, perhaps in deep sea vents (see Fig. 1, page 207). We must not forget that the Earth's crust and atmosphere, as we know them, have been shaped by the evolution of diverse organisms.

Life originated in anoxic environments (originally there was no oxygen in water and the atmosphere). The appearance of organisms with the ability to photosynthesize allowed the build-up of oxygen and the development of an atmosphere like the one we experience today.

In his book *What is Life?* the famous Nobel prize for physics Erwin Schrödinger (1944) predicted that the most essential part of a living cell is an aperiodic crystal. His prophecy, which somehow inspired James Watson (according to his statements, 2003), was confirmed by the discovery of the structure of DNA and other nucleic acids a few years later. Schrödinger pointed out that the genome must be on one side very stable – after all, one of the main characteristics of organisms is that they can make copies of themselves – but on the other side quite flexible, that is, capable of development, evolution, and ramification, in other words of diversification. In fact, the structure of DNA possesses exactly these remarkable features. Without knowing anything about genetics or molecular biology, one of the giants of modern scientific thinking, Charles Darwin, had already understood the main mechanisms of this incredible ramification (Darwin, 1859). Life diversification is driven by mutation, but if mutation, that is randomness, were the unique cause of diversification we would not see patterns and organization in the Earth's biosphere. Instead, life organization is shaped by the process of natural selection. First of all, mutation is anyway quite infrequent, because of genome stability, and many mutations are deleterious. Of the nondeleterious ones just a few can pass through the sieve of natural selection, which favors those mutants that have a demographic advantage. Selection is very severe, but the sieve acts continuously on myriads of organisms, so it is very effective in the long term and produces organisms adapted to their environment. In small populations neutral mutations can establish, due to a random process called genetic drift (this was pointed out more recently by Kimura and Crow, 1964). In addition, we must not forget that, during the course of life ramification, the evolution of the various organisms has been constrained by the presence of other organisms ecologically interacting with them: therefore evolution is actually co-evolution and adaptation is co-adaptation.

Each organism is unique as it is identified by its genetic code, but one can easily recognize groups of organisms, clusters of genotypes that are very similar. It is the well-known concept of species. The definition is quite clear for sexual beings, for which we refer to a species as to a set of individuals that interbreed freely with one another to produce fertile offspring. In the case of asexual species, it is much more difficult to group organisms and the choice can be to some extent arbitrary, because it is based on their 'characters'. More and more frequently, however, this classification is based on genetic differences. For instance, in the case of the ubiquitous cyanobacterion *Prochlorococcus* (perhaps the most important oxygenic photosynthesizer of the world's oceans), only the analysis of the genome can distinguish between two different strains (*Prochlorococcus marinus* MED4 and *Prochlorococcus marinus* MIT9313) that actually turn out to play significantly different ecological roles (Rocap *et al.*, 2003).

But genetics or taxonomy do not tell us the whole story. We can actually distinguish hierarchies of biodiversity. There is diversity of genomes inside each species, diversity of species and other taxonomic classes inside an ecosystem and diversity of ecosystems inside the landscape of a region. Traditionally, species diversity is the one most commonly used but there is a growing consensus among biologists that diversity of species functions within an ecosystem and diversity of habitats within a landscape play a very important role and deserve much more attention than that devoted to them up to now. If we consider a single ecosystem, we can for instance pay attention to its trophic structure distinguishing primary producers (e.g., plants), herbivores, carnivores, secondary carnivores and decomposers. Very often, it is reasonable to study species diversity inside each trophic level or guild (group of organisms playing a similar ecological role in the community). But the overall picture of ecosystem diversity can be obtained only by coupling these studies with the study of the food web structure and the flow of energy and materials within the web.

2. *Patterns of Biodiversity*

The most basic question one can ask is how much we do know about the biodiversity of our planet in simple descriptive terms. Actually, very little: we do not even know how many species are hosted by our mother Earth. At present, about 1.75 million species (Purvis and Hector, 2000) have been classified, but many more are still waiting for us to recognize their sheer presence (so much the less for describing their physiology or ecology). The best estimate is that there might be 10 million species, but the uncertainty of the estimate is very high (between 3 and 30 million). Also, the knowledge of world biodiversity is not the same across the taxonomic groups (see Fig. 2, page 208). It is very good for birds and mammals and very bad for bacteria. Insects are the dominators of our earth, because they have ramified into an incredible number of species.

Biodiversity is not spread evenly across the earth. There are a few regions that contain a high number of species, which are in many cases endemic, namely specific to that particular site. These regions (see Fig. 3, page 209) have been called hotspots by Norman Myers and colleagues in a keystone article (Myers *et al.*, 2000). Of course, hotspots are very important because they need a special attention when we want to design global policies that aim at preserving biodiversity on our planet.

From the available, though insufficient, data it is possible to recognize some precise geographic patterns of species diversity on our Earth. This empirical knowledge is preliminary to understanding the mechanisms that determine species diversity. First, there is a clear latitudinal gradient of biodiversity from the poles toward the equator (see Rohde, 1992). For any kind of guild or taxonomic group, be it butterflies or lizards or birds, we can say that there is an increasing number of species as we travel from the poles to the tropics. Second, there is a remarkable area effect. This is specially apparent in archipelagos, where there is a clear power law relating the number of species S to the area A of each island: $S = cA^z$.

Surprisingly, the exponent z is about 0.3 for a great variety of taxa and geographical locations (Preston, 1962). But the species-area power law operates even in the habitats that constitute islands inside the mainland, like lakes or caves or forest fragments. Third, there is a relationship between species diversity and climatic indicators (Gaston, 2000). For instance, summer temperature is a main determinant of bird diversity in Britain and sea temperature is a key factor for gastropod diversity in the Pacific. Evapotranspiration is not only the main explanatory variable for tree diversity, but is a main determinant of animal diversity, although the relationship for higher trophic levels is saturating.

Describing biodiversity only in terms of the number of species is too simplistic, since the concept of diversity is actually multidimensional and hierarchical as we already pointed out. In particular, species can be more or less abundant. Ecological communities with one or two species that are very abundant and dominate the landscape are intrinsically less diverse than communities in which all the species have more or less the same abundance. So, observed species-abundance relationships are crucial to properly describing biodiversity. Also, size, color, shape, physiological and genetic traits are yet other important components of diversity.

Can we explain the underlying causes of the various diversity patterns? The word 'explaining' here means formulating scientific theories that are validated by data and can make correct predictions. There are a lot of theories, and reviewing all of them goes well beyond the scope of this article. To give the flavor of how complex the problem is, we just provide a few ideas about how to approach this kind of questions.

The modern theory on what shapes the distribution of species within the same trophic level (for instance, herbivores) is due to one of the most brilliant ecologists of the past century, Robert H. MacArthur. He developed a clear methodological approach to the problem of competition for common resources and precisely defined the concept of ecological niche by means of his utilization functions (MacArthur, 1958). These are defined as the probability that different resources be utilized by each species. In general, similar species occupy the resource dimensions with niches that overlap, but not too much (limiting similarity). It was shown by May and MacArthur (1972) that species can coexist if approximately the niche width (measured, for instance, by the standard deviation of the utilization function in one-dimensional resource spaces) is smaller than the distance between niches. To what extent the principle of limiting similarity can be generalized is an open question, debated from the early 1970s to date (e.g., Meszéna *et al.*, 2006)

MacArthur's approach (1957) allows the prediction of several species-abundance relationships that might result from different competition rules.

If there is resource pre-emption with the arrival of a first species that utilizes a proportion *k* of the resources, then of a second species utilizing the same proportion *k* of the remaining 1-*k* and so on, the resulting abundance distribution is a geometric series. If the species arrivals are random, the distribution is a log-series. By contrast, suppose that all the competing species occupy the resource space simultaneously, but the allocation of resources among species is just random. Then the process is similar to taking a chocolate bar and dividing it at random. The species that gets a bigger chunk will have greater abundance. This paradigm is aptly called the *broken-stick model*. Finally, there might be many random factors and resources that are important for competition and act in succession. The central limit theorem would predict a log-normal distribution for this case.

When we look at the data we discover that, depending on the circumstances, they can actually match one or the other of the 4 models (or even a combination of two models as in the case of Bristol Channel fish shown in Fig. 4) or none of the models described above. This is not discouraging. It simply means that the problem of explaining biodiversity is complicated. There can be concurrent phenomena acting together, but accurate analysis of data and ecological theory can unravel, if not the totality, at least part of the underlying causes of the observed diversity patterns.

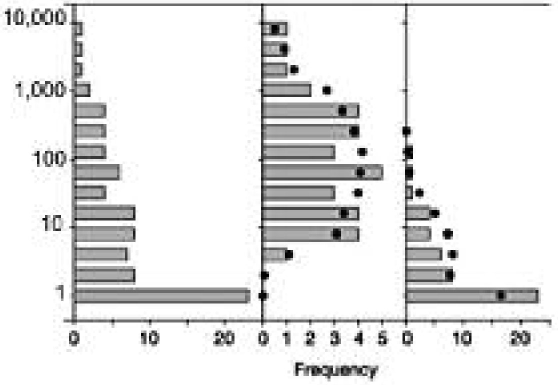

Figure 4. Reprinted with permission from Magurran and Henderson (2003). The data for a fish community in the Bristol Channel, UK. The abundance distribution for all species (left histogram) can be seen as the sum of the abundance distribution of the core species (central histogram) and the abundance distribution of the occasional species (right histogram). The black dots in the central and right panels represent a log-normal fit and a log series fit respectively.

However, biodiversity should not be understood only within a trophic level, but also across the food chains of the whole ecosystem. For instance, if we lose species from the ecosystem food web, how much is the ecosystem functioning (suitably defined) compromised? Given the present loss of species richness at the global level, this is not only a theoretical question but has important practical implications. It is generally recognized, from both data and theories, that fortunately there is some kind of redundancy. In other words ecosystem functioning does not linearly increase with species richness, but is saturating. There are several ways to quantitatively describe ecosystem functioning. One is productivity (for instance, net primary production or standing biomass per unit area). The experimental and theoretical work (especially important the analysis of grasslands by Tilman and colleagues, 2001, see Fig. 5, page 210) confirms that ecosystem productivity increases with species richness according to a nonlinear concave relationship.

A second way to describe ecosystem functioning is stability. Here the problem is much more complicated. The traditional viewpoint, which goes back to the 1950s and the work of Charles Elton (1958), is that more diverse systems, such as tropical forests, are intrinsically more stable than species-poor communities. The celebrated experiments by Robert Paine (1966) with the manipulation of rocky tidal communities seem to confirm this viewpoint. When Paine eliminated the top predator (the starfish) from the community, the ecosystem collapsed with mussels becoming the dominant species. However, the Elton-Paine viewpoint was challenged by the theoretical analysis conducted by Robert May (1973). He showed that in general more complex dynamical ecosystems are less stable. In fact May's condition for community stability in randomly assembled food webs is:

$$SC < i^{-2}$$

where S stays for the number of species in the community, C represents the probability that any pair of species will in fact interact (food web connectance) and i is the average interaction strength.

By assuming that both web connectance and species interaction strength are more or less independent of the species number, May obtained that the likelihood of having all the eigenvalues of the community equilibrium with negative real parts, which implies community stability, is higher when the number of species is smaller. Robert May's provocation stimulated a lot of work (reviewed by McCann, 2000). Many authors pointed out the weakness of May's assumption that (1) food webs are randomly assembled, (2) the interaction strength is constant, (3) stability is defined à la Lyapunov (internal stability of equilibria). These conditions are unrealistic because: first, food webs are not random, rather the result of coevolution; second, the links between different ecosystem components can be extremely strong or weak and variable in time; and third, community diversity can be maintained by external disturbance. In extreme synthesis, after a long debate it is now widely believed that both data and theory support the original Elton-Paine intuition that more diverse ecosystems are more stable or resilient or resistant to perturbation.

3. *The Loss of Biodiversity*

The problem of present and future biodiversity loss is confused by some people with the 'natural' ebbs and falls of diversity at the evolutionary timescale. Our Earth has always been experiencing biodiversity loss since the origin of life. More precisely, there have been five periods of mass extinctions followed by subsequent radiation. The causes of these extinctions are not very well-known. In contrast, the cause of the forthcoming sixth extinction is very well-known and it is man. That's why Paul Crutzen (2002) has termed the present era the *Anthropocene*.

When the skeptics say that species have always become extinct and we should not worry, they make a very common mistake: they pay no attention to the time and space scale. The problem is that the geological lifetime of species was of the order of millions of years, while it is now estimated to be of the order of tens of thousands of years. In particular, birds and mammals (Fig. 6, see over) are very much endangered, because their species lifetime is reduced to hundreds of years (Lawton and May, 1995). Islands are specially vulnerable, because of the species-area relationship we cited above. Of the many bird species presently inhabiting the Hawaii, few are indigenous because the majority of them have become extinct or are on the verge of extinction. Of the current 272 bird species found in the Hawaii, 54 are alien, 50 are native resident species, 155 are nonbreeding visitors and 13 breeding visitors. It is estimated that before man's arrival (about 2000 years ago) there were at least 128 species of native breeding birds (American Ornithologists Union, 1983).

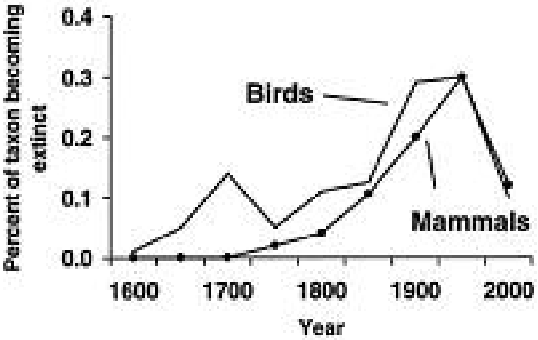

Figure 6. Reprinted with permission after Primack (1998). Changes in extinction rates over time in mammals and birds as estimated by Smith *et al.* (1993).

What are the main factors leading species to extinction? Statistics have been made. The most important one is the destruction and degradation of habitat, followed by the introduction of exotic species, by pollution and by overexploitation. There are many examples of habitat degradation, the most impressive being probably the daily destruction of tropical forests at unbelievable rates. While the forests of Europe have been destroyed and fragmented on a time scale of centuries, and with the aim of building villages and towns that originated our present culture, the Amazon forest is being destroyed on a much shorter time scale (just a few decades) and mainly to produce resources for what we call the developed countries. Often fragmentation is linked to road construction as in the example of Brazil rain forest. Sometimes, like in the example of Bolivian forests shown in Fig. 7 (see over), the land use is being converted to soybean cultivation for export, mostly funded by foreign loans. Destruction is unfortunately very fast and creates an unnatural mosaique of patches at different spatial scales.

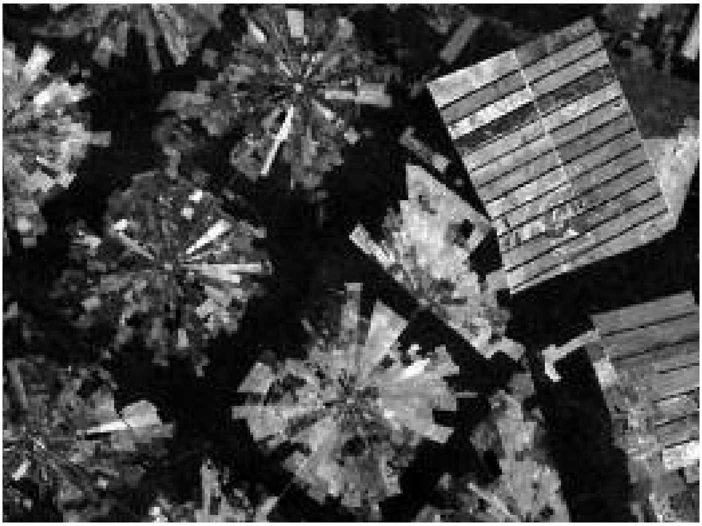

Figure 7. A Landsat7 image dated august 2000 showing the new agricultural settlements east of Santa Cruz de la Sierra, Bolivia in an area of tropical dry forest. (Credit Landsat image courtesy USGS EROS Data Center and Landsat7 science team. Photographs courtesy Compton Tucker, NASA GSFC).

Many modelling efforts are currently made to understand and predict the loss of biodiversity due to habitat fragmentation. First of all, it is important to remark that even unperturbed populations are in many cases fragmented. The butterflies *Melitaea cinxia* in the Ålan Island (Hanski *et al.*, 1995) and *Euphidra editha* in California (Harrison *et al.*, 1988) are just two famous examples. The first species lives in a landscape composed by hundreds of vegetation patches located in many islands while the second requires a particular habitat (serpentine grasslands) which is patchily distributed in California. The famous ecologist Richard Levins (1970) was the first who used the term metapopulations (namely 'populations of populations') to indicate a set of local populations in which local extinctions can be balanced by dispersal from other occupied patches. Metapopulation is now the current paradigm not only for populations inhabiting naturally inhomogeneous landscapes but also for populations endangered by habitat fragmentation. The key points are two: (1) local populations can become extinct, because they are small and subject to random effects, but (2) dispersal from occupied patches can lead to recolonization of empty habitat patches thus salvaging the global metapopulation. There are several models for studying the process of extinction in fragmented populations (see Hanski and Gaggiotti, 2004). The fundamental parameters that describe every metapopulation are the landscape structure (number and average size of fragments and distance among patches), the ability of the species to disperse and colonize empty fragments, the demographic potential of the species inside each habitat fragment. One of the fundamental points for appropriately evaluating the risk of extinction is that each fragment hosts very few individuals. So an appropriate model is one that considers individuals as discrete entities subject to demographic stochasticity (Casagrandi and Gatto, 1999; Casagrandi and Gatto, 2006).

Using a Markov model and assuming initially no space structure (i.e., an infinite number of equal and equally connected patches), we have shown that metapopulation persistence requires a sufficiently high rate of demographic increase (and this is somehow obvious) and an intermediate dispersal rate (this is less obvious). Therefore, species that are most at risk are those moving too little, because empty fragments cannot be effectively recolonized, or moving too much, because dispersing individuals can end up in unsuitable habitat without being able to reach suitable habitat patches. But the really interesting result is the one we obtain when we consider realistic, space-explicit metapopulations in which we have a finite, small number of patches, each hosting a local population with a discrete number of individuals that can disperse only to contiguous patches. The principle of intermediate dispersal is still valid. Obviously the likelihood of species extinction is higher than that in a very large network of patches connected at any space scale. We can actually quantify the proportion of species that are lost because only a few habitat fragments are left. There is a power law relating this proportion to the number of patches (Fig. 8, see over). The result is theoretical, but has some implication for applied problems too. For instance we can estimate that the cost of losing a habitat fragment when there are 5 patches left (each hosting at most 10 individuals) is the loss of a further 4% of the species living in the fragments. So, theoretical work can lead to important predictions on the loss of biodiversity we may expect in the future decades.

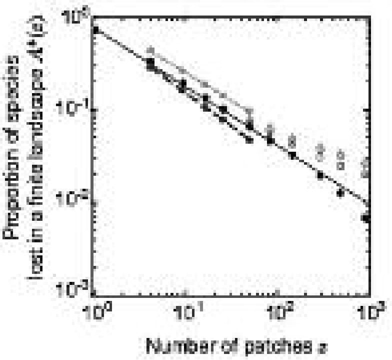

Figure 8. Reprinted with permission from Casagrandi and Gatto (2006). The proportion of species A*(z) that are lost in a fragmented landscape composed by less than infinite fragments is plotted against the number of patches z. As it is evident, there is a power law indicating that it is at least roughly possible to estimate the number of species lost by destroying a patch.

In addition to habitat fragmentation and destruction, there is now another major threat to future biodiversity loss and this is Global Climate Change (GCC). The golden toad (*Bufo periglenes*) of the mountains of Costa Rica is probably the first species that was officially declared extinct because of climate change. An estimated 67% of the 110 or so species of harlequin frogs (*Atelopus sp.*), which are endemic to the American tropics, have met the same fate (Pounds *et al.*, 2006). Other species escape from climate change by moving. Others, with possible effects on man's health, such as malaria carrying mosquitoes, thrive in the warming environments. In the oceans, coral reefs are the ecosystems hosting the most of diversity. They are very sensitive to temperature, because they can survive only inside a restricted range of water temperature. There have already been several episodes of coral bleaching and this is certainly related to increasing sea surface temperatures, as documented by the NOAA-NESDIS (National Oceanic and Atmospheric Administration, National Environmental Satellite Data and Information Service) and by the UNEP-WCMC (United Nations Environment Program – World Conservation Monitoring Centre).

A lot of modelling work is now being done to forecast the loss of biodiversity due to global climate change. Before discussing this matter, let us point out that organisms are among the best indicators of global warming. The ecological fingerprints of GCC, as they have been called, are clear. The shift in plant and animal phenology (namely the time of flowering or reproduction) is apparent. In the recent decades there has been a mean shift of 5 days per decade with birds being the most sensitive to the climatic signal (Root *et al.*, 2003). Poleward shift of indicator species like butterflies is also being discovered (Parmesan *et al.*, 1999). Very clear is the elevational shift too. For instance the response of Alpine vegetation (the beautiful flowers of European Alps) to warming is of a few meters per decade (Grabherr *et al.*, 1994).

Studying the effects of GCC on our planet biodiversity is not an easy task. The web of impacts is very intricate and there are a lot of pathways one should account for (Hughes, 2000). Different time scales are involved (physiological, demographic, behavioral and even genetic if we consider adaptation); different trophic levels and species interactions must be considered, at least in principle.

We can make a classification of models that can be used to predict the response to global climate change. First, models can be static or dynamic. Static models assume that we observe populations only at equilibrium (which is sometimes a reasonable approximation for short-lived species) and that species' distribution and abundance are related to exogenous factors, including climate, through a simple function. In practice, one assumes that species can track the climatic change without any delay. In dynamic models the response of species to the global warming trend is not instantaneous and time lags are considered. For instance models of this kind try to predict the shift of treeline. Second, models can consider species as isolated or describe the response of the whole ecological community. Clearly, it would be necessary to consider species interactions, but this is rarely done in practice, because it complicates the problem awfully. As of now, the most common approach is to use individualistic responses of the different species and simply make a collection of a great number of them. Finally, conceptually different models must be used for different spatial scales. For instance, the vegetation distribution at a broad scale (tens of kilometers) is mostly governed by the climatic tolerance of species physiology, while at a finer scale the soil composition and topography play an important role. Of course, regional governments would like to know what the global change will imply at a reasonably detailed local scale. '*Think globally and act locally*' is an often abused statement, which is however very sensible. A lot of effort is now being devoted to this point but there is an important problem: that of downscaling global climate models. Even the most recent coupled atmosphere-ocean general circulation models have a resolution of a few hundred of kilometers. Regional models with a resolution of 50 km are being developed for limited areas via suitable downscaling techniques. So, the problem is not solved at the climatic level yet, much the less at the ecological level.

Probably the most used models to predict the impacts of GCC on ecosystems are the so-called envelope models. Usually they are based on describing the climate or environment encompassing the current distribution of a species or ecosystem (the environmental envelope or climatic envelope), then mapping the location of this same envelope under a climate change scenario. The various envelope models of a great many species can be put together to produce predictions of changing biodiversity. Fig. 9 (see page 211) shows the results of this kind of simulation for Europe in 2100. Mediterranean countries and the Balkans will be most affected in the future. It must be remarked that habitat fragmentation and GCC can have a synergistic effect. Species would like to move to avoid global warming, but that might be impossible because there are barriers and few or no corridors left to escape. A recent projection for the world biodiversity by Thomas and colleagues (2004) indicates that 25% of the species might become extinct by 2050 (mid-range scenario). Even if this prediction were wrong by an order of magnitude the loss would be anyway devastating.

4. *The Value of Biodiversity*

A question that is frequently asked is why we should preserve biodiversity. Is it really so 'valuable'? Isn't it a waste of money, a luxury that only rich countries can afford? Clearly this question involves not only science, but also ethical considerations. Social scientists make a distinction among direct value (what we can extract from organisms, namely food, fiber, etc.), indirect value (the free services provided by ecosystems) and intrinsic value (aesthetic, spiritual, etc.). We will not discuss this third kind of value, which is in a way evident but in another way more debatable.

Let us first give a very clear example of ecosystem services. During the tsunami that hit the shores of East Asia in December 2004, in the areas of Sri Lanka where the coral was still intact, the wave travelled just 50 meters inland without causing any death. Unfortunately, this did not happen a few kilometers away where coral reefs had been illegally destroyed

(Fernando, 2005). Ecosystem services are indeed uncountable. The following list of benefits provided by ecosystems is certainly incomplete:

- moderate weather extremes, thus contributing to climate stability
- mitigate drought and flood impacts
- protect stream and river channels and coastal shores from erosion
- protect people from the sun's harmful ultraviolet ray
- cycle and move nutrients
- purify the air and water
- detoxify and decompose wastes
- control agricultural pests
- regulate disease carrying organisms
- disperse seeds, pollinate crops and natural vegetation
- generate and preserve soils and renew their fertility

While at the beginning of the 1970s there was a growing awareness that environmental evaluation and assessment is as necessary as economic evaluation (just think of the legislation on EIA – Environmental Impact Assessment – that was passed in North America and Europe), in more recent years the old logic that economic evaluation should prevail on any other consideration has gained new strength. This led Robert Costanza and colleagues (1997) to conduct a purely monetary evaluation of the resources and services that are provided to us by biodiversity. They estimated that these services were worth US$ 33 trillion (global GNP being US$ 18 trillion). Although that approach has been criticized (Gatto and De Leo, 2000), we must admit that its results should convince even the most skeptical economist. In other words, preserving biodiversity does pay off. Ecosystem services are worth at least twice the global GNP. Any time we lose a species, we may lose the potential remedy for a disrupting disease affecting humanity. In fact 80% of the world's population relies upon natural medicinal products. Of the top 150 prescription drugs used in the U.S., 118 originate from natural sources: 74% from plants, 18% from fungi, 5% from bacteria, and 3% from one vertebrate (snake species). Nine of the top 10 drugs originate from natural plant products. Over 100,000 different animal species – including bats, bees, flies, moths, beetles, birds, and butterflies – provide free pollination services. One third of human food comes from plants pollinated by wild pollinators. The value of pollination services from wild pollinators in the U.S. alone is estimated at four to six billion dollars per year.

Benefit-cost analyses can be conducted and they show that it is not true that preserving biodiversity is too expensive for developing countries. Actually, the cost of preservation is largely outweighed by the benefits (see Balmford *et al.*, 2002, 2003).

5. *Preserving Biodiversity*

An extremely difficult, but urgent, question we can make at this point is about what we should do, as humanity, to preserve biodiversity. A couple of ecologists alone, as the authors of this chapter, cannot face such a huge question in a serious way, of course. However, we can try to introduce the problem by hinting at the main discussion that is taking place right now: Where should the efforts at a global level be directed? Financial and other resources that can be devoted to preserving biodiversity are limited. So there is a problem of optimal allocation of money, time, labor, etc. Where should our dollars or euros go? To preserving the Mediterranean flora or the Australian fauna? As mentioned at the beginning of this chapter, Norman Myers and colleagues (2000) identified 25 hotspots of biodiversity in the world using species endemism and degree of threat. That work sparked a very useful debate. Obviously, the optimal allocation is really a multicriteria problem. The answer depends on the criterion being used. Recently, Orme and coauthors (2005) have performed a very interesting analysis on bird biodiversity (avian fauna is very well known) considering 3 different criteria: species richness, species threat, and endemic species richness. The resulting hotspots do not coincide, as you can see from the 3 maps overlaid in different colors in Fig. 10 (see page 212). However, there is some overlap among the areas identified by the 3 criteria. Endemic species richness is apparently the criterion that is most representative, in the sense that it includes areas and species that are also included by the other criteria. The hottest hotspot is Tropical Andes which is pinpointed by all 3 criteria. It is interesting to remark that the hotspots are mainly located in highlands and archipelagos.

This viewpoint is partially contradicted by another analysis which considers a different indicator of ecological diversity. It is true that the species is the key concept of diversity and the basic unit of life evolution. However, we already mentioned that ecosystem functioning is another important goal. And even the goal of preserving species might be better achieved by aiming at preserving not each species but rather the habitat where species live (Hoekstra *et al.*, 2005). So another possible target of conservation is that of preserving habitats and biomes that are fast disappearing, like the Mediterranean vegetation. It is interesting to note that, for instance, in Hoekstra *et al.*'s (2005) map Tropical Andes are no longer present. They have a very high endemic species richness, but the habitat as a whole is not currently critically endangered. Also, consider that some ecosystems hosting little biodiversity, like the vast tracts of boreal forests from Russia to Canada, provide important ecosystem services such as the uptake of carbon from atmosphere, which is fundamental for the mitigation of global warming. These ecosystems were not classified by Myers *et al.* (2000) as hotspots of biodiversity, yet they deserve conservation. So the debate is very much open.

An important issue for global conservation is that of gap species. In September 2003 it was announced that the global network of protected areas now covers 11.5% of the planet's land surface (at least formally). This seems a very good achievement, actually beyond the target set a decade ago. However, the protected areas are not designed in such a way as to really protect the necessary amount of biodiversity. In particular there are many species that are officially declared as endangered by IUCN (International Union for Conservation of Nature) and are not inside any protected area (Rodrigues *et al.*, 2004). Overall, 20% of all threatened species analysed were identified as gap species. In particular, amphibians are given little protection. By the way, from this analysis it turns out that Tropical Andes has a lot of gap species!

So what should we do? Personally, we think that the preservation of ecosystem functioning must be given special attention, more than it is currently given. The regulation of the climate of our earth is of paramount importance. For instance, no effort should be spared to conserve soils which are the most important terrestrial sink of carbon.

6. *Conclusions*

Understanding and protecting biodiversity is of paramount importance for humanity. As pointed out by Simon Levin (1999) our Earth is an incredibly complex yet fragile dominion. For millennia man has taken for granted that its functioning is very resilient and that human disturbance is small and can be absorbed by the surrounding environment. This is no longer true. The scale of human perturbation has become global. In 16,000 years the human population has expanded more than a thousandfold in numbers, from a few million to over six billion by the turn of the 21st century; fish stocks are now depleted all over the oceans (Watson and Pauly, 2001); the combustion of fossil fuels has driven the concentration of carbon dioxide to levels unprecedented in the past 650,000 years (Siegenthaler *et al.*, 2005), and tropical forests which are the most diverse biomes on our planet are being destroyed at very high rates (The Food and Agriculture Organization, FAO, estimates that 53,000 square miles of tropical forests – rain forest and other – were destroyed each year during the 1980s). As a consequence the bank of world biodiversity, an astonishing array of genotypes playing the most different roles in the wonderful theatre of life, is being disposed of day after day.

In the chapters of Bible describing the deluge and Noah's ark we can find the verses:

> The Lord then said to Noah, 'Go into the ark, you and your whole family, because I have found you righteous in this generation. Take with you seven of every kind of clean animal, a male and its mate, and two of every kind of unclean animal, a male and its mate, and also seven of every kind of bird, male and female, to keep their various kinds alive throughout the earth' (*Gen.* 7:1-3).

It is interesting to notice that God said to Noah he should bring with him any sort of animals, both clean and unclean. In this chapter we have shown that there exist compelling scientific and economic reasons for protecting our biosphere, but we think it is also a moral obligation for us to preserve biodiversity in its totality, from the beautiful giant pandas to the humble earthworms. They are all necessary to the well-being of our living planet.

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ECOHYDROLOGICAL OPTIMIZATION OF PATTERN AND PROCESSES IN WATER-LIMITED ECOSYSTEMS

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1. Introduction

The coupled nature of hydrological and ecological dynamics is perhaps nowhere more evident than in semi-arid ecosystems. Frequently stressed and sensitive to change (Guenther *et al.*, 1996), semi-arid ecosystems are responsive to climate variability over relatively short time scales, and water is the main driving force in shaping the vegetation distribution and composition (Rodríguez-Iturbe *et al.*, 1999; Smit and Rethman, 2000). The dynamical nature of the vegetation response to water availability is a prominent feature of semi-arid ecosystem function, as is evident from satellite observations (Goward and Prince, 1995; Scanlon *et al.*, 2002). Despite the close coupling that exists between water and vegetation structure, the challenge of predicting vegetation response to changing climate in these environments is particularly daunting (Daly *et al.*, 2000). Specifically, a central challenge is defining the ecologically and hydrologically relevant processes that led to the formation of vegetation patterns in water-limited ecosystems.

The complex interactions between plants, soils, and climates in semi-arid ecosystems make it difficult to define specific ecohydrological optimization mechanisms that underlie observed landscape-scale patterns in vegetation structure. Regional models of semi-arid vegetation structure are often biogeographical in nature, making predictions based exclusively on the role of external factors such as mean annual rainfall, or soil infertility imposed by geologic constraints. These kinds of relationships often yield reasonable predictions of savanna ecosystem structure (Sankaran *et al.*, 2005; Huxman *et al.*, 2005), but provide little additional insight in the specific ecohydrological processes that maintain vegetation-climate co-organization. At the scale of plant canopies, it has also been recognized that the role of vegetation itself

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on resource availability can be critical in semi-arid ecosystems (Archer *et al.*, 1988). Indeed, the strong control that individual plants can exert on local water balance has recently been highlighted by the field observations of Seyfried *et al.* (2005) and Ludwig *et al.* (2005) who demonstrate variation in surface moisture redistribution caused by the mosaic of vegetation patches and inter-patch areas in a variety of semi-arid ecosystems. The conceptual models arising from these field-scale studies explicitly couple biological pattern to abiotic factors; usually driven by soil moisture, but often also thought to be determined by nutrients, herbivory, or fire. Based on these considerations, more recent models of savanna structure have taken the small-scale spatial structure of semi-arid ecosystems into account (Jeltsch *et al.*, 1999).

There remains a need to clarify the manner by which vegetation self-organizes across scales within semi-arid landscapes, and how regional, landscape, and individual-based patterns of vegetation interact with their accompanying climates and soils. Such clarification necessitates the development of conceptual models capable of interpreting and predicting spatial pattern formation in savannas (and similar dry woodland ecosystems) as well as metrics for assessing optimization or organization of patterns as one scales from individual canopies to landscapes and beyond.

Here we highlight some recent efforts to link the surface hydrological cycle to the dynamics of vegetation pattern, which we have characterized through both observations and modeling across a suite of semi-arid ecosystems. We emphasize that the results presented here are an exploration of the general hypothesis that many semi-arid ecosystems tend to self-organize with respect to optimizing water use. In our view, a key difficulty arises in assessing which metrics of optimization are relevant at different spatial and temporal scales of interest. For instance, are there generalities of optimization regarding water use that exist across ecosystems? If so, do signatures of 'ecological fitness' leave hydrological fingerprints at the landscape scale? These questions lie at the heart of the emerging science of ecohydrology, and it is our hope that the following discussion demonstrates the utility in viewing semi-arid landscapes through the perspective of ecohydrological organization.

In the current discussion, we focus on the spatial aspects of interactions between plants, soils, and climates in two different water-limited systems. The first is a series of savanna sites spanning a large rainfall gradient within southern African, and the second is a semi-arid river basin organized around a drainage network in central New Mexico. We address these questions at a hierarchy of scales that range from climate gradients spanning thousands of kilometers to that of individual tree canopies spanning only a few meters.

2. REGIONAL PATTERNS OF OPTIMAL WATER USE MEDIATED BY VEGETATION DYNAMICS

Many water-limited ecosystems exhibit dynamic vegetation components whose annual extent resonates with wet season rainfall. A particularly compelling example is the case of dynamic grass vegetation cover determined by regional satellite observations of normalized difference vegetation index (NDVI) time series for the Kalahari Transect in southern Africa. The Kalahari Transect is one of a number of IGBP transects designated throughout the world (Koch *et al.*, 1995) and covers a latitudinal mean annual rainfall gradient varying from 1000 mm/year in the north to 250 mm/year in the south. Consistency in geomorphology over the entire region – primarily deep Kalahari sands (Thomas and Shaw, 1991) – allows for an analysis of vegetation structure and ecosystem processes relatively independent of soil type. The gradient in mean annual rainfall across the Kalahari Transect sites results in dramatic variation in vegetation structure along the transect (Caylor *et al.*, 2004a; Privette *et al.*, 2004; Scholes *et al.*, 2002).

The overarching control of hydrological factors on savanna vegetation structure across the Kalahari Transect is apparent from the substantial correlation between mean wet season rainfall and tree fractional cover derived from satellite data (Scanlon *et al.*, 2002), a finding that is consistent with relationships drawn from field data (Scholes *et al.*, 2002). However, it is often hypothesized that one or more additional disturbance factors must prevail in modifying the vegetation such that it reaches a mixed compositional form. Underlying this idea is an assumption that vegetation will tend toward a climax state that is characterized by minimal structural diversity (Jeltsch *et al.*, 2000). While such an argument is probably rooted in classical succession theory, an alternative view is that these savanna systems will tend toward a compositional organization that will maximize the use of the limiting resource, in this case water, and that disturbance drives the system away from this configuration. Fire, browsing, and herbivory are no doubt important modifiers to the savanna structure, especially at the local scale, but their respective influences are hardly sufficient to explain the large-scale patterns of vegetation composition throughout the Kalahari.

Scanlon *et al.* (2005) use the the coupled gradients of vegetation and climate to develop a modeling framework that evaluates the ecohydrological role of observed grass dynamics. Here we demonstrate the use of the model to explore the implications of dynamic grass vegetation on overall ecosystem water use. In particular, we use the model to investigate the degree to which savanna vegetation structure is organized with respect to patterns of regional water use and the occurrence of plant water stress. The dynamical simulation of both vegetation and rainfall adopted by Scanlon *et al.* (2005) is a natural extension of earlier, analytical work that assumed static rainfall and vegetation (Eagleson, 1978; Eagleson and Segarra, 1985), and variable rainfall and static vegetation (Laio *et al.*, 2001; Porporato *et al.*, 2001; Rodríguez-Iturbe *et al.*, 2001). The hydrological modeling scheme also builds on the mathematical framework of Scanlon *et al.* (2002), by allowing the fraction of grass cover, x_g, to evolve throughout each wet season according to a growth/decay equation that is governed by the soil moisture in the near-surface soil layer. These temporal dynamics of fractional grass cover, x_g are governed by the following equation presented in (Scanlon *et al.*, 2005) as

$$\frac{dx_g}{dt} = ET_g \chi (1 - x_t) - \xi_g \eta x_g, \tag{1}$$

where ET_g represents the transpiration of grasses, χ is a water-use efficiency parameter, and η is a measure of grass mortality associated with the occurrence of grass water stress ξ_g. Calibration is necessary only for χ and η, which are adjusted in order to match the model output with the satellite observations (Fig. 1, see over). All of the other model input and parameters are assigned based on satellite or ground-based observations or best estimates from field data (Scanlon and Albertson, 2003).

The daily model is applied over a timeframe of 16 wet seasons (1983-1998), at equally-spaced intervals along the Kalahari Transect for the section that receives less than 700 mm of mean wet season rainfall. In order to explore the role of the dynamic grass cover in terms of the savanna water use, the model is used to explore the impact of a dynamic grass cover on two quantities which we believe to be fundamental to the water-limited savanna system. The first is the total amount of water that is lost from the base of the root zone and thereby goes unexploited by the savanna vegetation, which is denoted as Σq_{loss}. The second quantity is the total tree water stress, $\Sigma \xi_t$, which accumulates when the soil moisture within the tree rooting zone drops below a critical value that represents at point of incipient water stress. Both of these quantities are summed over all of the days of the wet season. The first point tests a global metric, concerning how fully the overall savanna vegetation uses the limiting resource. The second point is specific to the tree cover, which requires a sufficient supply of water to be available for uptake by the relatively static woody vegetation cover and its accompanying root system. This is in contrast to grass cover, the extent of which adapts to the transient state of available soil moisture. The above

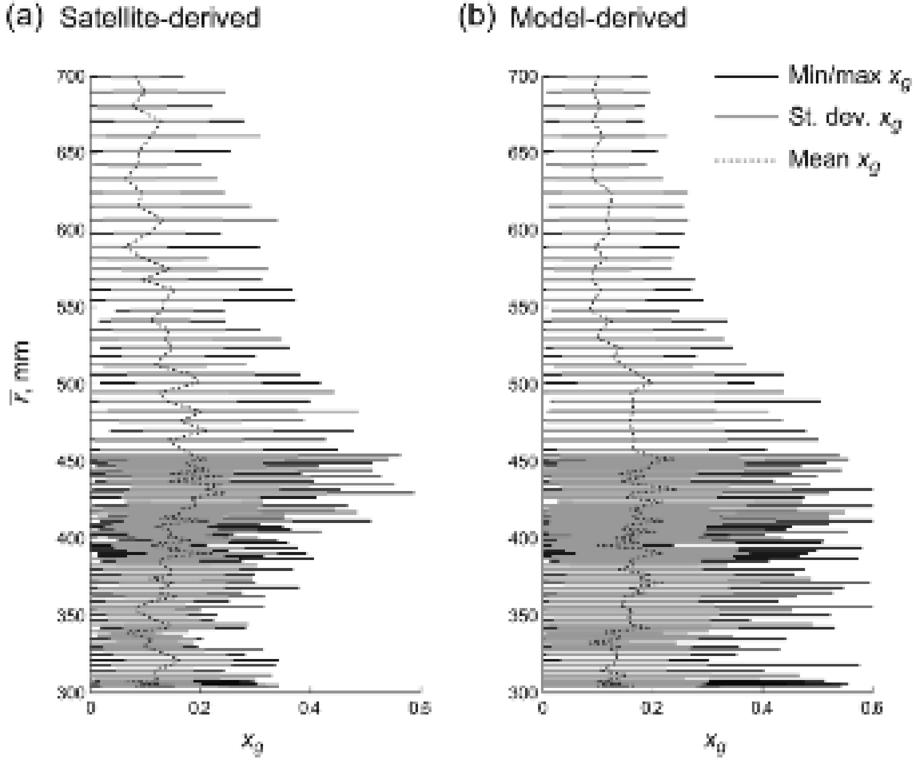

Figure 1. Mean, standard deviation, and range of fractional grass cover, x_g, with respect to the mean wet season rainfall, $\bar{r}$, for January-March at each position along the water-limited portion of the Kalahari Transect during the timeframe 1983-1998. Shown here are (a) satellite-derived x_g from the method of Scanlon *et al.* (2002), and (b) modeled x_g. The dynamic grass model (Equation 1) shows excellent agreement with the satellite estimates. Figure reproduced with permission from Scanlon *et al.* (2005).

conditions demand a tenuous balance between the water cycle and vegetation composition at the land surface for maximal use of the limiting resource. Tree cover should be dense enough to fully utilize the water that reaches the deeper soil layer, but not too dense as to induce water stress by removing too much of this water. Year-to-year variability in wet season rainfall, along with the role of dynamic grass cover, is a focus in our evaluation of this balance.

The results of the model show that during dry years, the reduced extent of the dynamic grass cover has a facilitative effect on tree productivity, in that more water is allowed to drain to deeper depth than if the grass cover was not dynamically responsive to water availability. This 'down-regulation' of grass production in dry seasons thereby reduces the tree water stress. In contrast, for wet years, a greater amount of water is removed from the upper soil layers with the increased dynamic grass cover, and therefore less water is lost from the base of the overall root zone. Therefore the dynamic grass cover helps close the tenuous water balance at the land surface by resonating with the high-frequency (i.e. sub-annual to annual) variability in rainfall. In a given wet season, the amount of water that reaches the deep soil layer is specified as ΣL_1, which represents the total leakage losses from the upper soil layer (the only one the grass has access to). The value of ΣL_1 should be enough to allow tree transpiration and carbon assimilation to proceed at a maximum rate (e.g. minimal $\Sigma \xi_t$), yet not be too much as to allow this limiting resource to be wasted (e.g. minimal Σq_{loss}). In order for the ecosystem water use to be most efficient, the wet season ΣL_1 should be constant, specific to the tree density at a given location. This would be an idealized situation, of course, whereas in reality there is variability in wet season ΣL_1, causing tree water stress during very dry years and leakage losses from the root zone during very wet years. What the dynamic grass cover does, however, is to reduce the variance in ΣL_1, thereby buffering the effects of climatic variability on the ecosystem water use.

An important consideration within the model is the balance between water availability and water use for deeply-rooted woody vegetation across the transect. As rainfall and tree cover increase, we may expect shifts in the amount of vertical percolation (driven by changes in annual rainfall) to deep root layers, as well as shifts in water uptake from these deeper layers (driven by changes in tree cover and potential evapotranspiration). Either supply in excess of demand or demand in excess of supply would indicate a system that was poorly organized for optimal water use. We define the seasonal water availability to deep tree roots as ΣL_1, which is the sum of water that leaves the upper soil layers by percolating downward. The seasonal water availability for the deep tree roots, ΣL_1, should ideally meet the demand of the trees at each position along the regional climate gradient. This demand is determined by the fraction of woody vegetation cover as well as the maximum potential evapotranspiration rate, and is noted here as $\Psi(x_t)$. In evaluating the optimality of vegetation patterns across the entire transect, Scanlon *et al.* (2005) use the expression $\Sigma L_1 - \Psi(x_t)$ as an independent variable in Figure 2. This formulation accounts for both the

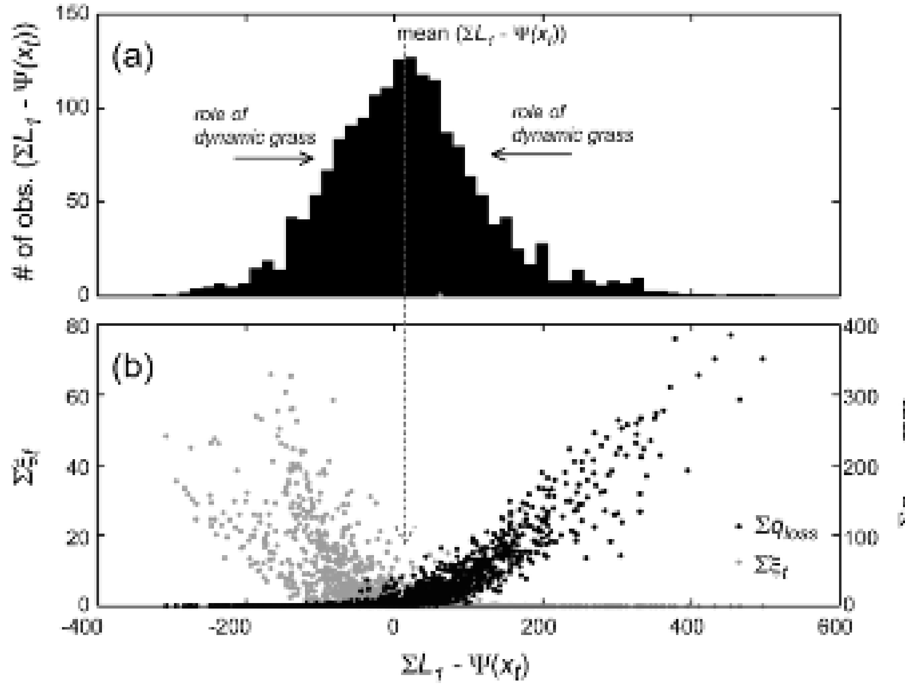

Figure 2. (a) Histogram of $\Sigma L_1 - \Psi(x_t)$, which represents the balance between the supply of water that drains into to the deep soil layer ΣL_1, minus the demand of water inferred from tree water use $\Psi(x_t)$ at a particular location. The dynamic grass cover reduces the variance in the distribution of supply and demand $\Sigma L_1 - \Psi(x_t)$ and keeps the value close to zero so that there is neither surplus ($\Sigma L_1 \gg \Psi(x_t)$) or deficit ($\Sigma L_1 \ll \Psi(x_t)$). Model results for the entire transect show that the mean value of $\Sigma L_1 \gg \Psi(x_t)$ arising from a dynamic grass layer (a) corresponds to a structural configuration that minimizes both total tree stress ($\Sigma \xi_t$, grey points) and total vertical percolation beyond the rooting zone (Σq_{loss}, black points) (b). Figure reproduced with permission from Scanlon *et al.* (2005).

changing supply and demand for water across the climate gradient. The position of the $\Sigma L_1 - \Psi(x_t)$ histogram peak (Fig. 2a) corresponds to a location of both minimal water loss, Σq_{loss}, and minimal tree water stress, $\Sigma \xi_t$ (Fig. 2b). Since the minimization of these two quantities (Σq_{loss} and $\Sigma \xi_t$) across the transect defines optimal ecosystem water use at each location (Fig. 2b), it is apparent that vegetation composition along the Kalahari Transect is highly organized with respect to these water-use considerations. Therefore, we find that the dynamic nature of the grass cover in response to variable rainfall enhances the degree to which the savanna ecosystem is optimized with respect to water use and helps to close the water cycle at the land surface.

From a water use perspective, a pure grassland or woodland situated in the Kalahari environment would be less efficient than the existing mixed tree/grass savanna in terms of exploiting this limiting resource. The shallow root system of grasses, combined with the sandy soils and the exponential distribution of storm rainfall depths, would allow significant amounts of water to bypass the root zone of grassland vegetation. Even though the absence of trees would allow the green grass biomass to be extraordinarily responsive to the rainfall in terms of growth, this would not make up for the decreased efficiency in water use imposed by the uniformly shallow root depth. In the case of the woodland ecosystem, the growth of the standing biomass would be constrained by the woody structure, making the ecosystem water use less adaptable to fluctuations in wet season rainfall. Tree density in such a system would have to be conditioned upon the mean wet season rainfall, but this would mean that tree water stress ($\Sigma\xi_t$) would be greater during dry years and total leakage loss (Σq_{loss}) would be greater in wet years in the absence of the grass cover to buffer the effects of rainfall variability. Ideal mono-specific vegetation for this climate and soil type would have the joint attributes of (1) non-definite lateral growth that is highly responsive to soil moisture, and (2) a deeply penetrating root system. No vegetation of this type exists, but the tree/grass mixture of a savanna ecosystem does, in a collective sense, have the benefit of possessing both qualities. This is an example of increased ecosystem robustness arising from the complex, adaptive nature of vegetation assemblages (Levin, 1999).

One further conclusion to be taken from the model results of Scanlon *et al.* (2005) is that as the savanna composition moves toward a grassland through tree thinning (Smit and Rethman, 2000) or toward a woodland through excessive grazing (Archer, 1995), the efficiency of the surface water balance closure will be reduced, leading to greater recharge rates. Recent findings by Walvoord *et al.* (2003) in the arid southwestern United States showed that large reservoirs of nitrate have built up in the soil below the root as a result of many years of leaching. Future shifts in the vegetation and climate of these areas could serve to make this nitrate available to plants (i.e. through the establishment of more deeply-rooted species). However, it also possible that changes in vegetation and climate may enhance vertical leakage such that the nitrate is transported downward to the water table. Regardless, it is clear that understanding the role of the dynamic vegetation in influencing the water balance at the land surface is key to this and many other issues in semi-arid environments, since the hydrological and biogeochemical cycles are so closely linked at the land surface.

The model results for this largely undisturbed Kalahari Transect savanna system reveal the degree to which the present vegetation structure appears to be optimized with regard to water use; alternately minimizing water loss in wet seasons and minimizing water stress in dry ones. We note that the use of a two-layer scheme for modeling regional tree/grass water use neglects the potential for horizontal variability in soil moisture and the impacts of such variability on vegetation dynamics. An assumption of horizontal homogeneity may be appropriate for large-scale vegetation/climate modeling. However, more complicated landscapes necessitate a more nuanced view of spatial heterogeneity at the landscape and individual-scale. The final section of this chapter introduces an approach for examining the role of horizontal spatial variance in soil moisture specific to the more localized individual-based savanna vegetation mosaic. However, before turning to these sorts of individual-based patterns, we next explore the landscape-scale dynamics of vegetation within a semi-arid basin of central New Mexico where regional topography plays a crucial role in the climate-soil-vegetation interaction.

3. LANDSCAPE-SCALE ECOHYDROLOGICAL ORGANIZATION OF VEGETATION WITHIN SEMI-ARID RIVER BASINS

While there is a growing awareness of the important role that geomorphology exerts on vegetation structural dynamics and the generation of landscape-scale vegetation patterns in many semi-arid landscapes (Coughenour and Ellis, 1993; Kim and Eltahir, 2004), the question of whether or not the interaction of vegetation, soils, and climate also display a similar set of unifying characteristics among the very different patterns they present in river basins has been relatively unexplored. This is despite the fact that research during the last 10 years has conclusively shown a high degree of organization and unifying principles behind the structure of the drainage network and the 3-dimensional geometry of river basins (Rodríguez-Iturbe and Rinaldo, 1997). The consideration of a river network as a dendritic structure characterized by minimum total energy dissipation (optimal channel networks, or OCNs) has provided a means of connecting the ubiquity of self-affinity and scaling in river networks with the physical dynamics of open, dissipative systems. However, it has been shown that in order to reproduce the observed scaling properties of river networks it is necessary to employ suboptimal minimization schemes which restrict their search for optimality to local minima that are accessible from initial conditions. The limitation of natural processes that search for optima which are dynamically accessible within the constraints of initial and boundary conditions has been termed feasible optimality, a condition also observed in systems like Ising ferromagnets (Swift *et al.*, 1997) and the aggregation of metal balls within open, dissipative electrical systems (Marani *et al.*, 1998).

In a series of papers, Caylor *et al.* (2004b), and Caylor *et al.* (2005) consider the argument that minimization of water stress in plants plays a fundamental role in the organization of the vegetation pattern within semi-arid river basins, but that the suite of possible patterns obtained is similarly constrained to a suboptimal configuration due to the limitation of local minima enforced by the structure of the river network. These efforts represent an attempt to integrate more fully the concept of self-organization observed to be present within many patterns of vegetation (Rietkerk *et al.*, 2002; Sole *et al.*, 2002) with the scale-invariance and self-organized complexity known to exist in the geomorphological organization of river basins (Turcotte, 1990; Turcotte and Rundle, 2002; Rodríguez-Iturbe and Rinaldo, 1997). The principles of such organization have important consequences regarding the impact of land cover change on hydrological dynamics in river basins, as well as the geomorphological evolution of landscapes under varying climate and vegetation regimes.

To this end, Caylor *et al.* (2004b) analyze and simulate the spatial distribution of water stress arising from different vegetation configurations in the Upper Rio Salado basin, located near the Sevilleta Long-term Ecological Research (LTER) site in central New Mexico. Using available geospatial data, Caylor *et al.* (2005) assign soil, climate, and vegetation properties across the basin and analyze the probabilistic characteristics of steady-state soil moisture distribution as well as in the distribution of observed vegetation patterns, simulated vegetation dynamic water stress and hydrological fluxes such as transpiration. The seasonal steady-state relative soil moisture probability distribution Laio *et al.* (2001) forms the basis for assessing the plant water stress at each location within the basin. Recent work on stochastic soil moisture dynamics across hillslopes has demonstrated that topography can lead to significant spatial gradients in soil moisture due to lateral soil moisture redistribution, but that such patterns only develop in relatively humid climates (Ridolfi *et al.*, 2003). Therefore, in this analysis of a semi-arid river basin hillslope dynamics associated with lateral soil moisture distribution are neglected.

To determine the ecohydrological organization of vegetation within the Rio Salado basin, a measure of water stress is adopted from the presentation of Caylor *et al.* (2005). This modified dynamic water stress (Θ') scales the statistical steady state stress condition according to the duration of the mean first passage time between an initial condition associated with the spring snow melt and the statistical steady-state mean. A resulting modified dynamic water stress profile is defined as the average value of the steady-state modified dynamic water stress, $\overline{\Theta'}(x)$, for all points located at the same distance x from the basin outlet measured through the network. Thus,

$$\overline{\Theta'}(x) = \frac{\sum_{i=1}^{N_x} \Theta'_i}{N_x} \tag{2}$$

where N_x is the number of elementary pixels at distance x measured through the drainage network flow path, and Θ'_i is modified dynamic water stress at each of these N_x locations. Therefore, this average modified dynamic water stress is an average quantity conditioned on the network width function, which is itself a well-studied metric of basin geomorphology (Marani *et al.*, 1994) and is derived from our analysis of the USGS digital elevation data described above.

To assess the importance of water stress in determining the distribution of vegetation within semiarid river basins, the existing vegetation pattern of vegetation (Figure 3a, see page 213) is compared to two alternative hypothetical vegetation distributions. The first is the distribution of vegetation that arises from a random assignment of vegetation type at each location within the basin, under the constraint that the proportions of overall land cover composition are preserved over the whole basin (Figure 3b, see page 213). The second hypothetical pattern is the one arising from the specification of the vegetation type that exhibits the lowest dynamic water stress at each location within the basin (Figure 3c, see page 213). From the sole point of view of water stress, the second pattern can be viewed to represent and optimal or ideal distribution of vegetation. A visual comparison of these three patterns (actual, random, and ideal) suggests that the actual pattern of vegetation distribution contains elements of both the highly organized large-scale ideal pattern, as well as the characteristic small-scale variation associated with the random pattern.

The existence of a distribution of water stress globally bounded by the random and ideal vegetation distribution may allow for the development of dynamic modeling approaches for predicting the distribution of vegetation pattern in river basins under conditions of changing climatic and edaphic regimes. Moreover, it is likely that the vegetation patterns in water-controlled ecosystems tend to approach an optimal configuration in terms of water stress but are subject to important and decisive random contingencies of an altogether different character. Conceptually, this is not different from the notion of feasible optimality at work in the organization of the drainage network (Rigon *et al.*, 1998).

This hypothesis of feasible optimality is explored by Caylor *et al.* (2004b) using two simple cellular automata approaches to model the statistical steady-state conditions of a vegetation mosaic initiated from a random condition (Figure 3, see page 213). Vegetation is initially distributed randomly in equal proportions within the basin (1/3 each of trees, shrub and grass). In both models, the initial random vegetation mosaic is modified through the iteration of local interactions that occur between adjacent locations. These interactions are defined such that vegetation replacement can occur when the stress at a randomly chosen location is less than the stress in an adjacent location. Following the initial random placement of vegetation, a cell at location i within the basin is randomly selected and allowed to replace an adjacent location n with probability $(1-\Theta'_i/(\Theta'_i+\Theta'_n))$. If a successful replacement occurs, the procedure is repeated with a new neighbor chosen from the locations adjacent to cell n, otherwise a new random location i is chosen.

Of critical importance is the manner by which the two models differ in how the adjacent neighborhood of each location is defined. The first approach (the 'neighbor' model) is based on stochastic local interactions that occur between each location and a random neighbor chosen from any of the locations adjacent to the cell under consideration. Therefore, in this model the spatially interactive neighborhood of each location i is given by the eight adjacent locations that share either an edge or a corner with location i. The second approach (the 'network' model) is also based on local interactions but is constrained such that interactions only occur between each location and its direct downstream neighbor. Therefore in the network model, the neighbor n_j is always given by the adjacent location that is the downstream neighbor of location i. In both models the procedure of probabilistic replacement is repeated until the initially random mosaic of vegetation evolves to a steady state condition in which no further replacements occur ($\sim 10^7$ steps).

The ability of each modeling approach to appropriately characterize the observed pattern of vegetation distribution within the Rio Salado basin is confirmed through a comparison of the steady-state modified dynamic water stress described above, and the steady-state patterns of tree distribution. The results of the cellular automata modeling reveal that the steady state configuration of the neighbor model (Figure 3c, see page 213) is identical to that of the ideal basin, with vegetation distributed in homogenous swaths based on the underlying variation in climate and soils across the Rio Salado basin. In contrast, the steady state configuration of the network model (Figure 3d, see page 213) is markedly different in character, preserving elements of both the ideal condition, as well as the type of spatial variation exhibited in the actual vegetation pattern (Figure 3a, see page 213).

Figure 4a portrays the basin patterns of water stress resulting from each of these two approaches to dynamic landscape pattern generation, as well as the actual pattern observed within the Rio Salado basin. The results of the three landscape configurations (random, actual and ideal) demonstrate that the current vegetation pattern is configured such that it is well constrained by these two extremes of vegetation organization, so that the basin tends to experience an intermediate level of water stress that is neither random nor ideal (Figure 4a, see page 214). However, the stress profile of the neighbour model (Figure 4b, see page 214) is identical to that of the ideal vegetation (Figure 4a, see page 214), which is consistently lower than that of the actual basin. In contrast, the agreement between the stress profile for the network model and that for the actual basin is much better (Figure 4c, see page 214).

Taken as a whole, these results support the hypothesis that in water controlled ecosystems the drainage network acts as a template for the spatial distribution of vegetation which self-organizes through local stress optimization within the network flow paths of the basin. The feasibly optimal vegetation patterns attained through these simulations correspond to stress profiles around the network that lie between those corresponding to the random and the ideal vegetation distributions.

The above analyses suggest the existence of a balance between the large-scale determinants of vegetation pattern reflecting optimality in the response to water stress and the random small-scale patterns that arise from local factors and ecological legacies such as those caused by dispersal, disturbance, and founder effects. In the Rio Salado basin, we observe an organization that yields an actual pattern of vegetation distribution found to lie within the envelope described by the ideal vegetation pattern that corresponds to the minimization of water stress within the basin, and a random one that preserves the overall percentage of the different types of vegetation. The dynamic origination of these patterns depends on the structure of the river network itself, which serves as a constraint on the suite of possible vegetation patterns through its effect on the dispersal of vegetation along hillslopes and between subbasins. Having explored the landscape-scale potential for ecohydrological optimization in water-limited ecosystems, we now turn to the role of individual tree canopies on surface hydrological dynamics and their impact on patterns of vegetation structure.

4. ECOHYDROLOGICAL OPTIMIZATION OF LANDSCAPES INFERRED FROM INDIVIDUAL-BASED TREE DISTRIBUTIONS

The structure of terrestrial vegetation communities is strongly governed by the spatio-temporal distribution of growth-limiting resources (Tilman, 1988). However, plants are not passive actors in this regard, and the biotic pattern of vegetation serves to redistribute key abiotic resources such as energy, water, and nutrients in important ways that are critical to the dynamics of the community through space and time. Therefore, any theory regarding the structural configuration of plant communities must explicitly consider the consequences of spatial vegetation pattern on the dynamics of resource availability.

Beginning with the analysis of spatial dynamics in tropical forests (Denslow, 1987), and continuing through the conceptualization of temperate (Runkle and Yetter, 1987) and boreal forest (Bonan and Shugart, 1989) community dynamics, it has become apparent that the nature of plant structural pattern and the dynamics of resource availability are highly interdependent (Tilman and Kareiva, 1997). Although the forest community structure is often thought to be determined by prevailing resource conditions (i.e. climate or soil age), it is now recognized that the forest structure itself serves to modify resource availability. Perhaps best known is the paradigm of gap dynamics – by which species regeneration and subsequent patterns of canopy emergence occur within the localized patches of higher light availability formed by the death of a large canopy tree (Shugart, 1984).

Recently, Caylor *et al.* (2006) proposed a simple model of soil moisture dynamics suitable for application to heterogeneous vegetation landscapes, such as those found in savannas or open woodlands. This approach was intended to provide a framework that can generate hypotheses related to the causes and effects of horizontal variation in soil moisture arising from the patchy vegetation structure of individual tree canopies that is characteristic of many semi-arid ecosystems. Under the assumption that trees are distributed randomly according to a 2-d Poisson process and have radii drawn from an exponential distribution with mean radius μ_r, the distribution of canopies occurring at any location in the landscape (n_C) follows a Poisson distribution. The focus of this presentation is on the interactions between the number of co-occurring tree canopies (n_C), root systems (n_R), and their combined effect on the overall dynamics of soil moisture. Therefore the quantity $a_t = \mu_R / \mu_r$ is specified as the ratio between the radius of a tree's root system (μ_R) and its associated canopy (μ_r). In this analysis, the value a_t of is assumed to be a fixed property of the vegetation in each landscape. Under the assumption of random tree spacing, tree centers are modeled as a 2-dimensional Poisson process of rate λ_t, where λ_t represents the mean number of centers per unit area. The areal extent of each tree is represented as a circle of random radius, *r*, drawn from an exponential distribution with mean μ_r. Thus the number, n_C, of canopies occurring at a randomly chosen point has a Poisson distribution (Cox and Miller, 1965) of mean $\langle n_C \rangle = \lambda_t (2\pi \mu_r{}^2)$, and the expected number of root overlaps is simply $\langle n_R \rangle = 2\pi (\mu_r a_t)^2 \lambda_t$.

The probability of finding a location in the landscape with n_R overlapping root systems and n_C overlapping canopies is the joint distribution n_R of and n_C, notated as $P(n_R \cap n_C)$. Under the condition that the specified ratio of root to canopy areas is set to be one (i.e. $a_t = 1$) so that all root systems are exactly the same size as all canopy areas, it is apparent that $P(n_R \cap n_C) = P(n_R) = P(n_C)$, since each root system is overlain by a single canopy area with probability 1. However, when the root systems are always larger than canopy areas (i.e. $a_t \geq 1$), the joint probability distribution of n_R and n_C is given by $P(n_C | n_R) P(n_R)$, where $P(n_C | n_R)$ is the conditional probability of n_C on n_R. Following the approach presented in Caylor *et al.* (2006), we define the quantity $\tau = 1/a_t^2$, and find that the general form of the conditional probability $P(n_C | n_R)$ is a binomial distribution with mean $n_R \tau$ and variance $n_R \tau (1 - \tau)$.

The distribution $P(n_C \cap n_R)$, for $a_t \geq 1$ is used to connect the distribution of canopies and root systems in the landscape to the soil moisture dynamics which occur therein. In order to assess the ecohydrological organization of individual-based vegetation patterns, we must fist determine the distribution of soil moisture, rates of evaporation, plant water uptake, and plant water stress within a structurally heterogeneous landscape of tree canopies and their accompanying root systems. Therefore, we formulate representations of evaporation and plant water uptake governed by n_C and n_R. In particular, we recognize that the parameter n_R determines the local rate of soil water uptake, while n_C controls the evaporative loss of soil moisture and regulates the partitioning of evapotranspiration into soil evaporation and plant water uptake. The vertical root profile is here assumed to be uniform and individual plant root uptake is evenly partitioned throughout the thickness of a single soil layer, Z_r. Our data on tree active rooting depth is taken from recent field observations of Kalahari root distributions (Hippondoka *et al.*, 2003) which find similar rooting depths across a series of sites in Botswana. Therefore, although the modeling approach could accommodate differences in rooting depth across the transect, we have not included variation in rooting depth between sites. This is in contrast to the regional approach described earlier in this paper that examined the efficiency of vertical niche partitioning as a measure of plant water use.

It is assumed that canopies reduce energy available for evaporation due to shading effects according to an exponential distribution (e.g. Beer's Law), such that $\phi_E(n_C)=e^{-kn_C}$, where ϕ_E is the fraction of incoming energy available for bare soil evaporation under n_C canopies and k is an extinction coefficient of evaporative demand taken to be equal to 0.35 (Brutsaert, 1982). Because root water uptake depends on the amount of energy incident on each root system's corresponding canopy, the plant water extraction rate from the soil is constrained by the total energy absorbed by individual plant canopies. The amount of fractional energy absorption per canopy (φ) for n_C co-occurring canopies is estimated as $\varphi=[1-\phi_E(n_C)]/(n_C)$. Given a statistical description of the landscape, the exact value of φ for the canopy associated with a particular root system at a random location within the landscape is unknown in this modeling framework. In the absence of specific values of φ for each location in the landscape, we can instead determine the expected amount of energy absorbed per canopy, $\overline{\varphi}$, which we use to constrain water uptake per root system. Finally, we approximate the fraction of potential water uptake that takes place at a location containing n_R root systems (connected to n_R separate canopies) according to $\phi_T(n_R)=\overline{\varphi}\cdot n_R$.

The values of $\phi_E(n_C)$ and $\phi_T(n_R)$ determine the relative amounts of evaporation and plant water uptake at a location with n_C canopies and n_R root systems. At any given location, the sum of evaporation and plant water uptake may exceed the potential evapotranspiration rate (*PET* mm/day). This is particularly true in open areas that contain many root systems under conditions of high water availability. However, the potential evapotranspiration rate does provide an upper bound on the landscape average evapotranspiration. In addition, the rate of evaporation and plant water uptake both depend on the available soil moisture at any given time. To accommodate the role of soil moisture limitation on evaporation, we assume that evaporation linearly increases from zero at the soil hygroscopic point, s_h, to a maximum evaporation rate, $\phi_E(n_C) \times PET$, at field capacity, s_{fc}. Similarly, we assume that water uptake from roots (i.e. transpiration) exhibits a linear response to soil moisture availability, increasing from zero at the plant wilting point, s_w, to the maximum, $\phi_T(n_R) \times PET$, at the point of incipient stomatal closure, s^*. At soil moisture values above s^*, water uptake proceeds at the maximum rate, just as evaporation proceeds at the maximum rate above field capacity. Finally, above field capacity, we consider leakage loss from the lower boundary of the soil layer.

At each location in a landscape containing n_C canopies and n_R roots, we consider the water stress distribution according to the frequency and magnitude of excursions of the relative soil moisture below the critical value of s^* that corresponds to the point at which plants begin to close their stomata. Porporato *et al.* (2001) review the physiological impacts of reduced water variability on plant performance and the onset of plant water stress. In order to account for the effects of increasing soil moisture deficit on plant physiological performance, we adopt the formulation of water stress (denoted as ξ) first proposed by Rodríguez-Iturbe *et al.* (1999). Any measure of 'optimal' conditions for plant water use must appropriately balance maximization of resource use with minimization of stress occurrence. For example, as the average root ratio (a_t) increases, an individual plant may be able to increase its plant water uptake rate. However, the increased number of overlapping roots associated with an increase in plant root ratio leads to higher landscape average uptake rates and more rapid onset of stress conditions whenever water becomes limiting. To relate these varying stress and water use patterns to the soil and vegetation parameters, we define an average stress-weighted plant water uptake, $\langle \zeta \rangle$, which is simply the product of the landscape-average plant water uptake rate, $\langle T \rangle$, and the complement of the average plant water stress, $1-\langle \zeta \rangle$, so that $\langle \zeta \rangle = \langle T \rangle [1-\langle \zeta \rangle]$.

The local measure of water stress for a location with n_C canopies and n_R root systems is combined with the joint probability of n_C and n_R to calculate the landscape average value of stress-weighted plant water uptake, $\langle \zeta \rangle$, across the Kalahari rainfall gradient. In particular, we investigate the dependence of $\langle \zeta \rangle$ on the landscape-scale vegetation structural parameters a_t and λ_t. Figure 5 shows the relation between average stress-weighted plant water uptake and the root-to-canopy ratio, a_t at four sites across the Kalahari Transect. As a_t increases, both water uptake and water stress increase, due to the enhanced ability of plants to exploit the soil water resources. At a critical value of a_t for each landscape, the increase in water stress associated with larger root areas offsets the increase in plant water uptake and the value of $\langle\overline{\zeta}\rangle$ begins to decrease. This fact explains the existence of an optimal value of a_t in Figure 5 where $\langle\overline{\zeta}\rangle$ is maximum. The optimal root-to-canopy ratio, a_t, decreases with increasing values of mean annual precipitation, suggesting that sparse semi-arid trees benefit from lateral root growth more than the denser woody vegetation growing in sub-humid environments.

Figure 6 shows the dependence of the landscape averaged value of

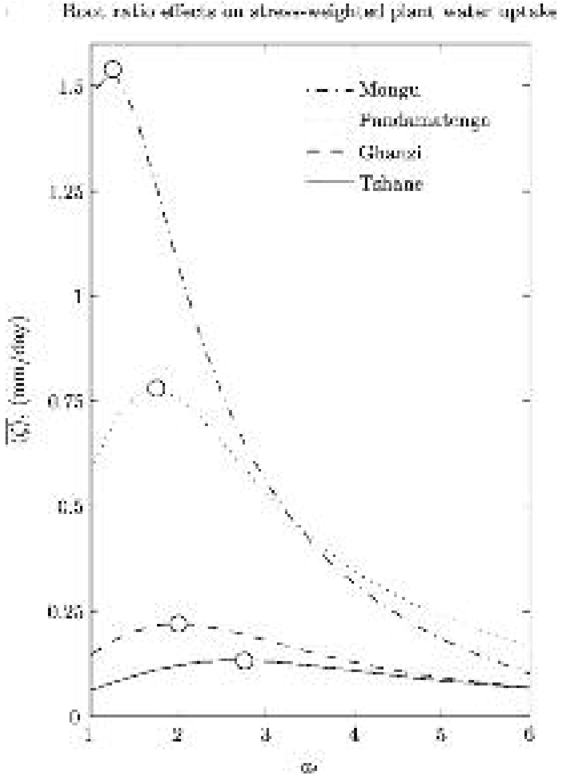

Figure 5. Effect of changing root ratio, a_t, on model predictions of the landscape averaged distribution of stress-weighted plant water uptake, $\langle\overline{\zeta}\rangle$ (mm/day), within four Kalahari landscapes. The landscape averaged stress-weighted plant water uptake is determined according the product of landscape average daily plant water uptake, $\langle\overline{T}\rangle$, and the complement of the landscape average daily water stress, $(1-\langle\overline{\zeta}\rangle)$. In each of the four landscapes, the maximum landscape averaged stress-weighted plant water uptake (open circle) occurs for increasingly lower values of a_t as rainfall rates increase, suggesting adaptive changes in the optimal size of lateral root extension across the rainfall gradient. Figure reproduced with permission from Caylor *et al.* (2006).

stress-weighted plant water uptake, $\overline{\langle\zeta\rangle}$ mm/day, on tree density, λ_t (ind/m^2). Plant water uptake increases with the tree density, while water stress initially decreases with λ_t (i.e. for low values of λ_t), due to the effect of shading on the soil water balance. As a result, an optimal value of tree density exists, which is associated with maximum stress-weighted plant water uptake. This optimal value of λ_t is found to be close to the tree densities observed in the field, suggesting that λ_t changes along the rainfall gradient to optimize the use of the water resources.

5. CONCLUSION

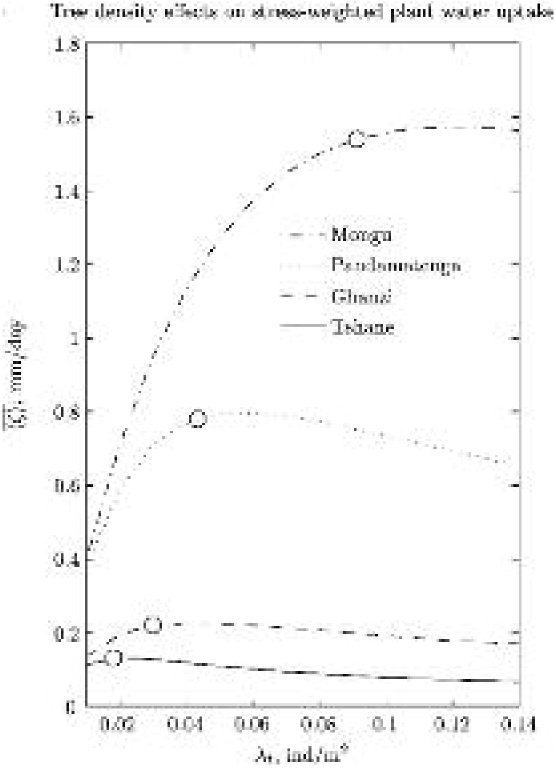

Figure 6. Effect of changing tree density, λ_t, on predictions of the landscape averaged distribution of stress-weighted plant water uptake, $\overline{\langle\zeta\rangle}$, within four Kalahari landscapes. All simulations are conducted using the estimated optimal values of root ratio, a_t, determined from Figure 5. Open circles represent the actual density of trees from previous field observations (Caylor *et al.*, 2003) and unpublished data on Ghanzi vegetation. In each landscape, the observed density of trees corresponds to a landscape averaged stress-weighted plant water uptake that is at or just below maximum values across a wide range of possible tree densities. Figure reproduced with permission from Caylor *et al.* (2006).

This chapter has briefly reviewed three efforts to examine the ecohydrological organization of vegetation patterns in water-limited landscapes. In each case, we have tackled a different scale of interest, from regional to individual, through a suite of numerical and analytical modeling approaches. Although the insights gained from each example are derived from specific modeling approaches that each contain their own unique set of assumptions and limitation, they are unified by their use of the water balance and resulting measures of plant water deficit/use as a diagnostic tool for assessing optimality of plant structural pattern. Clearly, such modeling approaches will likely continue to generate hypotheses at a much greater rate than they are able to confirm them. However, it is our hope that the continued development of generalized models capable of assessing a diversity of interactions between plants, soils, and climates will lead to the emergence of more generalized hypotheses regarding the manner by which ecological and hydrological patterns co-organize in landscapes.

6. ACKNOWLEDGEMENTS

K.K.C. and T.M.S. acknowledge the support of NASA's Interdisciplinary Science Program (NASA-NNG-04-GM71G). I.R.-I. acknowledges the support of NSF through grants in Biocomplexity (DEB-0083566) and the National Center for Earth-surface Dynamics (EAR-0120914).

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GLOBAL HYDROLOGY AND HYDROLOGIC DYNAMICS

WATER DISTRIBUTION AND AVAILABILITY AN OVERVIEW OF CLIMATE CHANGE IMPACTS ON WATER RESOURCES

BISHER IMAM & SOROOSH SOROOSHIAN

1. INTRODUCTION

Water resources management, distribution, and utilization were major beneficiaries of 20th century advances in civil engineering. As seen in Figure 1 (see over), which illustrates the number of large dams built during the past century, the core element of water resources development and management strategies for many nations has been the reliance on infrastructures to store and transport an ever increasing amount of surface water resources. In addition to hydroelectric power, these engineering solutions provided protection against floods and droughts and played a key role in attenuating the impacts of climate and weather variability on life and properties. Improved efficiency of ground water extraction and water treatment facilities, were also important elements of water resources development strategies.

Towards the end of the century, environmental degradation, along with increasing evidence of climate change, caused a shift in focus from structural solutions to non structural options. As many dams reached or exceeded their operational life, weighing the adverse ecological and environmental impacts of excessive streamflow regulation became an important factor in modern water resources management strategies. As a result, by the 1990s, several small dams were de-commissioned and/or removed for the purpose of river restoration. For example, to restore the salmon habitat in the Loire River Basin (France), the St. Etienne de Vigan, Barrage Mobile de Blois, and Maison Rouge dams were removed in 1998, 1998, and 2005, respectively. Five hundred small dams were decommissioned in the United States for various environmental, ecologic, and safety purposes. In parallel,

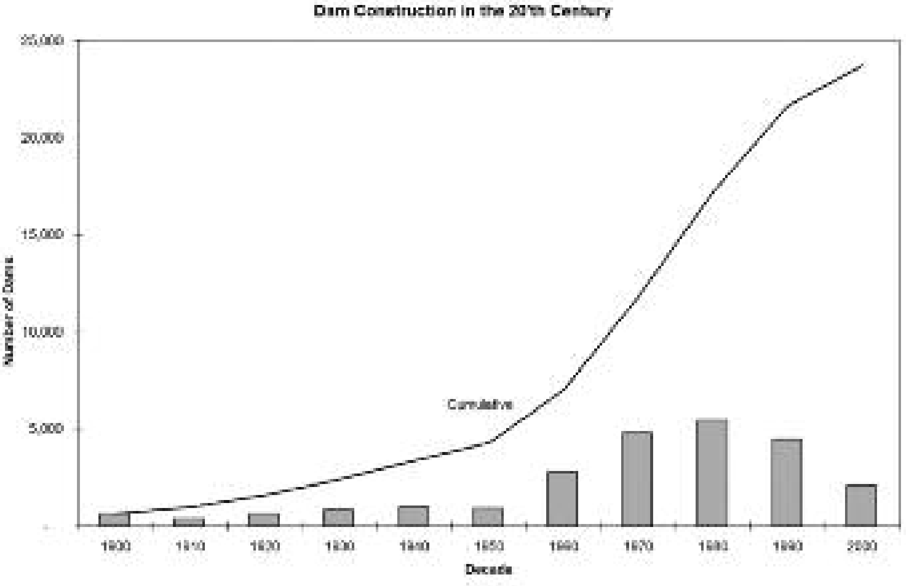

Figure 1. Patterns of large dam construction during the 20th Century.

the calls for conjunctive management of surface and ground water within integrated water resources management strategies gained recognition as the impacts of over-extraction of ground water on the structural integrity of overlying strata and on nearby streams were becoming more evident.

Decommissioning a few dams may address some local environmental issues. However, it does not address the overarching challenge of water availability, which is now recognized as a high priority development issue for the 21st century. In this regard, the Ministerial Declaration of The Hague on Water Security in the 21st Century has identified seven pertinent key challenges as: (1) meeting basic needs, (2) securing the food supply, (3) protecting ecosystems, (4) sharing water resources, (5) managing risks, (6) valuing water, and (7) governing water wisely. To meet these challenges, the declaration advocated integrated water resources management, which takes into account social, economical, environmental, and ecological aspects of water resources management. Addressing these challenges demands political commitment, both at national and international levels to develop and implement sound and sustainable integrated water resources management policies and practices. Such commitment becomes more necessary when taking into account the relationships between the three key stresses facing sustainable water resources management, which are: (a) limited fresh water supply, (b) population growth, and (c) climate change. It can be argued that quantifying the first two stresses requires that we improve our ability to understand, quantify, and predict the potential impacts of the latter, which is climate change, on various hydrologic responses.

2. OBSERVED HYDROLOGIC IMPACTS OF CLIMATE CHANGE

Motivating the growing interest in climate change is the well documented increase in the average global temperature since 1880 (0.3°C to 0.6°C), with 0.2 to 0.3°C increase observed during the more reliable period of record (after 1960). Changes in mean global temperature have also been measured through satellite observations, which have confirmed that warming is evident in both sea surface temperature (Cane *et al.*, 1997) and land-based surface air temperatures. In a recent study, Smith *et al.* (2005) treated uncertainties due to scarcity of reliable meteorological observations during the earlier part of temperature records and confirmed the above mentioned trends in global temperature (Figure 2a, see over). While an analysis of the causes of global warming is beyond the scope of this paper, the fundamentals of its potential impacts on the hydrologic cycle result from the well-known Clausius-Clapeyron law, which states that the increased temperature will result in an increase the atmosphere's moisture holding capacity. This increases the total amount of water in the atmosphere, which can affect the intensity of storms. It will also change the atmospheric moisture recycling ratio, with potential effects on drought frequency (Figure 2b, see over). The effect of higher temperature on atmospheric moisture content has been confirmed by various studies, most of which indicate that despite uncertainties in measurements, evidence obtained from satellite and radio-sound observations point to statistically significant upward trends in atmospheric moisture of several percents/decade (Ross and Elliott, 1996, 2001; Trenberth *et al.*, 2003; IPCC, 2001). This is consistent with observations of the increased mean global temperature. From a hydrologic and water resources perspective, recent, long-term, and paleo-climatic records must be examined to determine if 1) precipitation characteristics have changed due to increased temperature,

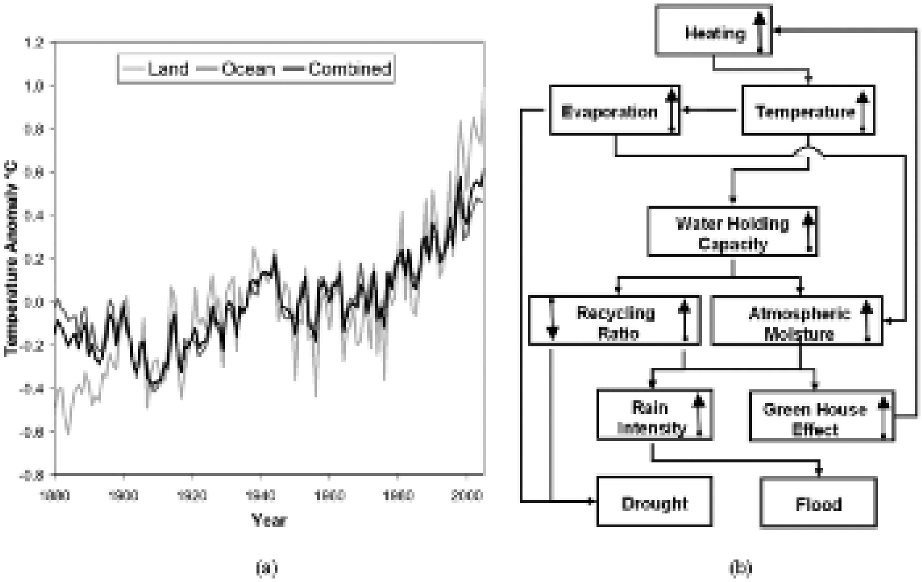

Figure 2. a) Trends in global temperature over land, ocean and combined. b) schematics of possible consequences of increased atmospheric temperature on the hydrologic cycle (revised after Trenbreth, personal communication).

2) droughts and/or floods are becoming more frequent, 3) the severity of droughts/floods is increasing in specific areas, 4) the timing and magnitude of snow-accumulation and snow-melt onset is changing, and 5) changes are taking place in regional vegetation cover. Needless to say, the global coverage of many state-variables over the longest possible time series is needed to understand the natural variability of the hydrological cycle so that deviations from the norm, such as a genuine progressive amplification of the cycle, can be detected with confidence.

a. *Precipitation*

At the global scale, the effects of changes in atmospheric moisture on precipitation have been confirmed by several studies. In general, a statistically significant increase of 2% in the average precipitation has been observed during the 20th century (IPCC, 2001). However, available records indicate large spatial and temporal variability in precipitation response to increased temperature. The northern hemisphere's mid and high latitudes show a marked increase, and the sub-tropical regions, particularly in western Africa show a decrease in precipitation. Changes in seasonal and inter-annual variability of precipitation patterns over some regions are consistent with stronger ocean circulation indices such as ENSO in South America, and the North Atlantic Oscillation in Europe.

b. *Severe Floods*

Concerns about the potential impacts of climate change on the hydrologic cycle have risen in recent years due to the rising catastrophic impacts of major floods in several countries. As seen in Figure 3 (see page 215), which maps severe floods since 1985, floods affect nearly all regions of the world. The underlying data indicates an upward trend in the number of severe floods since 1985 (Brakenridge, 2005). The question of whether climate change has altered the frequency of severe floods is rather complicated and it cannot be discerned for any individual flood. Most studies acknowledge that higher risk of human and economic losses due to large floods can be attributed to socio-economic factors such as expanding development in flood prone areas and over-reliance on flood protection infrastructure (Pielke and Downton, 2000; Kundzewicz *et al.*, 2005). Naturally, when discussing floods, changes in the total annual precipitation are less important than changes in other characteristics of precipitation including intensity, duration, and the number of consecutive days of heavy precipitation. The sparse network of hourly precipitation gauges on a global scale hinders assessing trends of these characteristics and, therefore, in isolating the climatic signal in recent severe floods. In the United States, where the density of a good quality precipitation network allows such analysis, the number of days with precipitation exceeding 50.8 mm (2 inch threshold for heavy rain) was found to be increasing (Karl and Night, 1998). However, measurable trends in extreme floods consistent with the above trends in heavy precipitation are lacking, even when the record indicates a general upward trend in annual streamflow such as reported by Lins (1999). Pielke and Downton (2001) proposed a framework for addressing this apparent paradox. Their framework argues for contextually defining heavy precipitation and for considering several precipitation characteristics in conducting trend analysis. A similar study by Small *et al.* (2006) over the eastern

US identified increases in the fall but not the spring precipitation as the main reason for lack of a climatic signal in extreme flood records and for the observed trends in low-flow series.

c. *Droughts*

Another aspect of the hydrologic impact of climate change is drought. This is a particularly critical issue in arid/semi-arid regions because even minor changes in climate regimes are likely to have significant incremental impacts on the availability of water resources. Prolonged droughts can be devastating as they evolve over multi-year duration. Many have questioned whether the increased severity, extent, and duration of recent drought episodes are related to increased temperatures and the consequent increase in evaporation rates over the past 50 years. In recent years, severe droughts in the southwestern US caused significant losses and contributed to widespread forest fire episodes. The longer historical perspective of major drought events during the past century shows that droughts were more common than expected from recent observations. The reconstructed climate record for the El Malpais area in the west-central region of New Mexico (Grissino-Mayer, 1996) shows that when the area's severe drought, which occurred in the 1950s, is compared to other droughts in the past 300 years, it seems typical. When the same event is considered at longer time scales, it seems fairly minor in comparison with multi-decade drought events that have occurred over the past 2000 years. Clearly, historical context of droughts and other extreme hydrologic events must be considered in climate impact assessment studies.

d. *Snow Cover*

Seasonal flow regimes of many of the world's major rivers are snowmelt dominated. Potential impacts of climate change on snow cover extent and timing will therefore affects water supplies across many regions, particularly in the springtime over the northern hemisphere. Satellite data show a 10% decrease in the annual snow cover extent (Robinson, 1999) with much of the decline occurring in the spring snow cover extent. Similar results are seen with respect to snow depth. On the other hand, snow fall observations indicate a statistically significant increase in the winter snowfall in North America and some areas in Russia consistent with the abovementioned observed increases in precipitation (IPCC, 2001).

3. HYDROLOGIC MODELING AND CLIMATE IMPACT ASSESSMENT

As seen above, observational evidence increasingly points to possible climate induced changes in the hydrologic cycle. Consequently, interest in assessing the potential future impacts of climate change on various aspects of the hydrologic cycle and their consequences to water resource has been increasing even before the publication of the IPCC 2001 report. In general, predicting the impacts of climate change on the hydrologic cycle first requires the ability to model the long-term climate change for the entire planet under various scenarios. The Earth's climate system is complex and difficult to understand and predict. The new generation of coupled land-ocean-atmosphere models, which are also known as Global Circulation Models (GCMs) do resolve the physical processes occurring within these compartments and at their interfaces, albeit at coarse spatial resolutions (2.5°). Results from these models are subsequently downscaled to hydrologically relevant spatial and temporal scales in order to conduct detailed hydrologic studies using appropriate hydrologic models. Downscaling GCM output is generally based on one of three approaches. The first approach directly forces hydrologic models using the output from a given climate model or ensemble of models under different scenarios. In this approach, the GCM output mainly provides the range of possible changes in long-term mean precipitation and temperature, which are introduced into hydrologic models in a manner similar to 'brute force sensitivity analysis' to determine the expected range of changes in hydrologic responses. For example, Nash (1991) conducted a detailed assessment of climate change impacts on water resources in the Colorado River basin using a two step approach. The first step consisted of applying several GCM derived, scenario-based deviations of long-term mean precipitation [-20% to +20%] and temperature [+2°C to +6°C] to historical precipitation and temperature, and then introducing the latter into the National Weather Service River Forecast System (NWSRFS) hydrologic model. In the second step, the NWSRFS output (i.e., streamflow) was introduced into the U.S. Bureau of Reclamation's Colorado River Simulation System (CRSS), which incorporates management rules and reservoir simulation to track the impacts of climate change scenarios on long-term water availability in key reservoirs within the system. The results indicated a potential range of change in water storage (-61%, +38%), power generation (-57% to +39%), and salinity (+15% to -15%).

The sensitivity analysis approach may provide information regarding the range of possible changes. However, it does not account for special variability of precipitation and temperature, especially at hydrologically-relevant local scales in the assessment of local impacts. A second approach utilizes statistical relationships derived from past observations to downscale climate model output into hydrologically relevant resolutions prior to hydrologic simulations (Wood, 2002a, 2002b; Coulibaly *et al.*, 2005). To a large extent, the statistical approach is based on an important development in hydrologic forecasting, particularly with respect to probabilistic forecasting using Ensemble Forecasts. In climate predictions, ensemble traces are generated using multiple models as well as multiple scenarios (Murphy, 2004). For regional weather forecasts, ensemble traces are generally generated by the model's initial conditions as well as through the utilization of multiple models (Legg *et al.*, 2004; Muller *et al.*, 2005). Similarly, operational probabilistic hydrologic forecasts are gaining wider recognition as the most viable forecasts for risk-based decision making. In most cases, probabilistic hydrologic forecasts are issued by fixing the model's initial conditions and then forcing the model using input traces of historical observation for the duration of the forecasting window (Bradley *et al.*, 2004). For climate impact assessment studies, output from climate mode are used to generate stochastic weather traces based on observations, which are then used to derive hydrologic models. The advantage of this approach is in its ability to spatially downscale model output to a gauge or a network of gauges scale, and thus to maintain coherence with commonly used hydrologic models. For example, Sharif and Burn (2006) used a modified Kernel Nearest Neighbor K-NN (Lall *et al.*, 1996; Lall and Sharma, 1996) to resample historical weather observations conditioned by potential climate scenarios. They argued that K-NN provides superior performance to commonly used autoregressive models by maintaining the spatial structure of precipitation events and the correlation between and among variables. Priarie *et al.*, (2006) argued that a significant advantage of the K-NN framework is that it enables the addition of new conditioning variables such as large scale atmospheric circulations and/or climate change scenarios to generate weather sequences that retain some of the spatial characteristics of observations (Clarke *et al.*, 2004; Wilks, 2002; Gangopadhyay and Clark, 2004; Yates *et al.*, 2003).

The third approach utilizes numerical weather prediction models to perform the dynamical downscaling (Benestad, 2001, 2002) and force hydrologic and water resources models. The extensive data requirement of the latter approach reduces its wide use in assessing the effects of climate model and scenario uncertainty on uncertainties in projected hydrologic impacts of future climate (Quinn *et al.*, 2001) as well as those uncertainties associated with hydrologic models' parameters (Wilby, 2005). For example, Cayan *et al.* (2006), argued that the downscaling of a 150-year transient climate scenario simulation over the state of California to hydrologically relevant resolutions will require months-to-years of computer time. More recent hydrologically-based climate impact assessment studies covered, among other topics, large flood risk at regional and continental scales (Milly *et al.*, 2002; King, 2005; Kundzewicz *et al.*, 2005; Lehner *et al.*, 2006), regional/large basin water supply (Barnett *et al.*, 2005; Koster *et al*, 2005), hydrologic modeling in small watershed (Quinn et. al, 2001; Menzel *et al.*, 2006), downscaling of climate model output (Dibike *et al.*, 2005), and snow cover extent and characteristics (Dankers *et al.*, 2005; Stuart *et al.*, 2004; Dettinger *et al.*, 2004; Barnett *et al.*, 2005). To address uncertainties associated with different predictions arising from different climate models, probabilistic distribution of precipitation and temperature generated using ensemble runs of weather forecasting models (Wood *et al.*, 2005) have been used to force the hydrologic models, and the probability distribution of the hydrologic variables are then used to assess risks associated with climate change (Georgakakos, 2003).

Needless to say, the complexity of the earth climate system along with differences in model formulations of such complexities lead to remarkable differences between the GCM's projections of future climate (Figure 4, see page 216). As seen in the figure, which is obtained from the IPCC 2001 report, there is a great deal of uncertainty in model predictions of future climates. However, it is evident that all of the models agree in their future predictions of increased temperature as a result of the continuing increase in green house gasses in the atmosphere. The uncertainties in precipitation predictions are larger, but they consistently show an increasing mean value. Greater uncertainties would be expected at the local scales, and more significantly in predicting changes in the precipitation characteristics (intensity, solid-liquid, event duration, recurrence) at an event scale (Trenberth *et al.*, 2003). Such uncertainties necessitate cautiousness in approaching climate assessment impact studies. The ensemble framework, described above, not only provides the means to address uncertainties in climate predictions from a hydrologic modeling perspective, but also the framework to obtain modeling results in a manner consistent with decision theory. The upcoming IPCC's fourth report

'Climate Change 2007', is currently undergoing revisions and comments by IPCC member states. This report will rely on a new generation of climate models, improved emission and development scenarios, and higher resolution model output to reach much of its finding regarding possible future climates. While the improved spatial resolution will facilitate an improved utility of climate model output in regional and sub-regional hydrologic studies, much remains to be desired in terms of model uncertainty before the output of these models can be used effectively to determine possible hydrologic impacts at local scale. International efforts and significant investments may be required to reach that goal. Arguably, further research and data-collection activities are needed in order to quantify the impact of the intensification of the hydrologic cycle on the magnitude, direction, and frequency of floods, droughts, and other weather hazards which impact water resources management and to extend the lead time of hydrologically-relevant weather forecasts in a manner that support operational management. Furthermore thorough analyses of existing water resources systems, their operational procedures, and their resiliency are necessary to determine the type and level of operational flexibility (Dracup, 2001) that may be required in the future.

In the meantime, water resources managers must ensure that existing and planned water resources systems infrastructure are only elements of integrated strategies that provide for resiliency and adaptability, while at the same time account for environmental, ecological, and socio-economic concerns.

Acknowledgments

The authors would like to acknowledge support for this research from NASA, NOAA, NWS, GEWEX, and NSF STC for 'Sustainability of Semi-Arid Hydrology and Riparian Areas' (SAHRA). The second author also wishes to express his appreciation for the support of the Pontifical Academy of Sciences in organizing and sponsoring this workshop.

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CLIMATE CHANGE AND HYDROLOGIC DYNAMICS

WORLDWIDE CHANGES IN EVAPORATIVE DEMAND

GRAHAM FARQUHAR and MICHAEL RODERICK

Introduction

Evaporative demand is a measure of the extent to which the environment is 'trying' to evaporate water. It does not necessarily relate to actual evaporation rate, as if there is little water supply there can only be a small evaporation rate, no matter how large the demand. Changes in evaporative demand affect fresh water supplies and impact on agriculture, generally the biggest user of fresh water.

Given that actual evaporation can depend on both water supply and on evaporative demand, any changes in either have social implications. There are also narrower scientific interests in such topics, particularly in the context of climate and global change. Water vapour is the main natural greenhouse gas. Under CO_2-induced greenhouse change, water vapour causes the greatest, positive feedback. As surface temperature, T, increases, so does the vapour pressure, e, in the atmosphere, and this in turn causes more warming. The gain of this feedback loop ($T\uparrow \rightarrow e\uparrow \rightarrow T\uparrow$) is thought to be ≈ 0.4 (Held & Soden, 2000).

Evaporation is the biggest 'user' of net radiation and global warming is initially a problem of changed radiation balance. Changes to radiation (both short and longwave) are common to trends in evaporative demand and in heat balance (temperature). There has been a widespread assumption, especially prevalent in the popular press, that global warming should be associated with an increase of evaporative demand. Yet the scientifically valuable time-course of the most common measure of evaporative demand, pan evaporation rate, has generally been one of decrease, typically about -3mm a^{-2} (-3mm per year per year)(Peterson *et al.*, 1995; Roderick & Farquhar, 2004; Gifford, 2005). This paper explores why that happened and speculates about the future.

How is Evaporative Demand Measured?

As noted above, pan evaporation is the most widespread measure of evaporative demand, but we refer below to other means by which demand could be assessed. Pan evaporation rate is the loss of water from an open pan, usually measured daily, after allowing for any precipitation that has fallen. In the USA, Australia, and many other places, a US Class A pan is used. Such pans were designed originally to assist irrigation scheduling. These are galvanized iron vertical-sided pans, with a diameter of 1.21 m and depth of 0.255 m placed on a 0.15 m high wooden frame and filled with water to a certain small distance from the top. To relate such evaporation to that from a sunken pan or from a grass sward, one has to take into account that the sides of the class A pan intercept more sunlight than would a horizontal surface. For that reason Class A pan evaporation rates are often multiplied by a pan-coefficient of about 0.7 before application to irrigation scheduling.

'Water-Limited Worlds' Versus *'Energy-Limited Worlds'*

Those parts of the Earth where evaporative demand exceeds supply (rainfall), like much of Australia, are very different from those parts where rainfall exceeds evaporative demand, like Holland. In the latter there is run-off and rivers, and evaporation rate largely depends on the available energy and especially the radiation received. In water-limited regions, there is an excess of energy (e.g. solar radiation), and the actual evaporation rate is close to, but a little less than, the rainfall.

People from these two worlds have very different views of their environment. Even environmental scientists from the two worlds often have difficulty communicating. In the water-rich, (solar) energy poor regions, potential evaporation rate ($\approx 0.7 \times$ pan evaporation rate) and actual evaporation rate are almost the same, the two terms are almost synonymous and are used interchangeably. In water-poor, (solar) energy rich regions, evaporative demand is only a measure of the evaporation from tiny parts of the environment – from the dams, from irrigated fields, or from swimming pools, perhaps. For water-limited landscapes in general, evaporative demand and actual evaporation can often bear little relationship.

These ideas are illustrated in Fig. 1 (Budyko, 1974). Following from above, the actual evaporation rate, E_a, must be less than or equal to evaporative demand, E_{pot} (meaning potential evaporation rate), and also less than or equal to precipitation, P, i.e., $E_a \leq \min\{E_{\text{pot}}, P\}$. Thus the straight line limits, $E_a = \min\{E_{\text{pot}}, P\}$ are upper bounds, and a synthesis of the relationships observed in practice is depicted by the Budyko curve shown in Fig. 1. The water-limited regions are on the left, and energy-limited regions on the right of the figure. We immediately see that in energy-limited regions, a decline in evaporative demand implies a decline in actual evaporation rate. However, in water-limited regions, actual evaporation is constrained by the available water.

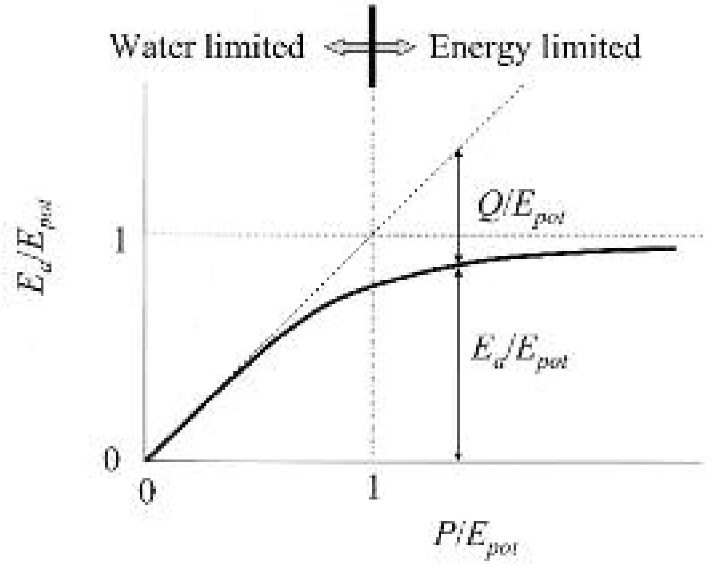

Figure 1. Inter-relationship between annual average precipitation (P), actual (E_a) and potential (E_{pot}) evaporation and runoff (Q). The full curve is known as the Budyko curve (Budyko, 1974).

What Has Been the Sign of the Recent, Multi-Decadal Trend in Evaporative Demand?

As noted previously, there is a general expectation, especially prevalent in the popular press, that as the world warms because of increased greenhouse forcing there will be a widespread increase in evaporative demand. This expectation has little scientific basis as we discuss later, but it is a widespread one, so that the public and leaders sometimes confound the dwindling of water supplies because of population increase, or natural variation in rainfall, with the mistaken idea that global warming has somehow dried up the water.

What have the observations been? The surprising result, published by Peterson and colleagues in *Nature* (Peterson *et al.*, 1995), was that when over 190 sites were examined in the former Soviet Union (FSU), the average trend in pan evaporation rate was a decline in the European sector, a decline in Siberia, and no trend in Middle Asian FSU. Further, averaging across 746 sites in the USA, there were declines also. Subsequent observations have been generally consistent with the 1995 study as far as the trend in evaporative demand is concerned. In India there has been a decrease in pan evaporation rate over the last 50 years (Chattopadhyay & Hulme, 1997). In China also there has been a decrease over the same period (Liu *et al.*, 2004, Wu *et al.*, 2006). Also in Venezuela (Quintana-Gomez, 1998), Thailand (Tebakari *et al.*, 2005), Australia (Roderick & Farquhar, 2004), New Zealand (Roderick & Farquhar, 2005), Canada (Hesch & Burn, 2005) and on the Tibetan plateau (Shenbin *et al.*, 2006). One exception was the report from Israel of a slight increase, but the results came from a single pan (Cohen *et al.*, 2002).

What Has Been the Magnitude of the Trends?

The magnitude of E_{pan} trends varies from pan to pan and needs to be averaged over many pans to obtain regional interpretations. Restricting ourselves to such studies, we note that for the USA, the Eastern US warm season (May-Sept), 1948-1993 showed a trend of -2.2 mm a^{-2} (Peterson *et al.*, 1995; Golubev *et al.*, 2001). In China, annually averaged over 85 broadly scattered pans, 1955-2000, the trend was -2.9 mm a^{-2} (Liu *et al.*, 2004). In Russia, in the NW corner of the FSU, 1960-1990, the trend was -3.7 mm a^{-2} (Golubev *et al.*, 2001). In India a much larger trend was reported, ~-12 mm a^{-2}, (Chattopadhyay & Hulme, 1997) and also in Thailand with a trend of ~ -10 mm a^{-2} (Tebakari *et al.*, 2005).

In the Southern Hemisphere, the trend from 1975 to 2002 averaged over 61 sites around Australia was -3.3 mm a^{-2} (Roderick & Farquhar, 2004) and this was later updated to -3.2 mm a^{-2} to account for the introduction of wire meshes (bird guards) to keep birds from drinking from the pans. (An addendum is available from the authors). In New Zealand the trend averaged over 19 sites since the 1970s was -2.1 mm a^{-2} (Roderick & Farquhar, 2005).

We conclude that a typical trend is -2 to -4 mm a^{-2} when averaged over many pans. This corresponds in an energy sense (via the latent heat of vaporisation of water) to ≈ -0.2 – -0.4 W m^{-2} a^{-1}.

Explanations

In order to understand what has been causing the trends we need to discuss the factors affecting pan evaporation rate directly. The fundamental driver is the difference between the vapour pressure at the water surface and that in the free air. As the surface warms, the water vapour pressure in the air contacting it increases and evaporation increases. This is the basis for the commonly held view that increasing temperatures mean greater evaporation. While this is true in the short term, for example the difference between sunrise and noon, it is unlikely to be the case on longer time scales such as decades, because the ocean surface temperature would increase and the humidity in the free air should also increase, and the evaporation required to maintain a constant vapour pressure deficit is minimal (as discussed later). Of course the temperature of the surface is affected by the heat balance there also – the actual evaporation cools the surface while radiation heats it. Penman (1948) was the first to describe the physics combining the vapour balance with the heat balance. Hence the term ‘combination formula’ is often used to describe the Penman approach. Basically the Penman formula can be reduced to the sum of a term dependent on radiation alone ($E_{\mathrm{pan,R}}$) plus one depending on aerodynamic factors (wind) and the vapour pressure deficit (a measure of how much more water vapour the air could hold if it were saturated), denoted $E_{\mathrm{pan,A}}$. In short, Penman’s combination equation is,

$$E_{\mathrm{pan}} = E_{\mathrm{pan,R}} + E_{\mathrm{pan,A}} \tag{1}$$

With a CSIRO colleague, we recently developed a Penman-based physical model called PenPan (Rotstayn *et al.*, 2006) and showed that it performed well over Australia when forced with observations. The radiative component is estimated using the global solar irradiance, the site latitude, and the albedo of the ground surrounding the pan. The aerodynamic component requires estimates of monthly mean air temperature, monthly mean vapour pressure deficit of the air, monthly wind run expressed as a mean wind speed and elevation.

Increasing Cloud

The trends in pan evaporation reported by Peterson *et al.* (1995) correlated with trends in the diurnal temperature range, and the authors noted that they were consistent with speculation by Karl *et al.* (1993) that cloud cover, particularly low cloud cover, had been increasing over preceding decades. They also proposed that their results implied that for the large areas examined the evaporative component of the hydrological cycle was decreasing. In fact the title of their correspondence was 'Evaporation losing its strength'. We would (Roderick & Farquhar, 2004) and they should, have been more careful to take into account the distinction between water- and energy limited- regions (Fig. 1). So we would say that among those regions where evaporation was energy limited, these reductions in evaporative demand implied a decrease in actual evaporation rate and this was later confirmed by observations (Golubev *et al.*, 2001). Peterson *et al.* suggested that their results partially explained increases in runoff in the European part of the FSU and northern US over the previous two decades. They then made the surprising and interesting observation that this corresponded well with both *decreases* in maximum summer temperatures over these regions (Karl *et al.*, 1993), and a *decrease* in growing-season degree-days in the European and Siberian FSU (Jones & Briffa, 1995). Their noting of this correspondence unfortunately tended to reinforce the notion that trends in pan evaporation rates and trends in temperature are directly related, although the discussion was set in the general framework of *increasing* average temperatures.

Increased Rainfall and Humidity: the Complementary Relationship

In further correspondence in *Nature* Brutsaert and Parlange (1998) introduced the idea of an 'evaporation paradox'. They noted that the reports of reduced pan evaporation were hard to reconcile with well-substantiated increases in global precipitation and cloudiness, which would normally require more evaporation as the only source of atmospheric water vapour, rather than less. They also pointed out that the reports seemed to run counter to predictions of increasing evaporation, as one of the more robust outcomes of radiative forcing, resulting from increasing atmospheric CO_2 in general circulation model calculations. They attempted to solve this paradox by appealing to the complementary relationship between actual evaporation and potential evaporation (Bouchet, 1963; Morton, 1983). While the details of this relationship are controversial, the general tenor is not. That is, in a dry environment (a water-limited one), when it rains, or soon after, there is a supply of water for evaporation, and the actual evaporation rate increases. This makes the air more humid, and cools the environment, thereby reducing the vapour pressure deficit and will also be associated with reduced net radiation if overcast conditions persist, all causing the evaporative demand/pan evaporation/potential evaporation rate to decrease. In mathematical terms, the complementary relation introduces the notion of wet area evaporation (E_w) via the expression $E_{pot}+E_a=2E_w$. (Brutsaert (2006) recently used $E_{pot}+5E_a=6E_w$. The discrepancy between the expressions seems to us to derive from differences in how the values of E_w arise. For example flooding an area from an irrigation pipe causes no immediate reduction of sunlight, whereas relying on rainy conditions will necessarily reduce sunlight considerably, albeit with increased downward longwave radiation from clouds). So Brutsaert & Parlange (1998) argued that a decreasing trend in evaporative demand was a sign of increased actual evaporation rate. This begs the question of why there would be an increase on the global scale in actual evaporation rate in this scheme, to which we return later. Again we would caution that one must distinguish between water-limited and energy-limited regions. The complementary relationship is only applicable in water-limited regions. In energy-limited regions, reduced evaporative demand generally means more runoff and river flow, as does increased rainfall. The Budyko approach would predict that decreasing pan evaporation means decreasing actual evaporation rate in energy-limited environments (see Roderick & Farquhar, 2004 for details of the successful Budyko predictions). The Budyko approach requires that in water-limited environments, one must examine the supply (i.e. rainfall) to determine if actual evaporation changes. Hence, in water-limited regions where the complementary relation appears to work, as in parts of the US (Hobbins *et al.*, 2004; Walter *et al.*, 2004), there has been more rainfall. However, there are many examples from water-limited environments where rainfall has decreased (implying decreasing actual evaporation) but pan evaporation has also decreased (e.g. for southeast Australia see Roderick & Farquhar, 2004; for several parts of China see Yang *et al.*, 2006). So while the trends for decreasing pan evaporation are associated with increasing rainfall in some regions, this cannot be a general explanation. Nevertheless it was the explanation used by the IPCC in their 2001 report to explain the observations.

Global Dimming

In a 24-page review of 'global dimming', Stanhill & Cohen (2001) had a single throw-away sentence: 'It should be noted that a worldwide reduction in open water surface evaporation has been noted in recent years (Peterson *et al.*, 1995)'. Soon afterwards they published their attempt to test experimentally whether or not dimming could be the cause (Cohen *et al.*, 2002). Unfortunately, at the single site they chose, at Bet Dagan in Israel, pan evaporation rate turned out to be stationary because of opposing effects of decreasing solar irradiance and increasing windspeed and decreasing humidity. The authors nevertheless felt that their site's data were inconsistent with the ideas of Brutsaert and Parlange. They suggested that the data supported the idea that global dimming was causing the general decrease in pan evaporation, but that locally they were seeing increases in the non-radiation component of evaporative demand because of local land-use changes.

Independently of Cohen *et al.* we too attempted to obtain a quantitative link between the pan evaporation trends and those in radiation (Roderick & Farquhar, 2002). Fortunately good records of pan evaporation and of solar radiance had been kept in the NW part of the former Soviet Union (FSU) and we were able to show that the regional trends were roughly consistent with each other, and that the downward trend in evaporative demand was about what one would expect from the downward trend of sunlight of between 2-4% per decade in those areas (Abakumova *et al.*, 1996). We also showed that the changes in diurnal temperature range imply that the vapour pressure deficit of the air was virtually unchanged. Given that vapour pressure deficit was constant, and with the untested assumption of no change in wind speed, we concluded that the observed trends in evaporative demand in the northwest of the FSU were largely caused by the reduction in sunlight brought about by some combination of cloudiness and aerosols.

The impact of aerosols on the hydrological cycle was reviewed by Ramanathan *et al.* (2001), who showed that greenhouse forcing in the northern hemisphere has probably been offset by aerosol release. They pointed out that aerosols affect rainfall via both sunlight reduction (a globally integrated reduction in actual evaporation also means reduced precipitation on a global scale) and by reducing the efficiency of condensation with an excess of condensation nuclei. A detailed case study was described by Ramanathan *et al.* (2005) for the Indian subcontinent. An analogous modeling treatment was given for Europe by Liepert *et al.* (2004), again showing a reduction of both rainfall and evaporative demand.

It therefore seemed important to us to examine sites in the southern hemisphere, as one would expect less effects of aerosols there. In 2003, with the advantage of our unpublished results on negative trends in Australian pan evaporation with the same magnitude (~ -3 mm a^{-2}) as elsewhere, we speculated (Farquhar & Roderick, 2003) that greenhouse gas emissions might reduce sunlight at the earth's surface. The subsequently published results on pan evaporation (Roderick & Farquhar, 2004) showed that at many sites in Australia evaporative demand was decreasing at the same time as rainfall was either decreasing or unchanged, ruling out the complementary relationship as being the cause there. Of course, in water-limited regions, the complementary relationship is strong when interannual variability is examined – it just cannot explain 30-year trends where both rainfall and pan evaporation are declining. We also raised the possibility of changes in wind.

Wind

With our findings (Roderick & Farquhar, 2005) that pan evaporation was also decreasing in New Zealand at ~ -2 mm a^{-2}, direct local effects of aerosols seemed very unlikely and we again speculated about effects of greenhouse forcing. In the United States, the decline in pan evaporation has been accompanied by increases in rainfall (Hobbins *et al.*, 2004; Walter *et al.*, 2004). In contrast, the New Zealand data, like those in Australia and China, show declines in pan evaporation at sites with both increases and decreases in rainfall. One needs to recognize that climatologically New Zealand and Australia are very different, with much of the former being (solar) energy limited, and much of the latter being limited by water supply. Yet the trends were similar!

While our speculation about greenhouse forcing as a common element related mainly to possible increases in cloud, as reported by Dai *et al.* (1997), we were careful to suggest that trends over time needed to be examined in temperature, net irradiance, vapour-pressure deficit, and wind speed. In doing so we were conscious of an intriguing and important paper by Chen *et al.* (2005), who examined pan evaporation in China and compared it with estimates made by the Penman-Monteith model (FAO version: Allen *et al.*, 1998) and by the Thornthwaite method (Thornthwaite, 1948). The main result was to confirm how unreliable the Thornthwaite version was when temperature was changing. However, in their very last paragraph Chen *et al.* wrote: 'A recent study (Xu *et al.*, 2004) shows that the decrease in ET is the result of decrease in wind speed and net radiation, which in turn can be attributed, to some extent, to the increase in urban areas and air pollution'. Unfortunately, and frustratingly, the reference to Xu *et al.* was not in the bibliography of Chen *et al.*!

The Xu *et al.* paper did eventually turn up – two years later (Xu *et al.*, 2006). It reported that decreasing pan evaporation in the Yangtze River basin (in China) was mostly due to declining solar radiation with declining wind speed also contributing. Changes in vapour pressure deficit, while important in a few regions, were generally minor. Detailed examination of the trends for Australia has found a similar story with decreasing sunlight and/or decreasing wind speed being the main reasons for decreasing pan evaporation (Roderick & Farquhar, 2006) but in Australia the main feature was declining wind speed. Results for the Tibetan plateau have also highlighted the importance of decreasing wind speed (Shenbin *et al.*, 2006).

Synthesis of Pan Evaporation

A dialectic is probably needed to ensure that the truth is reached. It probably involves all the hypotheses to some extent. However, there is one scenario that appears to have little experimental support. Although greenhouse warming has presumably caused the increase in average surface temperatures, it cannot have been causing a large increase in vapour pressure deficit over land – that would have increased pan evaporation.

We recognize the issue of time scales. If a hot dry wind arrives for a few days one expects evaporative demand to increase. But if temperatures increase because of enhanced greenhouse effects over several decades, there is plenty of time for absolute humidity to increase in parallel, so that relative humidity remains roughly constant, just as Arrhenius (1896) assumed it would when he made the early calculations of the effects of increasing levels of carbon dioxide in the atmosphere. Soden *et al.* (2005) suggested that observations and models show that humidity over the ocean follows ocean temperatures, so that increasing surface temperatures means increasing absolute humidity, and roughly constant relative humidity.

To give some intuitive basis we note that in Australia Darwin is warmer than Alice Springs (annual average T_a=27 *vs.* 21°C), yet the respective annual average pan evaporation rates are 2600 and 3100 mm a^{-1}. The point being that pan evaporation, and hence evaporative demand, depend on much more than just the average annual temperature (Rosenberg *et al.*, 1989). McKenney and Rosenberg (1993) compared eight methods of computing potential evapotranspiration. They made the comparison at several sites in North America. They used GCM predictions of change derived from GFDL and GISS modeling. They considered the Penman-Monteith method to be the most soundly based and showed that the Thornthwaite formula gave unreliable results. The latter was designed for sites where limited data were available, and used temperature as a surrogate for radiation. So in the Thornthwaite model when it warms, potential evaporation rate automatically increases. Unfortunately, the Thornthwaite model is embedded in the Palmer drought index (Dai *et al.*, 2004) used to determine changes in the severity of drought.

Just as we need to be careful examining the regions (water-limited *vs.* energy limited) when we interpret observations, we also need to be conscious of the time periods involved. It has been suggested that global dimming ceased and was replaced by global brightening at about 1990 (Wild *et al.*, 2005). However, the eruption of Mt. Pinatubo in 1991, and the loading of aerosols high in the atmosphere at that time, make it difficult to interpret the data. Further the data of Pinker *et al.* (2005) tend to suggest brightening over the ocean but not over the land, while those of Wild *et al.*, suggest brightening over land. The data reported by Xu *et al.* (2006) for part of China indicate that net radiation was fairly constant from 1990 to 2000 while data from Norway suggest continued dimming up to 2003 (Grimenes & Thue-Hansen, 2006). To our knowledge there has not been a systematic examination of global trends in pan evaporation rate to see whether they have reversed. In Australia the recent drought (2002 – still ongoing in January 2007) over much of eastern Australia has meant high pan evaporation rates there over the last few years.

While there is now reasonable agreement that pan evaporation rate did decline in many parts of the world for several decades there is disagreement about what this meant in terms of actual evaporation rate. Does declining pan evaporation mean declining evaporation? If E_{pan} declines because rainfall has increased in a dry, water limited environment, then it does not. If E_{pan} declines in a wet, energy limited environment, then it invariably does.

Gradually scientists are learning how to synthesise the concepts of Budyko, Penman and Bouchet. A good case in point is the work of Yang *et al.* (2006) in China. They summarised their work by saying that: ‘According to the Budyko hypothesis, change in actual evaporation is determined by the balance between the precipitation and potential evaporation. In non-humid regions, change in actual evaporation is dominated by change in precipitation rather than in potential evaporation, and the Bouchet complementary relationship between actual and potential evaporations comes about because actual and potential evaporations are correlated via precipitation... In humid regions, change in actual evaporation is controlled by change in potential evaporation rather than precipitation, and this is identical to the Penman hypothesis'.

What is Happening on a Global Scale?

With the success of approaches like that of Yang *et al.* (2006), are we in a position to say what is going on at a global scale? We first need to take into account that averaged over the entire land surface, rainfall has been constant or increasing, over the period of interest (New *et al.*, 2001). Similarly, runoff has generally increased (Labat *et al.*, 2004). That could be partly because of increased [CO_2] closing stomata, as proposed by Gedney *et al.* (2006). Or perhaps it is because of reduced evaporative demand (and hence reduced actual evaporation) in energy-limited regions. Where then does the extra water come from to supply the increased rainfall over the land? It seems to us that this requires there to have been increased evaporation from oceans (Linacre, 2005), or less rainfall there. Either way it implies greater transfer of water from the ocean to the land. This would be consistent with the reported brightening over the oceans (Pinker *et al.*, 2005). However it seems at odds with the results of Dirmeyer & Brubaker (2006) who examined the recycling ratio (the fraction of precipitation over a region that originated as evaporation from the same region) for areas north of 50°N over the period 1979-2003. They found a strong trend for increase in the ratio for North America, but not over Asia, and discussed the results in terms of vegetation-related responses to climate change. However, the analysis relies on National Centers for Environmental Prediction (NCEP) reanalysis of wind, and there are reports questioning the latter's reliability (Goswami & Sengupta, 2003; Smits *et al.*, 2005).

Just as scientists working in water-limited environments tend to have different intuition from those working in energy-limited environments, so, too, are there differences between those working over land and those working on oceans. The terrestrial surface has small heat storage and net radiation is dominated by incident sunlight. Thus energy transfers (sensible and latent heat) are roughly in phase with sunlight. Oceans are very different. They have large heat storage capacity and energy transfers can be out of phase with sunlight (large storage and currents). Reed (2003) demonstrated this for the Bering Sea (56-56°N, 169-171°W) with latent and sensible heat fluxes being least in summer and greatest in winter.

What Might one Expect with Greenhouse Forcing of Climate Change?

We give here a simple, intuitive approach to effects of greenhouse forcing on climate, obviously a complex issue. We rely heavily on Figure 2, the IPCC diagram of the global energy balance.

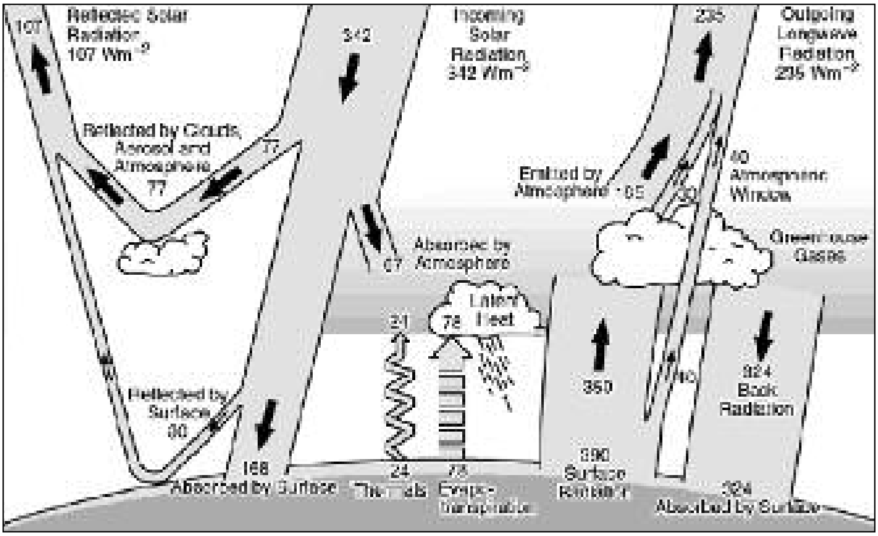

Figure 2. The Earth's annual and global mean energy balance. Source: Kiehl & Trenberth 1997 (and IPCC).

[CO$_2$] Doubling

An instantaneous doubling of [CO$_2$] while holding all else constant is estimated to effect a forcing of about 4 W m^{-2} at the top of the atmosphere (strictly the tropopause) (Ramaswamy *et al.*, 2001). The forcing at the top of the atmosphere is how much less longwave radiation comes out instantaneously when [CO$_2$] is increased instantaneously (not how much more is effectively going down to the surface). That is, the outgoing long wave irradiance of 235 W m^{-2} (Fig. 2) would drop to 231, giving an imbalance. To restore the energy balance, the emission of longwave radiation of the surface, presently 390 W m^{-2}, would have to increase. How much more? We note that the rate of energy input to the atmosphere, largely from below, is

(67+24+78+350=) 519 W m^{-2}. The simplest assumption is that this total would have to increase to 235/231 × 519=528 W m^{-2} to overcome the increased infrared opacity. This would lead to 'back' radiation increasing from 324 by an extra 9 W m^{-2}. Assuming that the partitioning of this extra radiation was roughly the same as before, sensible plus latent heat would go up from 24+78 by 9x102/(102+390)=1.9 W m^{-2} and surface radiation would increase from 390 by 7.1 W m^{-2}. The latter increase requires an increase of surface temperature. The dependence of black body flux, F, on temperature, T, is $F=\sigma T^4$, where σ is the Stefan Boltzmann constant. At an average earth surface temperature of about 288 K (15°C) this means that $\mathrm{d}F/\mathrm{d}T$=5.4 W m^{-2} per K. So the surface needs to warm by 7.1/5.4 = 1.3 K. This is the response to increased [CO_2] alone.

Water Vapour Feedback

As the air warms, it holds more water vapour which is a strong greenhouse gas. It causes a positive feedback, with a loop gain believed to be about 0.4 (Held & Soden, 2000). Thus the 1.3 K increase becomes 1.3/(1-0.4)=2.2 K. Strictly what we have called a water vapour feedback is a combination of water vapour and lapse rate feedback (Bony *et al.*, 2006).

Other feedback loops can modify this basic approach – clouds, ice cover, etc. The system could be quite sensitive to them. So for example, another feedback of loop gain β_{other} would mean a temperature increase of 1.3/(1-0.4- β_{other}), and for β_{other}=0.1, say, this would mean a 2.6K increase. Hence the interest in climate feedbacks!

Effects on Evaporation and Rainfall

We saw from the above that sensible plus latent heat increased by 1.9 W m^{-2} from a total of 102, i.e., a 1.9 % rise for an increase of surface temperature of 1.3 K. This is equivalent to 1.4% increase per degree rise in temperature. In this back of the envelope approach we assume no change in the partitioning between sensible and latent heat fluxes.

Current general circulation models have varying sensitivities, but the median in the comparison generated for the Fourth Assessment of the IPCC, described by Held and Soden (2006), was 1.7%/K. In terms of actual observations of global annual average precipitation, nobody knows the answer because rainfall onto the ocean is unknown. For the entire land surface, New *et al.* (2001) report a 8.9 mm increase over the twentieth century, in a background of 1002 mm annual rainfall, representing an increase of 0.89%. Over the same period the increase in surface temperature was about 0.6 K. Thus the observed increase in rainfall was 0.89/0.6=1.48% per K warming, comparing well with our back of the envelope estimate of 1.4%/K. We acknowledge the uncertainties in the data and modelling, and certainly in our estimations. For one thing, the increase in temperature and rainfall over the century was accompanied by large increases in aerosol loading, reducing insolation and hydrological fluxes. On the other hand, future temperature increases are likely to be accompanied by reductions in surface albedo (e.g. melting surface ice), which will supply additional energy for thermals and latent heat.

But Could Evaporation Exceed Rainfall?

At present the precipitable water column (mainly vapour) is about 28.5 mm (liquid water equivalent). Following a Clausius-Clapeyron relationship, a 1 K warming at 15°C (most atmospheric water vapour is near the earth's surface) means about a 7% increase or 2 mm. A 1 K warming over 50 years, say, would require a mismatch of evaporation and precipitation of 2 mm over a period when the total precipitation is 50,000 mm, i.e., evaporation of 50,002 mm. That is, the mismatch would not be discernible in its effects. We do not foresee much reason for assuming increasing soil water deficits, *on average*, as the earth warms, particularly given that increasing [CO_2] levels tend to increase plant water-use efficiency (Wong *et al.*, 1979).

An interesting further point is to compare the 7% increase in vapour pressure/K warming with the 1-2% increase in precipitation/K. This appears to require a reduction in atmospheric circulation (see discussion by Held & Soden, 2006) and may be relevant to observations of trends in wind speed.

What About Local Effects?

While soil water deficits may not change on average, it is important to concede that virtually nobody lives on the average earth's surface. It is likely that redistribution of rainfall and evaporative demand will occur, with some places becoming drier and others wetter. For example, a poleward movement of subtropical high pressure zones is predicted by some models (although this trend has not seen yet been observed in Australia, see Drosdowsky, 2005), and it has been suggested that wet regions might become wetter and dry regions even drier (Held & Soden, 2006). At the regional level the GCM predictions related to practical hydrology are still quite varied between models.

Sources of variation between models, apart from differences in treatments of greenhouse forcing and of such well-known problems such as cloud amount and properties, include treatment of aerosols (Rotstayn *et al.*, 2007; Lohmann – this volume), CO_2 effects on stomata and vegetation (Gedney *et al.*, 2006), deforestation and other aspects of land use change, and effects of ozone. An interesting feature is that local changes, such as land use change, can, at least in models, have effects at a distance (Hansen *et al.*, 2005).

Intrinsic Variability and Chaos

A fundamental issue is that the earth's climate is chaotic (Lorenz, 1963). This means that there is unforced variability, and this is recorded in past abrupt changes in climate, both globally and locally, in the ice ages (Dansgaard *et al.*, 1984) and in the current Holocene (deMenocal, 2001). It is usually interpreted to mean that multiple simulations from a single model are needed with slightly different starting conditions in order to obtain an ensemble mean.

A recent example was given by Rotstayn *et al.* (2007) for the modeled annual rainfall trends in Australia. They examined Australian rainfall trends over the period 1951-1996 in eight runs that had been given slightly different starting conditions. All members of the ensemble had a positive trend in annual rainfall when averaged over Australia, but the range was large, ranging from 0.24 to 2.80 mm a^{-2}. Further, the spatial patterns differed greatly among some of the runs. It is worth explaining the source of variation in initial conditions: each run covered the period 1871 to 2000, and used an initial condition taken from a preindustrial control run that had been integrated for several hundred years to reach a state of approximate (dynamic) equilibrium. The initial conditions for the individual runs were separated by 20 years to ensure independence of the runs. Each of the eight runs in the ensemble was forced by (identical) historical changes in long-lived greenhouse gases, ozone, solar variations, volcanic sulfate and anthropogenic emissions of aerosols and aerosol precursors. It raises the point that the actual climate is the result of a single 'run' of the earth over that period. In other words, if the clock were to be turned back to 1870 and the real earth allowed to move forward in time anew, but allowing a few butterfly wings to have flapped at 1870, then the statistics that climatologists subsequently calculated for a given region might have been different. It is likely not just the model of regional climate that is chaotic, but the true region's climate. These results emphasize that natural interdecadal fluctuations have probably contributed to the observed trends in the Australian hydrological cycle. See also discussion of chaos over shorter periods in modeling results for Argentinian rainfall (Hunt, 1997).

In order to make the eight runs for their ensemble in reasonable time, Rotstayn *et al.* had to use a model of somewhat coarse resolution (5.6° in longitude and 3.2° in latitude). The authors commented that the low-resolution simulations may have overestimated interdecadal rainfall variability and noted that the power spectrum of global temperature differed from the observed. There is obviously a need for more work in this area to better understand the nature of internal variability.

In closing we return to the data, and emphasis the importance of maintaining good networks of observations on evaporative demand and related variables. It would be helpful to have more such measurements over the oceans, also.

Conclusions

In this article we have described observations of pan evaporation rate, a measure of evaporative demand. We discussed the differences between a water-limited environment and an energy-limited one, and how changes in evaporative demand have quite different consequences in the two environments. The distinction is useful in recognising distinct issues for the people involved. In representative areas of both types of environment there have been trends of decrease in pan evaporation rate, despite warming of the surface. We discussed the complementary relationship between actual evaporation and potential evaporation in water-limited environments. We pointed out that pan evaporation has been declining in places with declining rainfall as well as in places where it has been increasing. We described associations to varying degrees with decreased net radiation ('global dimming' caused by changed cloud amount or properties or by aerosol loading), and with decreased wind speed. We emphasised that heat storage and currents in the ocean give quite different relationships from those on the land.

We gave a simple version of what we expected with enhanced greenhouse forcing, including positive water vapour feedback, and including near constant relative humidity and about 1-2% increase in hydrological fluxes per degree of warming. We emphasised that there could be little globally averaged difference between evaporation and precipitation. However, we noted that local and regional changes could be significant. We mentioned the large number of ways that hydrology could be perturbed by humans, and that there was natural internal variability in regional climate.

We emphasise that on the time scale of global warming, there is a partial decoupling between temperature and absolute humidity on the one hand and the fluxes of latent and sensible heat on the other. We mentioned that this could lead to reduced atmospheric circulation. From a policy point of view it is important to realise that global warming does not equate to global drying.

Acknowledgements

We thank the former Cooperative Research Centre for Greenhouse Accounting for its support. GDF acknowledges support from the Australian Research Council and a Gary Comer Award.

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IMPACT OF AEROSOLS ON THE HYDROLOGICAL CYCLE

ULRIKE LOHMANN

Anthropogenic aerosol particles such as sulfate and carbonaceous aerosols have substantially increased the global mean burden of aerosol particles from preindustrial times to the present-day. These aerosol particles can interact with clouds and precipitation by acting as cloud condensation or ice nuclei. Thus they have an influence on the radiative balance of the Earth-Atmosphere system but they could have an influence on the hydrological cycle. While the cloud albedo enhancement (Twomey effect) of warm clouds received most attention so far and traditionally is the only indirect aerosol forcing considered in transient climate simulations, here I discuss the multitude of effects. These indirect effects can be subdivided into different contributing processes, as summarized in Table 1 (see over) and shown in Figure 1 (see page 217).

The cloud-albedo effect, i.e. the distribution of the same cloud liquid water content over more, hence smaller, cloud droplets leading to higher cloud reflectivity, is a purely radiative forcing. The other effects involve feedbacks in the climate system. The albedo effect cannot be easily separated from the other effects; in fact, the processes that decrease the cloud droplet size per given liquid water content also decrease precipitation formation, hence prolonging cloud lifetime (cloud lifetime effect). The glaciation effect refers to an increase in ice nuclei resulting in a rapid glaciation of a supercooled liquid water cloud due to the difference in vapour pressure over ice and water. Unlike cloud droplets, these ice crystals grow in an environment of high supersaturation with respect to ice, quickly reaching precipitation size, and with that can turn a non-precipitating into a precipitating cloud. The thermodynamic effect refers to a delay in freezing by the smaller droplets causing supercooled clouds to extend to colder temperatures.

TABLE 1.

Effect	Cloud Types Affected	Process	Sign of Change in TOA Radiation	Sign of Change in Precipitation
Cloud albedo effect	All clouds	For the same cloud water or ice content more but smaller cloud particles reflect more solar radiation	Negative for water clouds, positive or negative for ice clouds	n/a
Cloud lifetime effect	All clouds	Smaller cloud particles decrease the precipitation efficiency thereby prolonging cloud lifetime	Negative	Negative
Glaciation indirect effect	Mixed-phase clouds	An increase in ice nuclei increases the precipitation efficiency	Positive	Positive
Thermodynamic effect	Mixed-phase clouds	Smaller cloud droplets delay freezing causing supercooled clouds to extend to colder temperatures	Positive or negative	Positive or negative

Aerosol Effects on Water Clouds and Warm Precipitation

The indirect aerosol forcing of increasing cloud albedo for warm clouds does not have any direct impact on precipitation and therefore is not discussed any further. In addition aerosols increase the lifetime of clouds because increased concentrations of smaller droplets lead to a decreased drizzle production (Albrecht, 1989). It has proven difficult to devise observational studies that can separate the cloud lifetime from the cloud albedo effect; thus, observational studies in most instances provide estimates of the combined effects. Similarly, climate modeling studies cannot easily separate the cloud lifetime indirect effect once aerosol are interacting with clouds.

Evidence of a cloud lifetime effect due to anthropogenic emissions of aerosols and their precursors stem, for instance, from the absence of a drizzle mode in ship tracks that perturb marine stratus cloud decks off the coast of California (Ferek *et al.*, 1998). Also regionally this effect is found when separating polluted from clean clouds off the Atlantic coast of Canada (Peng *et al.*, 2002). One remaining problem is that most climate models suggest an increase in liquid water when adding anthropogenic aerosols, whereas newer ship track studies show that polluted marine water clouds can have less liquid water than clean clouds (Platnick *et al.*, 2000; Coakley and Walsh, 2002). Ackerman *et al.* (2004) attributed this phenomenon to enhanced entrainment of dry air in polluted clouds in these instances. On the other hand, satellite observations have been used to conclude that the aerosol indirect effect is likely primarily due to an increase in cloud cover, rather than an increase in cloud albedo (Kaufman *et al.*, 2005).

Smoke from burning vegetation reduces cloud droplet sizes and delays the onset of precipitation (e.g., Warner and Twomey, 1967; Andreae *et al.*, 2004). Also, desert dust suppresses precipitation in thin low altitude clouds (Rosenfeld *et al.*, 2001; Mahowald and Kiehl, 2003). Givati and Rosenfeld (2004) evaluated changes in orographic precipitation over the last 100 years. They indicated surface precipitation losses over topographical barriers by 15-25% downwind of major coastal urban areas in California and in Israel likely caused by aerosols. Contradictory results are found regarding the suppression of rainfall from aerosols in Australia (Rosenfeld, 2000; Ayers, 2005).

Global Climate Model Estimates of the Total Anthropogenic Aerosol Effect

The global mean magnitude of the cloud albedo effect since pre-industrial times is estimated between -0.5 and -1.9 W/m^2 from different climate models and the cloud lifetime effect to be between -0.3 and -1.4 W/m^2 (Lohmann and Feichter, 2005). Thus, whether the cloud lifetime or the cloud albedo effect is more important, is still an open question. Whereas some models predict that the cloud albedo effect is four times as important as the cloud lifetime effect, other models predict that the cloud lifetime effect dominates over the cloud albedo effect (Figure 2, see page 218). If the individual indirect effects values are summed up, the indirect effect could amount to almost -3 W/m^2. This exceeds estimates from simple inverse models, that start from the observed land temperature raise and increased ocean heat uptake in the 20th century, which bracket the overall indirect aerosol effect to be between 0 and -2 W/m^2 (Anderson *et al.*, 2003). Thus, either climate model predictions of the cloud albedo and/or cloud lifetime effect are too large, or a counteracting effect is missing.

One possible counteracting effect is the glaciation aerosol effect by which an increase in ice nuclei will cause some supercooled droplets to freeze. Because the vapor pressure is lower of ice than over water, the ice crystals quickly grow at the expense of cloud droplets (Bergeron-Findeisen process) and the supercooled liquid water or mixed-phase clouds turns into an ice cloud. Because the precipitation formation via the ice phase is more efficient than in warm clouds, these glaciated clouds have a shorter lifetime than supercooled water clouds (Rogers and Yau, 1989).

Motivated by laboratory studies, Lohmann (2002) and Lohmann and Diehl (2006) show that if, in addition to mineral dust, hydrophilic black carbon aerosols are assumed to act as ice nuclei at temperatures between 0°C and –35°C, then increases in ice nuclei in the present-day climate as compared to pre-industrial times result in more frequent glaciation of supercooled stratiform clouds and increase the amount of precipitation via the ice phase. This decreases the global mean cloud cover and leads to more absorption of solar radiation. Whether the glaciation or warm cloud lifetime effect is larger depends on the chemical nature of the dust (Lohmann and Diehl, 2006). Likewise, the number and size of ice particles in convective mixed phase clouds is sensitive to the chemical composition of the insoluble fraction (e.g., dust, soot, biological particles) of the aerosol particles (Diehl and Wurzler, 2004).

Aerosols and Sahel Drought

Several studies have considered the response of a global climate model (GCM) with a mixed-layer ocean to indirect aerosol effects (e.g., Williams *et al.*, 2001; Rotstayn and Lohmann, 2002) or to a combination of direct and indirect aerosol effects (e.g., Feichter *et al.*, 2004; Kristjansson *et al.*, 2005). All of these found a substantial cooling that was strongest in the Northern Hemisphere, with a consequent southward shift of the Intertropical Convergence Zone (ITCZ) and the associated tropical rainfall belt (Figure 3, see page 219). Rotstayn and Lohmann (2002) went on to suggest that aerosol effects might have contributed to the Sahelian droughts of the 1970s and 1980s. The southward shift of the ITCZ was less pronounced in the Feichter *et al.* (2004) study than in the other studies, perhaps due to their more complex treatment of cloud droplet nucleation, which tends to give less weight to the effects of sulfate than simpler schemes do. In contrast, Chung and Seinfeld (2005) considered the response of a GCM to direct forcing by black carbon aerosols, and found a northward shift of the ITCZ due to enhanced warming of the Northern Hemisphere.

Effects of Aerosols/Clouds on the Solar Radiation at the Earth's Surface

By increasing aerosol and cloud optical depth, emissions of aerosols and their precursors from human activity contribute to a reduction of solar radiation at the surface ('solar dimming') between 1961-1990 (e.g., Gilgen *et al.*, 1998; Liepert, 2002; Stanhill and Cohen, 2001). The decrease in solar radiation at the surface resulting from the increases in optical depth due to the direct and indirect anthropogenic aerosol effects is more important for controlling the surface energy budget than the greenhouse gas induced increase in surface temperature. There is a slight increase in downwelling longwave radiation due to aerosols, which in the global mean is small compared to the decrease in shortwave radiation at the surface. This has been shown in equilibrium simulations with a global climate model coupled to a mixed-layer ocean model with increasing aerosol particles and greenhouse gases from pre-industrial times to present-day (Liepert *et al.*, 2004; Feichter *et al.*, 2004), and in transient simulations (Roeckner *et al.*, 1999). The other components of the surface energy budget (thermal radiative flux, sensible and latent heat fluxes) decrease in response to the reduced input of solar radiation, which may explain the observations of decreased pan evaporation over the last 50 years reported in several studies. As global mean evaporation must equal precipitation, a reduction in the latent heat flux in the model led to a reduction in precipitation (Liepert *et al.*, 2004). This is in contrast to the observed precipitation evolution in the last century and points to an overestimation of aerosol influences on precipitation, or to an important ice cloud aerosol indirect effect. The decrease in global mean precipitation from pre-industrial times to the present may, however, reverses into an increase of about 1% in 2031-2050 as compared to 1981-2000, because the increased warming due to black carbon and greenhouse gases then dominates over the sulfate cooling (Roeckner *et al.*, 2006 and Figure 4, see over).

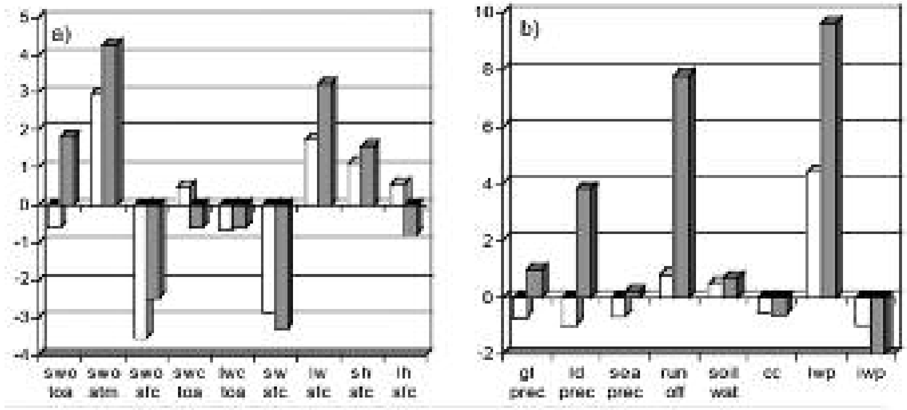

Figure 4. Changes in annual and global mean heat fluxes (left, units are Wm^{-2}) and components of the hydrological cycle (right, percentage changes) between 2031-2050 and 1981-2000 [grey columns] and between 1981-2000 and 1861-1880 [white columns] (adapted from Roeckner *et al.*, 2006).

Notations: toa=top-of-atmosphere, atm=atmosphere, sfc=surface, swo=net clear-sky, shortwave radiation; swc, lwc=shortwave/longwave cloud forcing; sw, lw=net shortwave/longwave radiation; sh, lh=sensible/latent heat flux (negative upward); prec=precipitation; evap=evaporation (positive upward); soil wat=soil water; cwv=column water vapor; cc=total cloud cover; lwp, iwp=cloud liquid water/ice path.

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LAND-ATMOSPHERE INTERACTIONS

PLANT HYDRAULIC PROPERTIES LIMIT PHOTOSYNTHETIC CAPACITY AND REGENERATION POTENTIAL

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1. INTRODUCTION

The fossil spore record suggests that non-vascular plants appeared in wet tropical and temperate areas on the terrestrial surface some 450 million years ago [1-3]. Since that time, plants increased their efficiency of capturing sunlight and photosynthesizing by vertically distributing chlorophyll and photosynthetic machinery, packaged mostly in leaves, along crowns. More sparsely distributed foliage can utilize light more efficiently than compactly arranged foliage, an arrangement in which a small proportion of the foliage receives an oversupply of light while a large proportion of the foliage must do with very low light level. Moreover, in forest settings, positioning leaves above those of the neighbors' is a common strategy for increasing light harvesting and photosynthesis. Thus, since plants moved to land, some species developed crowns that attained great lengths and are positioned at great heights. For species that rely on wind dissemination of pollen and seed, attaining height increases the dispersal distance. Further increase in dispersal distance is gained when attaining height brings a plant crown above those of its neighbors, because of the effect of canopy leaf area on the flow of air. However, not all species rely on height to obtain sufficient photosynthates to grow and reproduce, and not all species rely on height to increase dispersal distance of wind disseminated pollen and seeds. Species that rely on height to support photosynthesis and dispersal must make adjustments to overcome the limitations to water flow between the soil and leaves, so leaves can keep stomata open enough to permit a reasonable rate of photosynthetic CO_2 uptake.

Operating in a desiccating atmosphere, terrestrial plants must maintain photosynthetic tissues at the proper state of hydration. As height increases, the delivery of water to leaves becomes more difficult because of the longer transport path and greater loss of energy for moving water. Thus, attaining height to support photosynthesis and dispersal requires a hydraulic transport system that can adjust as trees grow taller and deliver the necessary amount of water to leaves. Such adjustments do not come without costs, which may ultimately put a limit to height as a solution for increasing photosynthesis and dispersal distance. A trade-off must exist between carbon uptake and water loss, with direct implication to the potential distance of wind dispersal of pollen and seed. This study focuses on assessing the trade-off and its impact on pollen dispersal distance.

Great advances have been made over the past century in understanding of (i) radiation attenuation, scattering, and absorption by leaves within canopies, [4-8] (ii) the relationship between leaf photosynthesis and its inter-cellular CO_2 concentration, [9-15] (iii) delivery of water from the soil pores to the leaves or soil-plant hydrodynamics, [16-28] and (iv) dispersal of seed and pollen [29-36]. These four research thrusts each produced a set of radiative, physiological, hydraulic, and dispersal parameters that can be considered independent. Here we concentrate on hydraulic, biochemical, and dispersal attributes of forest trees. In particular, we analyze two inter-related questions: 1) whether hydraulic and biochemical properties of plants are independent of one another, or do they change in concert as tree height increases, and 2) whether the key attributes that describe the relationship between hydraulic and biochemical properties also explain seed and pollen dispersal. Preliminary experimental and theoretical work on the first question has received recent attention, [37,38] and we use these preliminary findings as a starting point.

2. THEORY

We first identify the plausible functional parameters that link hydraulic and biochemical properties of plants and then proceed to assess their significance on seed and pollen dispersal. To establish the interdependency between hydraulic and physiological properties, the leaf transpiration rate and leaf photosynthesis formulations are reviewed.

2.1. *Plant Hydraulics*

Within forested ecosystems, the transport of water (per unit leaf area) from the soil to the leaf may be described by Darcy's law, given as

$$E_l = \left(\frac{\psi_s - \psi_l - \rho g h_c}{h_c}\right) k_s \frac{A_s}{A_L}, \tag{2}$$

where E_l is the average transpiration rate per unit leaf area, ψ_l and ψ_s are the leaf and soil water potential, h_c is the canopy height and is used here as a surrogate for the hydraulic path length from the soil to the leaf, ρ is the density of water, g is the gravitational acceleration, k_s is the soil-to-leaf tissue specific hydraulic conductivity, A_s is the sapwood area, and A_l is the leaf area.

Since the interest is in deriving simplified expressions relating plant hydraulic to physiological attributes, we adopt two simplifications:

1) $|\psi_s| \ll |\psi_l|$;

2) $(-\psi_l - \rho g h_c) k_s \approx c$ where c is a constant.

The first simplification assumes that the soil system is sufficiently hydrated (typical values of $|\psi_l| \sim 1.5 MPa$ while typical values for $|\psi_s| < 100 kPa$ even at 50% the field capacity of the soil). [Care must be taken when extrapolating the low-dimensional model used in our analyses to cases when $|\psi_s|$ is not much smaller than $|\psi_l|$ (e.g. during drought conditions). During drought conditions, plant function and structure changes with the intensity and duration of water deficit]. The second simplification is approximate because it assumes that leaf pressure must adjust to counteract the extra weight of water that must be pulled up to the leaf surface (i.e., $\psi_l = \psi_R + \rho g h_c$ where ψ_R is a reference leaf pressure). Detailed xylem pressure measurements within redwood trees (*Sequoia sempervirens*), including the tallest known tree on Earth (=112.7 m), collected in the wet temperate forests of northern California supports the argument that $\partial \psi_L / \partial z = \rho g$ [39].

With these two simplifications, we find that:

$$E_l \approx c \frac{A_s}{A_L} \frac{1}{h_c}. \tag{3}$$

Several studies in forested canopies also reported that the ratio of the sapwood area to leaf area is approximately linear with h_c so that: [40,41]

$$A_s / A_l = A' + B'h_c\,, \tag{4}$$

although exceptions have been noted in some species [42]. The parameters A' and B' vary among species. *Mathematically*, for species that conform to eqn. (4) for a large portion of h_c, $A' \sim a_1 A_l$. Hence, the leaf transpiration rate is given by

$$E_l = \left(c\,a_1 A_l\right)\frac{1}{h_c} + (cB') \tag{5}$$

2.2. *Photosynthesis*

Leaf photosynthesis is given by the Farquhar *et al.* [11] model, which assumes that photosynthesis is either limited by light or enzymatic properties (i.e. Rubsico), and can be represented as:

$$A_n = \frac{\alpha_1(C_i - \Gamma^*)}{C_i + \alpha_2} - R_d \tag{6}$$

where R_d is dark respiration, $\alpha_1 = \alpha_p Q_p e_m$ and $\alpha_2 = \Gamma^*$ for light-limited photosynthesis, and $\alpha_1 = V_{c\max}$ and

$$\alpha_2 = \kappa_c\left(1 + \frac{o_i}{\kappa_o}\right)$$

for Rubisco-limited photosynthesis. Here, α_p is the leaf absorptivity for photosynthetically active radiation (*PAR*), e_m is the maximum quantum efficiency for CO_2 uptake, Q_p is the *PAR* irradiance on the leaf, Γ_* is the CO_2 compensation point, $V_{c\max}$ is the maximum catalytic capacity of Rubisco per unit leaf area (μmol m^{-2} s^{-1}), κ_c and κ_o are the constants for CO_2 fixation and O_2 inhibition with respect to CO_2, respectively, and o_i is the oxygen concentration in air (~210 mmol mol^{-1}).

2.3 Linking Hydraulics and Photosynthesis:

Noting that leaf-stomatal conductance is given by

$$g_s \approx \frac{E_l}{1.6VPD} = \frac{A_n}{C_a - C_i} \tag{7}$$

permits us to establish a relationship between α_1 and the plant hydraulic attributes:

$$\alpha_1 \approx \frac{C_a\left(1-\frac{C_i}{C_a}\right)}{1.6VPD}\left(\frac{\frac{C_i}{C_a}+\frac{\alpha_2}{C_a}}{\left(\frac{C_i}{C_a}-\frac{\Gamma^*}{C_a}\right)}\right)\left[\left(c\,\alpha_1 A_l\right)\frac{1}{h_c}+cB'\right]. \tag{8}$$

The ratio C_i/C_a varies by about 20% (between 0.65 and 0.90 for C3 plants), and may be treated as a constant [37,43] when compared to variations in h_c. In fact, a near-constant C_i/C_a approximation appears to be valid across a wide range of species as can be inferred from the linear relationship between maximum bulk conductance and maximum photosynthetic capacity per unit ground area [44] for tropical, temperate deciduous broadleaved forests, temperate evergreen broad-leaved forests, and herbaceous tundra with an approximate slope consistent with $C_i/C_a=0{\cdot}82$. Hence, with a constant C_i/C_a, we find that in the case of Rubisco-limited photosynthesis, the maximum carboxylation capacity can be related to the canopy height via

$$V_{c\max} \approx R'\frac{C_a}{VPD}\left(A''\frac{A_l}{h_c}+B''\right) \tag{9}$$

where, R', A'', B'' can be readily computed from coefficients in equation (8). Having shown that the maximum leaf photosynthetic rate is controlled by A_l/h_c (for a given atmospheric dryness) the next logical question is whether A_l/h_c governs pollen spread.

2.4. *Pollen Dispersal*

To link the canopy attributes A_l and h_c to pollen dispersal, it becomes necessary to show how these two variables impact pollen trajectory inside and above canopies. These trajectories are difficult to describe because complex turbulent processes govern them. However, using a low-dimensional turbulent transport model, Katul *et al.* [35] showed that the canonical shape of the dispersal kernel is a Wald distribution, given by:

$$p(x_1)=\left(\frac{\lambda'}{2\pi x_1^{3}}\right)^{1/2} Exp\left[-\frac{\lambda'(x_1-\mu')^2}{2\mu'^2 x_1}\right], \tag{10}$$

where

$$\mu' = \frac{x_{3,r}\,\overline{U}}{V_t} \text{ and } \lambda' = \left(\frac{x_{3,r}}{\sigma}\right)^2,\ x_{3,r}\ ,$$

$x_{3,r}$ is the release height, V_t is the pollen terminal velocity, x_1 is the distance from the source, and $\overline{U}$ and σ are the mean longitudinal velocity and the flow velocity standard deviation that can be linked to the vertical velocity standard deviation (σ_w) via

$$\sigma^2 = \kappa_d\, h_c \left(2\frac{\sigma_w}{\overline{U}}\right) \tag{11}$$

where $\kappa_d \in [0.3, 0.4]$ is qualitatively connected to the structure of turbulence inside the vegetation (i.e. the mixing length) but must be considered as a semi-empirical parameter here because all the model assumptions (including vertically homogeneous and low intensity flows, instant attainment of terminal velocity upon pollen release, zero inertia of the pollen grain, and the negligible effects of vertical velocity correlation relative to pollen settling time) are lumped into its numerical value. Both $\overline{U}$ and σ_w can be predicted from the leaf area density distribution and drag properties of the canopy using higher order closure principles [45-49]. Figure 1 (see over) illustrates how pollen disperses away from the source as a function of leaf area index (*LAI*) and release height (often proportional to tree height) for a typical above canopy friction velocity of $u_*=0.5\text{m s}^{-1}$. It is clear that a finite number of pollen grains can travel up to 10 km, and with decreasing leaf area index the tails of the dispersal kernel become 'heavier'. That is, the extreme long-distance events become more probable with increasing height and decreasing *LAI*. We note that A_l and *LAI* are not the same quantity, but are directly related through the density of individual trees in a stand and are used interchangeably.

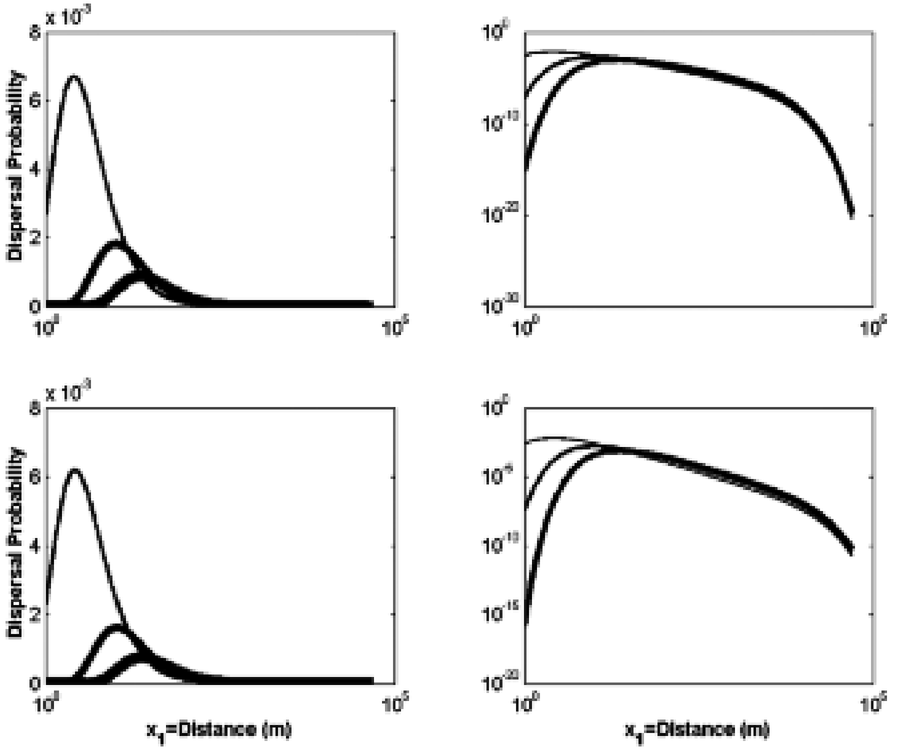

Figure 1. Computed dispersal kernals for a forest with h_c=35m, a typical friction velocity (u_*=0.5m s^{-1}), and *LAI*=5 m^2 m^{-2} (top panels) and *LAI*=2m^2 m^{-2} (bottom panels). The lines indicate different pollen release heights starting with 0.25 h_c (thinnest), 0.5 h_c, and 0.75 h_c (thickest). The semi-logarithmic (left) and log-log (right) plots demonstrate the impact of variations in h_c and *LAI* on the mode and the tails. The assumed terminal velocity (V_t) is 0.05 m s^{-1}.

3. RESULTS AND DISCUSSION

3.1. *Linking Plant Hydraulics and Photosynthetic Potential*

To explore whether equation (9) correctly predicts the relationship between $V_{c\max}$ and A_l/h_c, we used published data summarized in Table 1 (see over). As predicted, $V_{c\max}$ varied linearly with LAI/h_c for a wide range of forest types (Figure 2, see over), including boreal conifers, temperate broad-leaf forests, maturing loblolly pine forests, and young southern

TABLE 1. Published values for canopy height (h_c), leaf area index (*LAI*), and maximum carboxilation capacity ($V_{c\max}$) at 25°C for a wide range of forested ecosystems.

Ecosystem	h_c(m)	$V_{c\max}$ (μmol m^{-2}s^{-1})	LAI (m^{2}m^{-2})
Boreal Conifers [73]	14	46	2.04
Temperate Broadleaf Forest [73]	24	40	4.70
Maturing pine plantation [74]	16	59	3.80
6-year-old pine plantation, control [75]	4.1	85	1.65
6-year-old pine plantation, fertilized [75]	6.8	100	3.51

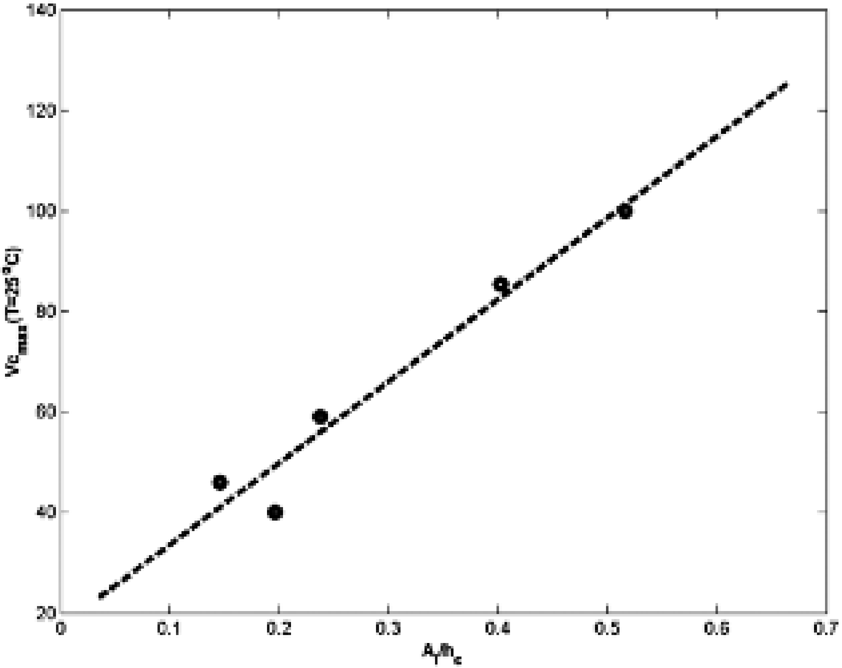

Figure 2. Testing the predicted linearity in $V_{c\max}$ with LAI/h_C from equation (9) for the forest canopies in Table 1.

pine plantations (unfertilized and fertilized with nitrogen). Hence, based on this finding, it is safe to state that canopy height and leaf area can explain variations in the maximum carboxylation capacity (at a reference temperature of 25°C), which is the upper limit for leaf photosynthesis.

Equation (9) is consistent with the linear relationship between photosynthetic capacity and plant hydraulic conductivity reported by Brodribb and Feild [38] (their Fig. 2) who used a combination of chlorophyll fluorescence and hydraulic analysis on seven conifers and 16 angiosperm rainforest species in New Caledonia and Tasmania (Australia). We are unable to directly employ equation (9) with their results because they reported the mean quantum yield of photo-system II electron transport and provided no information about the other requisite variables. Equation (9) is also consistent with the field observations that photosynthetic rates tends to decline with age even after stands reach a stage of approximately constant *LAI* [40,50-54].

3.2. *Linking Plant Hydraulics and Dispersal Potential*

It is difficult to test whether equation (10) correctly predicts the entire dispersal kernel, including long-distance dispersal tails. Katul *et al.* [35] tested the Wald predictions against seed dispersal data for a wide range of species, release heights, terminal velocity, leaf area density, and u_* conditions and noted good agreement ($r^2=0.89$) between predictions and measurements. However, the furthest seed distance reported in their comparison did not exceed 100 m.

It is possible to use the Wald model in equation (10) to predict the probability of seed uplifting above the canopy, a necessary condition for long-distance seed dispersal [33,35,36,55]. As shown in Katul *et al.*, [35] the probability of seed or pollen uplifting by the Wald model is given by

$$\Pr(x_{3,r} > h_c) = \frac{\exp\left(2\dfrac{V_t}{U}\dfrac{x_{3,r}}{\sigma^2}\right) - 1}{\exp\left(2\dfrac{V_t}{U}\dfrac{h_c}{\sigma^2}\right) - 1} \tag{12}$$

Predictions from equation (12) can be compared with uplifting probability estimates determined from vertically arrayed seed traps within and above the canopy. Using the seed release height and terminal velocity data reported in Nathan *et al.*, [33] Figure 3 (see over) shows the comparison between predictions from equation (12) and uplifting probability measure-

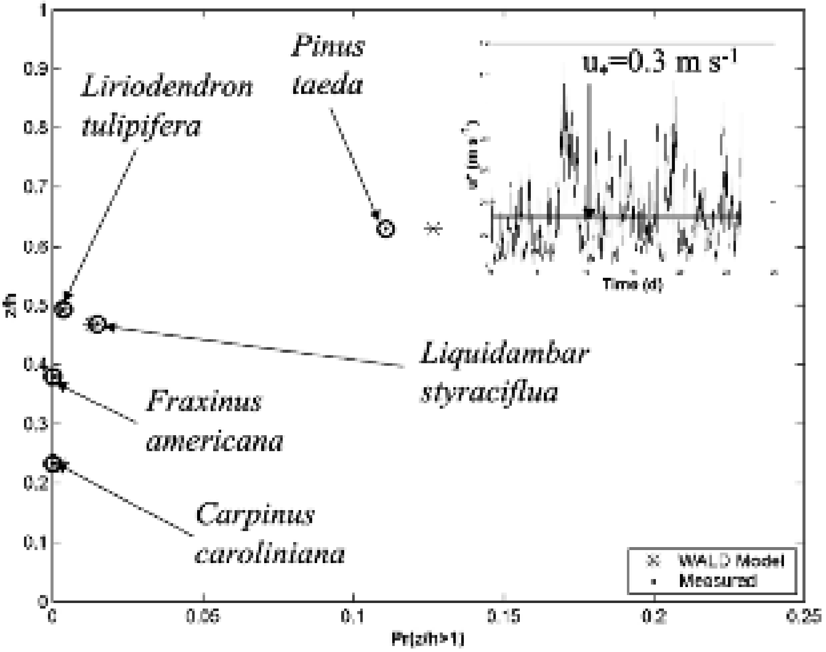

Figure 3. Comparison between measured and modeled uplifting probability for 5 species co-occurring in one 80-100 year-old second-growth mixed Oak-Hickory forest in the Blackwood Division of Duke Forest, near Durham, North Carolina, USA. The ordinate is the seed release height of the species normalized by the mean canopy height (data taken from Nathan *et al.*, 2002, their Table 1). *Inset*: The time series of the friction velocity and its mean value used in the model calculations.

ments (also in Table 1 in Nathan *et al.* [33]). The good agreement between measurements and predictions, despite the uncertainty in the data, lends confidence in the capability of the Wald model to reproduce the necessary conditions leading to long-distance dispersal (LDD, the minimum distance which 99% of the particles do not exceed).

The effect of variations in pollen release height (which is often proportional to tree height [56]) and *LAI* can be combined via simulations to describe the LDD of pollen (Figure 4, see over). We use LDD as a 'surrogate measure' for the dispersal potential most relevant to rapid colonization. The analysis in Figure 4 clearly demonstrates that LDD dramatically decreases with decreasing release height and increasing *LAI*. That is, the attributes that regulate maximum photosynthesis also regulate LDD.

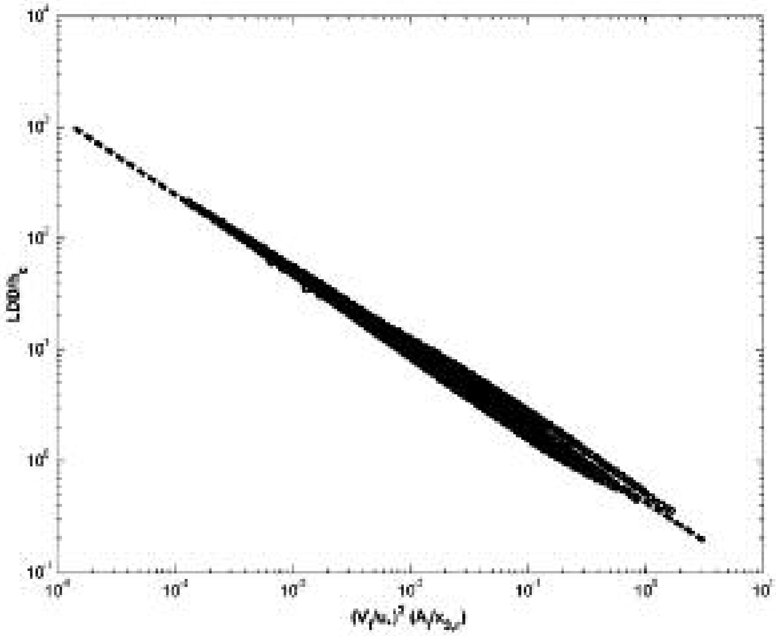

Figure 4. The dependence of normalized long-distance pollen dispersal (LDD) on leaf area index (*LAI*) and pollen release height ($x_{3,r}$). LDD is normalized by the overall mean canopy height (h_c). LDD is defined as the minimum distance for which 99% of the pollen did not reach. In the simulations, the maximum $A_l=5\,\text{m}^2\ \text{m}^{-2}$, and $h_c=35\,\text{m}$ (typical for a southern hardwood forest).

The dashed line is the regression $\frac{LDD}{h_c}=0.43\frac{V_t^2}{u_*^2}\left(\frac{A_l}{x_{3,r}}\right)^{-0.69}$ with $r^2=0.97$.

The model calculations were conducted for $V_t=0.01-0.2\,m\,s^{-1}$ (typical for pollen) and $u_*=0.1-0.9\,m\,s^{-1}$.

When combining Figures 2 and 4, we find that for a given *LAI*, as h_c increases, $V_{c\max}$ decreases (and hence the ability of trees to accrue more height diminishes) in proportion to h_c^{-1} but the dispersal potential (measured via LDD) increases in proportion to $h_c^{0.69}$ (see caption of Figure 4). It is clear from the height exponents that for tall trees, the tradeoff between increasing dispersal potential and reductions in photosynthetic capacity favors the latter. That is, photosynthesis is more sensitive to plant hydraulics than dispersal.

4. BROADER IMPACT

The origin and early evolution of land plants was a significant event in the history of life, with far-reaching consequences for the evolution of terrestrial organisms and global environments. By exploring the engineering solutions that permitted plants to function in a dry atmosphere and, thus, exist on land, we can begin asking about their adaptation and colonization potential in future climates – likely to be warmer, enriched with CO_2, and experiencing higher stochasticity in rainfall. Advances in systematics of living plants, when coupled with low-dimensional ecological theories, may hint at plausible future evolutionary strategies (or extinction).

It is well-worth quoting Lumley's statement [57] about low-dimensional models in the context of turbulent flows: 'in our present state of understanding, these simple models will always be based in part on good physics, in part, on bad physics, and in part, on shameless phenomenology'. Exploring the relationship between the photosynthetic, hydraulic, and dispersal strategies is fundamentally more challenging than turbulence; indeed, turbulence is only one element of the problem. However, recent advances in theory and measurements make it a topic ripe for progress. Perhaps, the recent advances in remotely sensed measurements of canopy vegetation structure and function [58], the estimates of past vegetation spread from the pollen record [59-67], and the advances in measurements and modeling of photosynthesis and plant hydrodynamics [21,41,68-72] will allow us to sieve out the bad physics and shameless phenomenology.

Acknowledgements

This study was supported, in part, by the United States Department of Energy (DOE) through both the Office of Biological and Environmental Research (BER) and the National Institute of Global Environmental Change (NIGEC) Southeastern Regional Center at the University of Alabama (Cooperative Agreement DE-FC02-03ER63613) and by the National Science Foundation (NSF-EAR and NSF-DMS).

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PRECIPITATION SUPPRESSION BY ANTHROPOGENIC AIR POLLUTION: MAJOR LOSS OF WATER RESOURCES WHERE WE NEED THEM MOST

DANIEL ROSENFELD

1. THE EFFECT OF AEROSOLS ON CLOUD COMPOSITION AND PRECIPITATION FORMING PROCESSES

Precipitation forms by coagulation of many small cloud particles into precipitation-size particles. The typical size of cloud drops is 10 μm, whereas the size of small raindrops is 1000 μm, or 1 mm. Therefore the mass of about one million cloud drops must be combined to form one rain drop. The rate of coagulation of cloud drops to precipitation critically depends on their size. At least some of the cloud drops must have a radius >15 μm for the effective formation of precipitation in that cloud.

The size of the cloud drops is determined to a large extent by the properties of the aerosols. Cloud drops nucleate on aerosol particles when the air cools and reaches super-saturation with respect to water vapor, similar to the way that dew forms on the surface of cool objects. Aerosols that contain some water soluble materials serve as good cloud condensation nuclei (CCN). Such are smoke and air pollution particles. Therefore, clouds that form in polluted air are composed of a larger number of smaller drops than similar clouds that form in pristine air. The size reduction of cloud drops slows down their coagulation and so acts to suppress the precipitation from polluted clouds. This principle has been known since the 1950s (Gun and Phillips, 1957). However, the extent and practical importance of the effects of air pollution on precipitation were not known until very recently, when space-borne measurements of cloud properties and precipitation became available. Here we will review the main findings achieved with these new capabilities.

The effect of pollution aerosols suppressing precipitation is best seen on the pristine background of marine layer clouds, when polluted by effluents from ship stacks (Rosenfeld *et al.*, 2006a) (see Figure 1, page 220).

2. Impacts of Urban and Industrial Air Pollution on Precipitation

Rosenfeld (2000) used both satellite remote sensing in the visible and IR, and measurements from the radar aboard the TRMM satellite, to examine how urban and industrial pollution might inhibit precipitation development. They illustrated that ship track-like features occur also over land. The showed such pollution tracks can be found in the Middle East, in Canada, and South Australia (see Figure 2, page 221). He inferred that the pollution tracks were clouds composed of numerous small droplets that inhibit precipitation formation. It is interesting to note that this effect is not limited to warm clouds. Some of the clouds exhibiting pollution tracks were in Canada, where ice precipitation processes are prevalent. Perhaps most significant in Rosenfeld's analysis is the conspicuous absence of pollution tracks over the United States and Western Europe, in a background of clouds that already have small effective radii (Rosenfeld and Woodley, 2003). Furthermore, the pollution tracks in Australia could be clearly identified as far as 1500 km inland, indicating that without anthropogenic aerosols the clouds remain pristine well inland, at least in this case. The implication is that these regions in the USA and Europe are so heavily polluted that clouds affected by local sources cannot be distinguished from the widespread pollution-induced narrow cloud droplet spectra in surrounding regions.

Figure 3a (see page 222) shows an image taken from TRMM over Australia in which a pollution plume affects clouds over a large distance. In Figure 3b (see page 222) the TRMM radar measurements show that the region affected by the polluting aerosols had no radar reflectivity (the minimum detectable signal was 17 dBZ, which corresponds to about 0.7 mm hr^{-1}), suggesting negligible rain. Figure 3c (see page 222) shows the effective drop radii at cloud tops in three regions (1, 2 and 3). The effective radius in region 2 never exceeded the precipitation threshold of 14 μm.

3. Impacts of Smoke From Burning Vegetation on Precipitation

Rosenfeld and Lensky (1998) retrieved cloud particle effective radius and temperature from satellite data for inferring that smoke from forest fires in Indonesia suppressed rain in the tropical clouds over Indonesia and Malaysia. These inferences were validated by cloud physics aircraft measurements over Indonesia (Rosenfeld and Lensky, 1998), as well as by spaceborne radar and passive microwave measurements (Rosenfeld, 1999). Rosenfeld (1999) used the Tropical Rainfall measuring Mission (TRMM) satellite measurements over Indonesia that showed clouds ingesting smoke were devoid of precipitation up to the −10°C isotherm, whereas nearby clouds in smoke free air developed significant warm rain (i.e., rain that forms without involvement of the ice phase). The TMI (TRMM Microwave Imager) detected a large amount of water in the smoky clouds, but the lack of detectable precipitation echoes by the TRMM radar meant that all this water remained in the form of cloud drops, which are too small to create radar echoes (see Figures 4-6, pages 223-224). Similar evidence for smoke suppressing warm rain processes in deep tropical convective clouds up to the −10°C isotherm were made using TRMM in clouds ingesting smoke over India (Rosenfeld *et al.*, 2002) and over the Amazon (Rosenfeld and Woodley, 2003). Aircraft measurements in smoky and smoke-free clouds validated these satellite inferences in both the Amazon and Thailand (Andreae *et al.*, 2004). Heavy smoke from burning oil wells showed similar impacts on the clouds (Rudich *et al.*, 2003). Very heavy smoke from fires was also observed to suppress precipitation, except for large hail, up to the anvil level (From *et al.*, 2006).

The importance of coalescence in the production of rainfall from tropical convective cells that were tracked by radar throughout their life cycle has been investigated by Rosenfeld and Woodley (2003) using volume-scan radar observations from the AARRP (Applied Atmospheric Research Resources Project) 10-cm, Doppler radar in northwest Thailand, where most of the aerosols were generated by agricultural fires. The radar estimates of the tracked cell properties were partitioned using in-situ observations of the presence or absence of detectable raindrops by the aircraft as it penetrated the updrafts of growing convective towers, 200 – 600 m below their tops at about the –8°C level (about 6.5 km MSL). Figure 7 (see over) shows that on conditions with suppressed coalescences negligible rainfall was produced by cells with echo tops <~5 km compared to the rainfall amounts from similar clouds that have active warm rain processes. The rainfall from the deepest clouds is greater by more than a factor of 100, but still the deep convective clouds with suppressed coalescence produce only about half the rainfall of similar clouds but with observed warm rain.

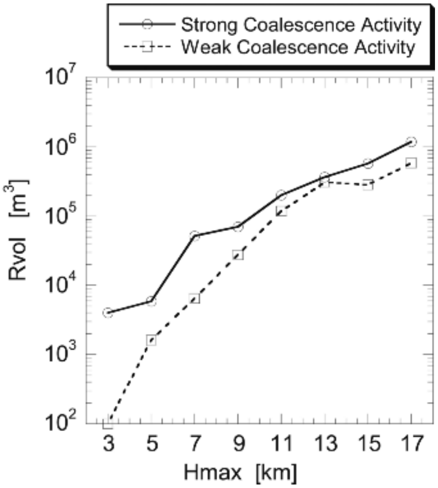

Figure 7. The mean rain volumes of convective cells as a function of maximum precipitation echo top height for cells growing on days with weak coalescence activity and on days with strong coalescence activity. The data are plotted at the center point of 2 km intervals of maximum echo top height. For the purpose of showing the trend on a logarithmic scale, a value of 10^2 m^3 was used instead of the zero value of RVOL for the 3 km maximum echo top height interval for cells growing on days with weak coalescence activity. From Rosenfeld and Woodley (2003).

4. IMPACTS OF POLLUTION AEROSOL ON THE VIGOR OF DEEP CONVECTIVE CLOUDS

Pollution aerosols have been documented to suppress precipitation from shallow clouds (cloud heights below about the −10°C isotherm) (Rosenfeld, 1999 and 2000, Phillips *et al.*, 2002, Albrecht, 1989, Rosenfeld *et al.*, 2002). When polluted clouds develop to greater heights (lower temperatures), however, as often happens in the summertime over land, D. Rosenfeld suggested (in Williams *et al.*, 2002 and Andreae *et al.*, 2004) that suppressed rainout enables unprecipitated water to reach greater heights, where freezing can release additional latent heat and further invigorate the cloud updrafts. This might in turn delay the onset of precipitation and the development of downdrafts and so prolong the growth of the convective cloud, allowing more water vapor to be ingested and further invigorate the storms (Andreae *et al.*, 2004). This conjecture is supported by the observations of Devasthale *et al.* (2005). They compared the AVHRR retrieved cloud top temperatures over central and Eastern Europe that saw radical infrastructural changes after the fall of the East Bloc in 1989 that has affected the pollution levels and hence cloud properties. Four years in the late 1980s (1985-1988) and in the late 1990s (1997-2000) were compared, as these are distinctively marked as episodes of very high and lower air pollution (sulfates and particulate matter). During the late 1980s, convective cloud tops were colder by 4 K. Devasthale *et al.* (2005) concluded that 'cloud-tops over and around polluted regions are higher, and their temperatures showed stronger variability, suggesting an indirect aerosol effect in the thermal spectral range as well'. This is also supported by satellite observations showing that clouds develop to greater heights in more polluted air masses (Koren *et al.*, 2005).

Cloud simulations (Khain *et al.*, 2005, Seifert and Beheng, 2006, Teller and Levin, 2006, Van Den Heever *et al.*, 2006) lend further support for the suggestion that pollution aerosols in moist unstable atmosphere can induce clouds to develop stronger updrafts and downdrafts, grow taller, trigger secondary storm development, and produce more rain.

5. EFFECTS OF AIR POLLUTION ON OROGRAPHIC CLOUDS AND PRECIPITATION

Borys *et al.* (2000) and Borys *et al.* (2003) provided some evidence that pollution can suppress precipitation in winter orographic clouds in the Rocky Mountains. Their analysis shows that pollution increases the concentration of CCN and therefore cloud drops, leading to the formation of smaller cloud drops. The reduced drop size leads to less efficient riming and therefore to smaller ice crystals (Fig. 8, see over), smaller fall velocities, and less snowfall.

Borys *et al.'s* observation was supported by Givati and Rosenfeld (2004) who analyzed about 100 years of precipitation records in regions downwind of pollution sources and compared them to precipitation in regions unaffected by these sources. Givati and Rosenfeld (2004) documented the trends in the orographic enhancement factor, Ro, which is defined as the ratio between the precipitation over the hill with respect to the upwind lowland precipitation amount. Two geographical areas were chosen for this study: California and Israel. The topography in both regions is similar, although the mountains in Israel are much lower than the Sierra Nevada. The statistical results for both locations show that downwind of pollution sources, on the upslope of mountains and mountain tops, orographic precipitation is reduced by ~20% and ~7%, respectively (Figure 9, see page 225). It was hypothesized that this decrease is due to an increase in droplet concentrations and a decrease in droplet size. Farther downwind on the lee side of mountains, the amount of precipitation is increased by ~14%. The authors postulate that this increase is due to smaller cloud particles taking longer time to grow, allowing the winds aloft to carry them over the mountain top (see earlier study of similar effects, produced by deliberate over seeding with ice-producing particles, by Hobbs, 1975). However, the integrated rainfall amount over the whole mountain range appeared to be reduced by the pollution. The possible effects of moisture and low level winds were considered using a radiosonde regression model, which showed that the relevant meteorological conditions during rain days did not change systematically along the years, and the observed trends in the ratio of hill / plain precipitation are likely caused by non-meteorological reasons (Givati and Rosenfeld, 2004).

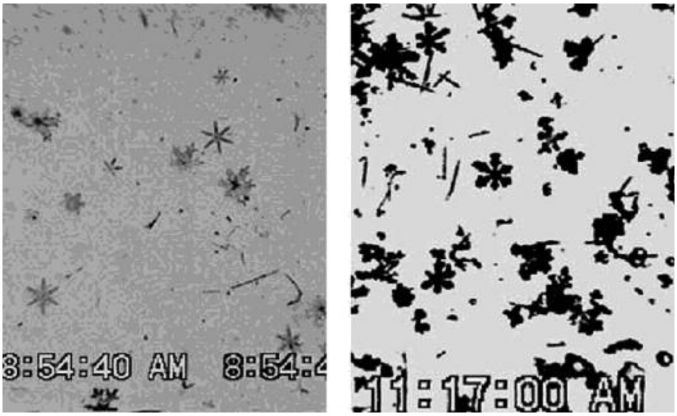

Figure 8. Light riming of ice crystals in clouds affected by pollution (left) compared to heavier riming in non-polluted clouds (right). From Borys *et al*. (2003).

Rosenfeld and Givati (2006) expanded this analysis to the whole western USA. The analyses of trends of the orographic winter precipitation enhancement factor, Ro, along the coastal mountain ranges of the west coast of the USA show a pattern of decreasing Ro during the last century by as much as −24% from the southern border to central California, to no decrease in northern California and Oregon, and to a renewed decrease of Ro (−14%) in Washington to the Seattle area east of Puget Sound. Similar decreases occurred also well inland, over Arizona, New Mexico, Utah

(Rosenfeld and Givati, 2006) and the east (already documented by Jirak and Cotton, 2006) slopes of the Colorado Rockies. Both absolute precipitation amounts and Ro are affected by fluctuations in the atmospheric circulation patterns such as those associated with the Pacific Decadal Oscillation and the Southern Oscillation Index. However, these climatic fluctuations can not explain the observed trends in Ro. Although the trends of aerosols are available only since 1988, aerosol measurements from the IMPROVE aerosol monitoring network show that negative trends in Ro are associated with elevated concentrations of fine aerosols (PM2.5). The PM2.5 showed stability or some increase in the areas where their levels were elevated and decreasing trends of Ro were noted. Strong decreasing trends of the coarse aerosols (PM10-PM2.5) were noted especially in the areas with elevated levels of PM2.5. The decreasing trend in coarse aerosols (the coarse aerosols may act to initiate and enhance precipitation) in conjunction with the constancy and/or increases of the small aerosols (small aerosols suppress precipitation), can explain the continuing losses of orographic precipitation during the last two decades despite the indicated improvement in the conventional air quality standards (Rosenfeld and Givati, 2006).

In line with these considerations, despite the reported decreases in the pollutant emissions in California during the last two decades, the total amount of soluble pollution ions in precipitation particles before falling below cloud base has not shown any decreasing trend and even showed a slight increasing trend in Sequoia National Park. Therefore, the expectation for a recent recovery of the orographic precipitation with the improving standards cannot be supported by these observations of the recent trend of steady to increasing concentrations of pollution in the precipitation. The concentrations of the pollution ions in the rainwater were only half the values in Lassen Volcanic National Park, where no decreasing trend of orographic precipitation was observed (Givati and Rosenfeld, 2004).

Evidence for the role of air pollution in suppressing precipitation in California was provided by in situ cloud physics aircraft measurements over central California during winter storms (Rosenfeld *et al.*, 2006d). They showed a clear maximum in the CCN concentrations downwind of San Francisco that were ingested into clouds and suppressed the coalescence and warm rain in them. In contrast, clouds in nearby sparsely populated areas remained maritime and with ample warm rain all the way to the Central Valley, where elevated CCN concentrations suppressed the warm rain from clouds that were formed at the foothills of the Sierra Nevada. The source of the CCN in populated areas was revealed as tracks of clouds with reduced effective radius emanating from the urban areas of San Francisco and the Central Valley.

Jirak and Cotton (2006) reached similar conclusions about the suppression of precipitation due to pollution on the Front Range of the Rocky Mountains. They report that the ratio of upslope precipitation for elevated sites west of Denver and Colorado Springs, Colorado to upwind urban sites has decreased by approximately 30% over the past half-century. Similar precipitation trends were not found for more pristine sites in the region.

These reported decreasing trends of the orographic precipitation were observed during the winter season. No decreasing trend was indicated in the amount of summer convective clouds over the hills (Rosenfeld and Givati, 2006). Furthermore, Diem and Brown (2003) partially attributed downwind summer convective precipitation enhancement in Phoenix to increased pollution-derived CCN, although they acknowledged that increased humidity from irrigation projects, and urban land-use induced surface convergence, were likely the dominant factors.

6. Impacts of Large Salt Particles on Enhancing Precipitation

Super-micron salt particles act as giant CCN that enhance precipitation, especially on the background of large concentrations of small CCN. The most common source of such particles is sea spray. Rosenfeld *et al.* (2002) suggested that clouds forming in polluted air over the ocean regain their precipitation ability mainly due to the added sea spray. They used the TRMM satellite and the in-situ measurement done in the INDOEX projects to document the evolution of aerosols and the related cloud microstructure and precipitation in the polluted air flowing off the Southeast Asia continent in the winter monsoon. Apparently raindrops initiated by the sea salt grow by collecting small cloud droplets that form on the pollution particles, thereby cleansing the air, as indicated by the gradual growth of the cloud drops farther away from land. Therefore, sea salt helps cleanse the atmosphere of the air pollution, via cloud processes.

An alternative explanation to these observations is updraft velocities over ocean are weaker than over land; therefore a smaller fraction of the aerosols is nucleated into cloud droplets. In addition, more time is available for the coalescence to progress and form warm precipitation. However, simulations of the impacts of sea spray on clouds with base updrafts of only

1 ms^{-1} were able to replicate most of the observed differences between polluted clouds over land and ocean. To neutralize completely the effect of sea versus land surface Rudich *et al.* (2002) compared clouds that ingested salt dust that was raised by the wind from the desiccated bed of the Aral Sea. The clouds in the salt storm developed much larger drops than clouds sidewind of the salt dust source and exceeded the precipitation threshold of 14 μm (see Figure 10, page 226). These results are consistent with the earlier observations of effluents of giant CCN from paper mills enhancing precipitation (Hindman *et al.*, 1977).

7. CONCLUSIONS

The recent development of Earth observations made it possible to quantify the impacts of natural and manmade aerosols on clouds and precipitation. We are still at the early stages of this important task. At this time we can already say the following:

1. Small pollution aerosols from smoke of burning vegetation, urban and industrial air pollution serve as good cloud condensation nuclei. When ingested into clouds, these aerosols reduce the cloud drop size and this in turn suppresses the precipitation forming processes within the clouds.
2. Precipitation can be completely shutoff in polluted clouds with tops warmer than −10°C.
3. Air pollution can substantially reduce precipitation from short living shallow clouds such as typically occur over topographical barriers in winter storms. Climatology of winter precipitation over hills downwind of pollution sources shows reductions of 10% to 25% of the seasonal precipitation. This was found to be the case in western USA and in Israel, which are both areas where water shortage is already a major problem.
4. Air pollution suppresses precipitation also in deep convective clouds in the tropics and summer mid-latitude. However, when the unprecipitated cloud water is carried to the high and cold parts of the cloud it freezes there and contributes to the invigoration of the cloud and enhancs the risk of hail and damaging winds.
5. Large salt aerosols were observed to have the opposite effects with respect to those caused by small pollution particles.

The precipitation losses appear to affect mainly densely populated areas with high demand for the water resources. Possible mitigation action obviously would be less pollution of small aerosols. Another method would be cloud seeding for rain enhancement, because clouds that are most susceptible to suppression by pollution aerosols would be also the most conducive to rain enhancement cloud seeding. This was shown to be the case in Israel (Givati and Rosenfeld, 2005), where air pollution and cloud seeding were documented to have similar and opposite effects on the precipitation over the Galilee Hills.

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CLIMATE AND LAND USE CHANGES IN AMAZONIA: IMPACTS ON THE HYDROLOGICAL CYCLE AND ON BIOME DISTRIBUTION

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1. INTRODUCTION

Climate and vegetation interact biodirectionally on many time and spatial scales. One clear manifestation of such interactions is the global pattern land cover and its relationship to climate. It can be said that climate is the single factor that exerts the largest influence on vegetation and its characteristics on a global context (Prentice, 1990). Thus, deserts, tropical forests, savannas, and other types of vegetation are determined to a first approximation by climate. And climate change affects the global distribution of vegetation from the distant past and likely into the future. On the other hand, changes in the distribution and structure of the vegetation may influence climate. The biophysical characteristics of vegetation and soils control to a great extent the exchanges of energy, water, momentum and trace gases between the land surface and the atmosphere. Changes in vegetation imply changes in many biophysical parameters of the vegetation such as the surface albedo and roughness, total leaf area, root density and depth, and all affect the energy balance at the surface and the soil water availability.

A large fraction of the land surface is being used by agriculture, grazing or other human activities such as urban areas. These uses represent about 35% (55 million km^2) of land cover. Significant agriculture expansion can only take place, excluding very cold and desert area, over the tropical forests of South America, Africa and Southeast Asia and also over the boreal forests of Canada and Russia (Foley *et al.*, 2003). Currently, a great amount of the tropical forests has been converted to agricultural land or is degraded. (Nepstad *et al.*, 2002). Particularly for Amazonia, total deforestation of the tropical forests over the last 40 year has reached an area in excess of 650.000 km^2 (18% of the forest area) in Brazilian Amazonia alone (INPE, 2006) due mostly to cattle raising and agriculture expansion into the forest, including that of the soy bean agriculture in the last decade (Soares-Filho *et al.*, 2006). The tropical forest plays an important climate regulation role in view of the relatively large recycling of water vapor into the atmosphere throughout the year via evapotranspiration (Gash *et al.*, 1996; Rocha, 2001).

In addition to land cover and use changes, global warming due to increase greenhouse gases emissions by human activities present another challenge for natural ecosystems of the world, reflecting as one more serious threat to biodiversity. Past climate changes are known to coincide with large changes in species composition in ecosystems and even episodes of mega-extinctions of animals and plants. The acceleration of human-driven climate change poses serious questions and challenges to conservation strategies to cope with the expected changes in the distribution, physiology and ecology of most species, and this is specially true for the tropical forests with its tremendous species diversity.

The ecosystems of Amazonia are subjected to two different, but interconnected climatic driving forces: one is regional deforestation and other land use changes such as biomass burning and forest fragmentation, which affects local and regional climate; changes associated to global climate change are the second one (Salati *et al.*, 2006). Many studies indicate that both of these changes in climate will contribute to regional increases in temperature, but the uncertainly is still considerably high for projections of regional changes of the hydrological cycle (e.g., Li *et al.*, 2006 and Figure 3, see page 229).

In Amazonia there remains the largest contiguous tropical forest of the planet. The vegetation, including its deep root system, is efficient in recycling water vapor, which may be an important mechanism for the forest's maintenance. Deforestation and forest fragmentation can alter the hydrological cycle and causes other impacts as well. For instance, in the event of severe droughts the forest can become highly susceptible to fires due to soil water deficits (Nepstad *et al.*, 2001).

In a recent study, Soares-Filho *et al.* (2006) have shown that if the current high deforestation rates are to continue into the future, about 40% of the Amazonian tropical forests will have disappeared by 2050 (Figure 1, see page 227). In principle, deforestation and global warming acting synergistically could lead to drastic biome changes in Amazonia. Oyama e Nobre (2003) have shown that two stables vegetation-climate equilibrium states are possible in Tropical South America. One equilibrium state corresponds to the current vegetation distribution where the tropical forest covers most the Basin. The other equilibrium state corresponds to a land cover in which most of the eastern Amazonia is covered by savannas. It is not a trivial scientific question to find out at which point the current stable state could switch (perhaps abruptly) to the second state, given the combined forcings of deforestation, forest fragmentation, increased forest fire, global warming with a likely consequence of more intense droughts such as the severe drought which affected western and southwestern Amazonia in 2005. All these factors may accelerate the 'savannization' of Amazonia and if the current pace of change is kept unaltered we may well only find out that the second equilibrium climate vegetation has been reached after we have passed the threshold for its establishment.

In the sections below we describe some of the impacts of land use change and climate on the tropical forests on Amazonia, including future biome changes due to global climate change.

2. Deforestation and Changes in the Hydrological Cycle in Amazonia

Most of the water vapor participating in rainfall over Amazonia is transported from the Tropical Atlantic Ocean by the trade winds. The rainfall is made of water vapor directly imported from the ocean and of water vapor originated by local evapotranspiration. A number of studies attempted to quantify the water balance of the Amazon Basin. Some of the earlier studies examined periods when deforestation was not much high, that is, up to the 1970s (Salati *et al.*, 1979, Salati e Marques, 1984; Salati, 1987). That was followed by many other studies (Nobre *el al.*, 1991; Matsuyama, 1992; Eltahir e Bras, 1994; Marengo *et al.*, 1994; Vorosmarty *et al.*, 1996; Costa e Foley, 1999; Zeng, 1999; Roads *et al.*, 2002; Marengo, 2004, 2005) which highlighted the difficulties of water balance closure for the basin. For instance, estimates of evapotranspiration range from about 35% to over 80% of precipitation. The closure of the water balance of the Amazon Basin is a scientific goal yet to be achieved and the difficulties arise mostly due to the scarcity of reliable observations of precipitation and atmospheric moisture transports in the Basin.

The lack of agreement about the magnitude of the water budget can be seen in Figure 2 (see page 228)(Marengo *et al.*, 2006) in which results of 4 different calculations yield quite different results for the basin evapotranspiration, from 59% to 82% as percent of precipitation.

Due to the strong interaction between vegetation and atmosphere in Amazonia, it is highly likely that deforestation will alter components of the water balance, decreasing evapotranspiration and in consequence, if deforestation is relatively localized, an enhancement of river flow due to an increase of surface runoff in the deforested areas. That, in turn, will reduce the available moisture for the soil-plant system and its residence time for the ecosystems.

There is interesting temporal and spatial variability in Amazonia that has to be accounted for. For instance, for one tropical forest site in central-eastern Amazonia – the Santarem area – measurements of evapotranspiration showed higher values for the dry season (3.96 mm/day) than for the wet season (3.18 mm/day). In that area seasonal patterns of evapotranspiration are controlled by solar radiation and not by soil moisture deficits in the dry season due to the effectiveness of very deep roots reaching deeper than 6 m to extract water (Nepstad *et al.*, 1994) and also due to the nighttime hydraulic redistribution through the root system from deeper layers to the surface roots (Oliveira *et al.*, 2005). In other forest measurement sites, such as central Amazonia (Manaus) and SW Amazonia (Rondonia), less seasonal variability was observed (Gash *et al.*, 1996). It is noteworthy, however, that in all sites, dry season evapotranspiration ranged from 3.5 to 4 mm/day, clearly indicating high levels of water recycling. This moistening of the atmospheric boundary layer during the dry season may be critically important for facilitating dry season rainfall episodes. Although the amount of rainfall is not high during the dry season, it may be particularly relevant to keep a moist liter and upper soil layer, contributing to the functioning of the tropical forest and diminishing the likelihood of forest fires.

Considering the current deforestation area and patterns in Amazonia, can we say anything about observed changes in the hydrological cycle? For the basin as a whole, the Amazon river streamflow does not show any trend over the last 30 years. There have been few studies based on analyses of satellite-derived rainfall observations for the last 20 decades, comparing rainfall over deforested and forest areas for parts of Amazonia. The results of such studies are inconclusive even with respect to the sign of the observed rainfall differences for the two contrasting land covers: one study revealed an amplification of the seasonal cycle of rainfall for deforested areas, with more rain in the wet season and less rain in the dry season (Laurent *et al.*, 2002) whereas a similar analyses showed increase in the dry season rainfall over deforested areas (Negri *et al.*, 2004) or decrease at the end of the rainy season and increase at the end of the dry season (Chagnon and

Bras, 2005). These discrepancies are likely the result of intrinsic error in satellite-derived rainfall estimates.

On the other hand, impact of land cover change may be already evident for large river sub-basins of the Amazon Basin. Costa *et al.* (2003) showed an increase of 24% in the Tocantins river streamflow by comparing two 20-year periods (1949-1968 and 1979-1998). Throughout the analysis period, rainfall did not change significantly and the authors, thus, concluded that sub-basin evapotranspiration declined due to the change of the savanna-dominated land cover to agriculture and grazing lands (pasture). Their results are explained in terms of increased surface runoff during the wet season due to the shallower rooting system of the grassy vegetation. The area of the sub-basin converted to agriculture and pasture increased from about 30% in 1960 to 50% in 1995 (Costa *et al.*, 2003). These land cover alterations can lead to increases in streamflow during the wet season and decrease during the dry season as suggested by Bruijnzeel (1990), although the reduction of dry season streamflow was not evident for the Tocantins river.

3. IMPACTS OF CLIMATE CHANGE SCENARIOS FOR 2070-2099 ON THE BIOMES OF SOUTH AMERICA

Field observations (e.g.,Gash and Nobre, 1997) and numerical studies (e.g., Nobre *et al.*, 1991) revealed that large scale deforestation in Amazonia could alter the regional climate significantly. Evapotranspiration is reduced and surface temperature is increased for pastures. That effect might lead to a 'savannization' of portions of the tropical forest domain. Recently, as mentioned above, Oyama and Nobre (2003) showed that a second stable biome-climate equilibrium with savannas covering eastern Amazonia and semi-deserts in Northeast Brazil may exist. However, there have been fewer studies on the impact of global climate change on South America, particularly on its biomes such as Cox *et al.* (2000). This session addresses this question by showing one calculation (Nobre *et al.*, 2005) on how natural biomes could change in response to various scenarios of climate change.

Figures 3 and 4 (see pages 229-230) show average temperature and rainfall anomalies for the decade 2070-2099 derived from 6 different Global Climate Models (GCM) available at the IPCC Data Distribution Center (IPCC DDC, 2003): models from the Max Planck Institute for Meteorology (ECHAM), Germany; Geophysical Fluid Dynamics Laboratory (GFDL), USA; Hadley Centre for Climate Prediction (HADCM3), UK; CSIRO (CSIRO-Mk2), Australia; Canadian Climate Center (CGCM2), Canada; and, CCSR/NIES, Japan. Two different GHG emissions scenarios (IPCC, 2000) were used: the A2 emissions scenario of high GHG emissions and B2, of low GHG emissions (the figures show only the scenarios for the high emissions scenarios A2). Typical model horizontal resolution is about 300 km. Analyses of these figures reveal larger differences in temperature and rainfall changes among models than among emission scenarios for the same model. As expected, the main source of uncertainty for regional climate change scenarios is that one associated to rather different projections from different GCMs. The projected temperature warming for South America range from 1 to 4°C for emissions scenario B2 and 2 to 6°C for A2. The analysis is much more complicated for rainfall changes. Different climate models show rather distinct patterns, even with almost opposite projections. For instance, GFDL GCM indicates increase in rainfall for tropical South America, whereas other GCMs show reduction (e.g., HADCM3) or little alteration. In sum, current GCMs do not produce projections of changes in the hydrological cycle at regional scales with confidence. That is a great limiting factor to the practical use of such projections for active adaptation or mitigation policies.

The CPTEC Potential Vegetation Model (PVM) (Oyama and Nobre, 2004) was used to study the possible alterations of South American biomes in response to the projected climate changes of Figures 3 and 4 for the decade 2070-2099. PVM is a model that describes reasonably well the large-scale distribution of world's biomes as a function of five climate variables. Figure 5 (see page 231) shows the projected biome redistributions in South America. As could have been foreseen, the major differences in biome distributions are found among different models rather than from the two emissions scenarios for a given model. In 5 out of the 6 GCMs a tendency for reduction in the tropical forest area can be seen and, in general, replacement for drier climate biomes (savannas replacing forests, dry shrubland replacing savannas, semi-desert vegetation replacing dry shrubland) in tropical South America. Impact on extratropical South America is somewhat smaller. The combination of warming and rainfall changes indicates less water availability for large portions of tropical South America in 5 out 6 GCMs. Impacts on agriculture and water resources can be expected for those regions.

Figure 6 (see page 232) shows changes in model calculated global land cover for tropical forests and savannas for three 30-year time-slices in the future for two emissions scenarios (A2 for high GHG emissions and B2 for low GHG emissions). Consistently, there is a reduction of 1/3 of areas covered by tropical forests for A2 and 22% for B2 and a corresponding increase of areas covered by savannas, indicating that, in general, the scenarios of future climate may favor the expansion of tropical savannas worldwide. By and large, other similar projections of vegetation changes in response to climate change lend credence to a substantial reduction of forest areas (e.g., White *et al.*, 1999; and Cramer *et al.*, 2001) or a complete forest die-back (Cox *et al.*, 2000; Jones *et al.*, 2003; Cox *et al.*, 2004).

In simple terms, the increase in temperature induces larger evapotranspiration in tropical regions. That, in turn, reduces the amount of soil water, even when rainfall does not reduce significantly. That factor by itself can trigger the replacement of the present-day biomes by other vegetation types which may be more adapted to less soil water. That is, tropical savannas replacing tropical forests, dry shrubland replacing savannas, semi-desert replacing dry shrubland. If severe droughts become more frequent in the future, which is a common projection for a warmer planet, then the process of savannization of eastern Amazonia could accelerate, since there is a higher probability for that area to experience droughts in the forest-covered areas of Amazonia (Hutyra *et al.*, 2005).

Another disturbance factor arises as a consequence of the increasing forest fire frequency. The dense primary forest of Amazonia has been by and large impenetrable to fire due to the high level of soil and litter layer humidity. However, forest fragmentation mostly due to selective logging and the widespread use of fire in agricultural practices in that region account for a substantial increase of the frequency of forest fires in the last two decades. For instance, the large forest fire that took place in northern Amazonia from January through March 1998 is an illustration of what may be in store for the future. Caused by an intense and persistent drought associated to the strong 1997-98 El Niño and the indiscriminate use of fire in agriculture, over 13,000 km^2 of forests burned in which is likely to have been the largest forest fire of modern times in Amazonia (Nobre *et al.*, 2005).

The synergistic combination of regional climate impacts due to deforestation and climate impacts resulting from global warming, resulting in warmer and possibly drier climates, and the increasing forest fire frequency, adds tremendously to the vulnerability of tropical forest ecosystems. The more adapted species to withstand the new conditions are typically those of the tropical and subtropical savannas, which are naturally more adapted to hotter climates with marked seasonality in rainfall and long dry seasons and where fire plays an important ecological role.

4. Concluding Remarks

The future of biome distribution in tropical South America in face of the synergistic combination of impacts due to both land cover and climate changes points out to 'savannization' of portions of the tropical forests of Amazonia and 'desertification' of parts of Northeast Brazil. For Amazonia, that trend would be greatly exacerbated by fires (Nepstad *et al.*, 1999). Considering that the time scale for ecosystem migration of centuries to millennia is much larger than the expected time scale of decades for GHG-induced climate change, global change has the potential of profoundly impacting ecological diversity of plant and animal species on a mega-diverse region of the planet. In sum, one cannot really expect effective adaptation policies when it comes to the potential of massive ecosystem disruptions that could be brought about by the project climate changes of this century. That would reinforce the case of mitigating climate change to avoid a dangerous interference with the ability of natural ecosystems to adapt to it.

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RIVER BASINS

RIVER BASINS:
WATER AND COMPLEX ADAPTIVE SYSTEMS

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1. INTRODUCTION

The study of empirical and theoretical evidence on the structure of river basins suggests somewhat disparate linkages of features shown by natural networks, whether living or inanimate. Part of the similarity might indeed be spurious, as certain topological properties, for instance, tend to be reproduced by a variety of tree-like forms regardless of wide – even visible at eyeball – differences of other nature. If indeed distinctive of different forms, linkages of geometrical or topological features could be important because the embedded function – one speculates, in fact, that it should be possible to precisely the geometrical features as the signatures of the evolutionary properties that molded them. A comparative study of networks thus possibly relates to the general theme of the PAS Workshop, and deeply concerns hydrologic research.

Of great importance, in this context, is the outstanding progress of the observations (and their objective manipulations) recently achieved for the description of river basins from the scale of a few meters (down to O(1) m) to several thousands of kilometers. In this respect, river basins constitute one of the most reliable and fascinating laboratories for the observation of how Nature works across a wide range of scales (Rodríguez-Iturbe and Rinaldo, 1997). Only the solid reference to natural observation in very particular cases, in fact, allows the search for consilient mechanisms aiming at general rules. On this basis alone the importance of the study of the river basin can hardly be overestimated.

Two problems, both related to the dynamic origin of natural forms, have interested scientists for a long time. One is the fundamental dynamic reason behind Mandelbrot's (1977) observation that many structures in nature –

such as river networks or coastlines – are fractal, i.e. looking ‘alike’ on many length scales. The other is the origin of the widespread phenomenon called *1/f* noise, originally referring to the particular property of a time signal, be it the light curve of a quasar or the record of river flows, which has components of all durations, i.e. without a characteristic time scale. The name *1/f* refers to the power law decay with exponent -1 of the power spectrum S(f) of certain self-affine records and is conventionally extended to all signals whose spectrum decays algebraically, i.e. $S(f) \sim f^{-\alpha}$. Power-law decay of spectral features is also viewed as a fingerprint of spatially scale-free behaviour, commonly defined as critical. In this framework criticality of a system postulates the capability of communicating information throughout its entire structure, connections being distributed on all scales. The causes and the possible relation for the abundance found in nature of fractal forms and *1/f* signals have puzzled scientists for years. Per Bak (e.g. 1996) and collaborators have addressed the link of the above problems, suggesting that the abundance in nature of spatial and temporal scale-free behaviours may reflect a universal tendency of large, driven dynamical systems with many degrees of freedom to evolve into a stable critical state, far from equilibrium, characterized by the absence of characteristic spatial or temporal time scales. The key idea and its successive applications address such universal tendency and bear important implications on our understanding of complex natural processes. The common dynamic denominator underlying fractal growth is now central to our interests in landform evolution.

The resistance to Bak’s idea of universality was (and still is in some circles) noteworthy. Science, and geomorphology in particular, is largely committed to the reductionist approach. The reductionist tenet is that if one is capable to dissect and understand the processes to their smallest pieces then the capability to explain the general picture, including complexity, is granted. However, the reductionist approach, affected as it is by the need of specifying so many detailed processes operating in nature and the tuning of many parameters, though suited to describe individual forms, is an unlikely candidate to explain the ubiquity of scaling forms and the recursive characters of processes operating in very different conditions. Are scale-free, recursive characters of the evolution of complex systems tied to the detailed specification of the dynamics? Or, on the contrary, do they appear out of some intrinsic property of the evolution itself? I believe, following Bak, that the invisible hand guiding evolution of large interactive systems should be found in some general properties of the dynamics rather than in some unlikely fine-tuning of its elementary ingredients (Rodríguez-Iturbe and Rinaldo, 1997).

One crucial feature of the organization of fractal structures in large dynamical systems is the power-law structure of the probability distributions characterizing their geometrical properties.

This behaviour, characterized by events and forms of all sizes, is consistent with the fact that many complex systems in nature evolve in an intermittent, burst-like way rather than in a smooth, gradual manner. The distribution of earthquake magnitudes obeys Gutemberg-Richter law (1956) which is a power-law of energy release. Fluctuations in economics also follow power-law distributions with long tails describing intermittent large events, as first elucidated by Mandelbrot's (1963) famous example of the variation of cotton prices. Punctuations dominate biological evolution (Gould and Eldridge, 1993) where many species become extinct and new species appear interrupting periods of stasis. Levy distributions (characterized by algebraic decay of tails, i.e. of the probability of large events) describe mathematically the probabilistic structure of such events. They differ fundamentally from Gaussian distributions – which have exponential decay of tails and therefore vanishing probabilities of large fluctuations – although both are limiting distributions when many independent random variables are added together. In essence, if the distribution of individual events decays sufficiently rapidly, say with non-diverging second moment, the limiting distribution is Gaussian. Thus the largest fluctuations appear because many individual events happen to concert their action in the same direction. If, instead, the individual events have a diverging second moment – or even diverging average size – the limiting distribution could be Levy because its large fluctuations are formed by individual events rather than by the sum of many events. Thus the keywords now are fractal, chaos and power laws (e.g. Schroeder, 1991).

When studying large, catastrophic events in a large system with interacting agents one can try to identify an individual event as the particular source. Rather than the recognition of the achievement of a critical state, a 'Gaussian' observer may discard the event as atypical – as noted by Mandelbrot (1983) when studying the statistics of fluctuations because the remaining events trivially follow Gaussian statistics. A rather common reaction to catastrophic concerted actions is to find specific reasons for large events. Economists tend to look for specific mechanisms for large stock fluctuations, geophysicists look for specific configurations of fault zones leading to catastrophic earthquakes, biologists look for external sources, such as meteors hitting the earth, in order to explain large extinction events, physicists view the large scale structure of the universe as the consequence of some particular dynamics. In essence, as Bak put it, one reluctantly views large events as statistical phenomena.

Bak noted that there is another explanation, unrelated to specific events and embedded in the mechanisms of self-organization into critical states. In such states each large event has a specific source, a particular addition of a grain of sand landing on a specific spot of a sand-pile triggering a large avalanche, the burning of a given tree igniting a large forest fire, the rupture of a fault segment yielding the big earthquake, or the slowing of a particular car starting a giant traffic jam. Nevertheless even if each of the above particular initiating events were prevented, large events would eventually start for some other reason at some other place of the evolving system. In critical systems no local attempt to control large fluctuations can be successful unless for directing events to some other part of the system.

What are the signatures and the origins of the process of self-organization? Bak suggested that self-organized critical systems have one key feature in common: the dynamics is governed by sites with extremal values of the 'signal', be it the slope of a sandpile or the age of the oldest tree in a burning forest, rather than by some average property of the field. In these systems nothing happens before some threshold is reached. When the least stable part of the system reaches its threshold, a burst of activity is triggered in the system yielding minor or major consequences depending on its state. Complexity arises through the unpredictable consequences of the bursts of activity suggesting that the dynamics of Nature may often be driven by atypical, extremal features. This is suggestive, among other things, of Kauffman's example of biological evolution as driven by exceptional mutations leading to species with a superior ability to proliferate or to Bak's example of the introduction of program trading causing the crash of stock prices in October 1987. In both cases a new fact leads to breakthroughs propagating throughout an entire concerted system because it generates chain reactions of global size. Another feature of self-organizing processes is that, in order to have a chance to appear ubiquitously, they must be robust with respect to initial conditions or to the presence of quenched disorder and should not depend on parameter tuning.

A major challenge thus lies in the explanation of the dynamic origin of fractal forms. Considerable efforts have been devoted to define static or dynamic models able to reproduce the statistical characteristics of fluvial patterns, and general concepts like self-organized criticality have been explored in this context (Rinaldo *et al.*, 1993). It should be observed that real drainage basins are not static but usually evolve on extremely long time scales. Nevertheless, statistical properties seem to be preserved during most of the evolutionary process of a basin – most features characterizing the river basin morphology are irrespective of age. Some geomorphological signatures like valley densities (the relative extent of unchanneled concave areas), however, reflect climate changes without appreciable changes in the basic scaling features of aggregated area and length (Rinaldo *et al.*, 1995).

It is worthwhile recalling that it is not appropriate herein to review the theoretical background of landscape evolution models. Yet river networks may be defined by nodes on a regular lattice representing the elevation field, and links determined by steepest descent on the topography whose evolution determines the structure. Thus to find the simplest model that simulates the dynamical evolution of morphologically realistic landscapes and that preserves certain features during evolution is of interest. The reader is referred, for a recent account of the subject, to Rinaldo *et al.* (2006).

'Water making its environment' is thus a variant of the PAS Workshop's title that describes well the proposed contents of my contribution. All this applies to the river basin, carved by water and weathered by other agents, including biological ones. In the case of living, ecological agents one usually talks about complex adaptive systems rather than of critical self-organization (Levin, 1999). Hence my title reflects the forecast that soon solid theoretical and observational relations will link food webs, ecological communities and river drainages both as hierarchical networks and complex adaptive systems (Power and Dietrich, 2002; Muneepeerakul *et al.*, 2006).

2. OF FORM AND FUNCTION

Numerical simulations of the proper equations have shown that landscape evolution is characterized by two distinct time scales. The soil elevations are lowered in a nonuniform way by erosion, causing variations in the drainage directions during the evolution. In a lattice model, at any given time, one may represent the drainage directions at all sites by means of a two dimensional map. After a first characteristic time, some sort of 'freezing' time, the spanning graph determining the drainage directions in the basin does no longer change. Erosion keeps acting on the landscape and changes the soil height, but preserves the drainage structure. The second characteristic time, which is much longer, is the relaxation time at which the profile reaches its stable shape. Because many of the measured quantities, such as the distributions of drained areas and mainstream lengths, depend only on the two dimensional map, the existence of a freezing time much smaller than the relaxation time may provide an explanation for the fact that several statistical properties are found to be almost the same for many rivers, irrespective of their age. Thus the spatial analysis of riverine forms at any time on the geological process makes sense almost in general.

Natural and artificial network patterns, however, show a great variety of forms and functions and many do not show the tree characters (i.e. a unique path from any site to the outlet) that rivers exhibit. One thus wonders what is the basic dynamic reason for radically different forms and functions. Figures 1 to 5 illustrate a sample of the above variety. A reference framework for different types of hydrologic networks is meant to show that departures from trees and tree-like networks spanning a given area commonly arise. A choice of real and abstract structures relevant to hydrology is proposed (Figure 1, see over). Optimal channel networks (OCNs) are described elsewhere in detail (see e.g. Rodríguez-Iturbe and Rinaldo, 1997) and briefly in the next section of this paper. Suffice here to mention that they hold fractal characteristics that are obtained through a specific selection process from which one obtains a rich structure of scaling optimal forms that are known to closely conform to the scaling of real networks even in the case of unrealistic geometric boundaries. To design a very inefficient tree, a non-directed structure is shown (Figure 1d) constrained to be tree-like. This basically corresponds to an algorithm that accepts any change attributed sequentially at random sites of an evolving spanning network – an existing link is disconnected at a random site and rewired randomly to another nearest neighbor provided the change maintains a tree-like structure. Hot OCNs, so called because they correspond to high temperatures of a Metropolis scheme where every spanning tree seeded in the outlet is equally likely, are thus abstract forms meant to reproduce a rather undirected tree. Peano's or Scheidegger's constructs are briefly described in the caption. They are particularly important because many of their geometrical or topological characteristics can be solved exactly.

Loops are also observed in earth landscapes. Powerful or weak tidal forcings (Figures 2 and 3, pages 164-165) introduce preferential scales related to crossovers of processes operating with comparable ranges into an otherwise aggregated pattern. However, deltaic networks arising from the interplay of distributive drainage patterns and of marine and littoral processes can substantially alter the similarity of the parts and the whole. One notes, in fact, that the structure of deltaic networks shows major loops, differently from rivers in runoff-producing areas. Differences in the sinuosity of the branches prevent any detailed statistical similarity of the parts and the whole across scales.

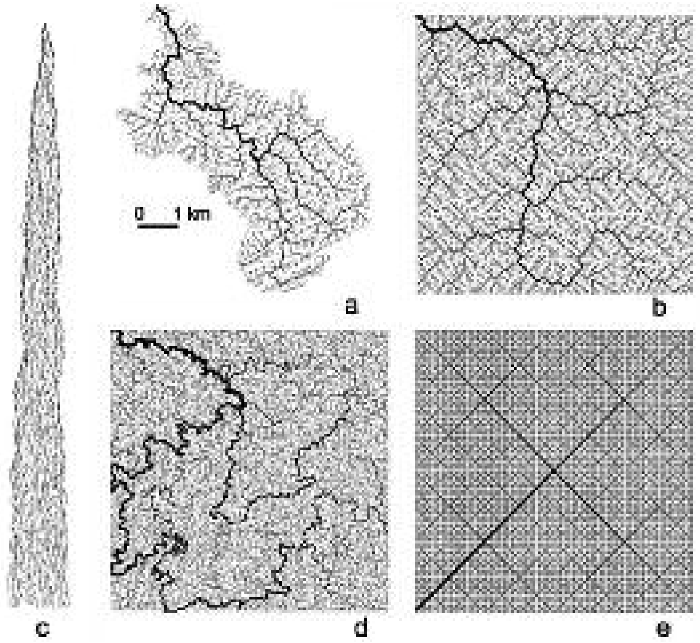

Figure 1. Samples of trees where a unique pattern links any inner site to the outlet of the network: a) A real river network, the Dry Tug Fork (CA), suitably extracted from digital terrain maps. Notice its clear tree-like structure, usual in the runoff production zone of the river basin. Its morphological features (like aggregation and elongation) are typical of fluvial patterns and recurrent 'modules' appear regardless of the scale of total contributing area, such that the parts and the whole are quite similar notwithstanding local signatures of geologic controls, here marked by a fault line clearly visible across the landscape; b) a single-outlet optimal channel network (OCN) selected starting from an arbitrary initial condition by an algorithm accepting random changes only of lowering the total energy dissipation of the system as a whole – thus incapable of reaching the ground state and settling in a local minimum dynamically accessible; c) Scheidegger's construction is generated by a stochastic rule – with even probability, a walker chooses between right or left forward sites only. The model was devised with reference to drainage patterns of an intramontane trench and maps exactly into a model of random aggregation with injection or voter models and also describes the time activity of a self-organized critical (Abelian) avalanche; d) a 'hot' OCN where any arbitrary change randomly assigned to an evolving network is accepted provided it maintains a tree-like form. It is clearly unrealistic fora variety of reasons; e) Peano's construct, where a perfectly recursive rule is adopted to produce a structure whose topological features resemble admirably those of real rivers. It is a deterministic fractal, whose main topological and scaling features, some involving exact multifractals, have been solved analytically. The basic prefractal is a cross seeded in a corner of the square domain that covers the cross and its ensuing iterations. All subsequent subdivisions cut in half each branch to reproduce the prefractal on four, equal subbasins. Here the process is shown at the 11th stage of iteration (from Rinaldo *et al.*, 2006).

Legitimate questions naturally arise by looking at the structures in Figures 1-5: why should loopless trees develop? Are the observed landforms random structures? Are different network configurations equally probable? If not, to what selective pressure do they respond? Are there universal features shown by fluvial landforms, and what is their proper characterization? The fluvial network context alone thus proposes the need for some settlement with respect to the general dynamic origin of network scale invariance, possibly towards an understanding of a general framework for the processes of network growth and selection.

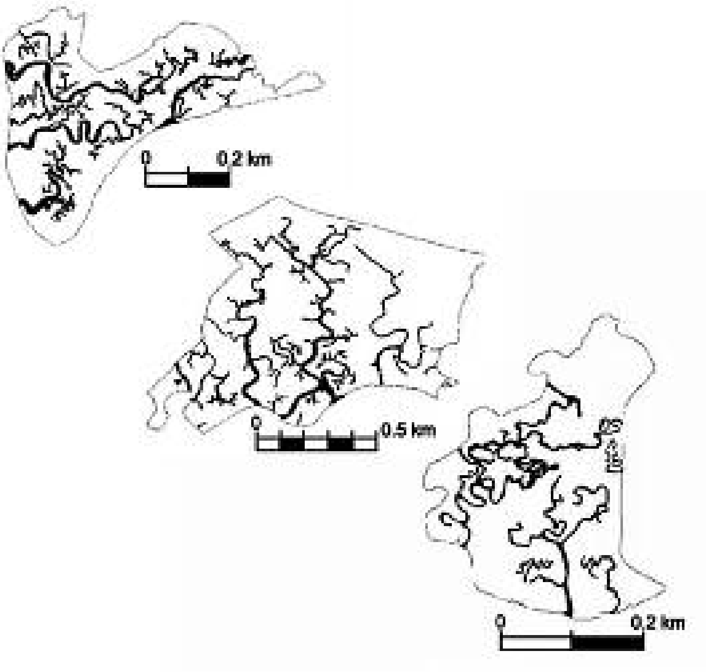

Figure 2. Drainage patterns that form in the tidal landscape are much diverse according to local conditions and develop over a different range of scales. In addition, they may or may not develop loops. Here we show three tidal networks developed within saltmarshes of the lagoon of Venice suitably extracted from remote sensing (Feola *et al.*, 2005). The tidal networks are observed a few km away in space and roughly within the same microtidal range, have similar scales and very different aggregation. Sinuosities of the tidal meanders vary greatly from site to site, possibly reflecting the age of the salt marsh, and the drainage density describing the average distance one has to walk before encountering a creek within a saltmarsh is widely different from site to site (Marani *et al.*, 2003). The presence of loops much depends on local conditions, and is not necessarily affected by flood- or ebb-dominance (after Rinaldo *et al.*, 2006).

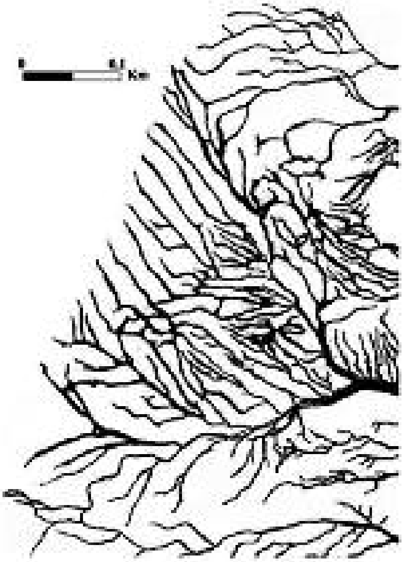

Figure 3. A small-scale drainage pattern developed within a macro-tidal environment, here the Eden estuary in Scotland. Channeled pathways are extracted by suitable digital image processing techniques (courtesy of Enrica Belluco). Here we see an organized sequence of regular ditches reminding of the organization of trenches draining into a complex, looping network structure. Even at eyesight, one catches the lack of a fundamental similarity of the parts and the whole that characterizes river networks (after Rinaldo *et al.*, 2006).

Branching river networks are striking examples of natural fractal patterns which self-organize, despite great diversities in forcing geologic, lithologic, vegetational, climatic and hydrologic factors, into forms showing deep similarities of the parts and the whole across up to six orders of magnitude, and recurrent patterns everywhere (Rodríguez-Iturbe and Rinaldo, 1997). Form and function coevolve. Interestingly, the drainage network in a river basin shows tree-like structures that provide efficient means of transportation for runoff and sediment and show clear evidence of fractal behavior. Numerous efforts to model the production zone of a river (where the system is open, i.e. water is more or less uniformly injected in space and later collected through the structure of the network implying that landscape-forming processes are well defined) have focused on reproducing the statistical characteristics of the drainage network.

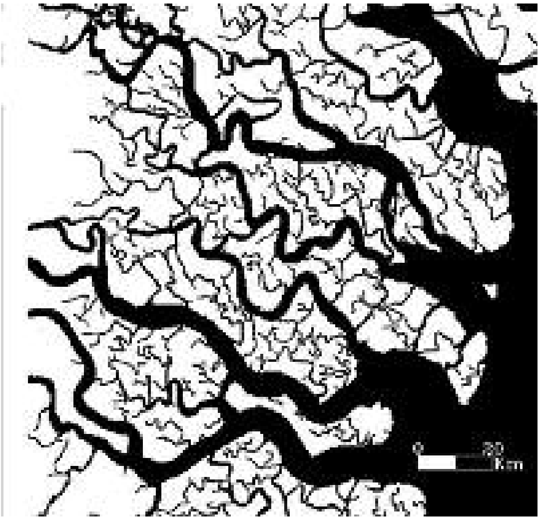

Figure 4. A large-scale, space-born image of the Brahmaputra-Ganges deltaic network. The original NASA image is taken from *http://www.visibleearth.nasa.gov/* and the channelized pattern is extracted via suitable image processing techniques that recognize the spectral signatures of water (courtesy of Enrica Belluco). The complex interplay of the distributional characters typical of deltaic patterns and of the drainage patterns affected by strong tidal forcings (emphasized by the pronounced gradients of channel widths) produces loops appearing on all scales (after Rinaldo *et al.*, 2006).

Much attention has also been paid to the temporal behavior and to the evolution of the topography of the basins, the so-called landscape evolution problem.

Our observational capabilities are also noteworthy. Accurate data describing the fluvial landscape across scales (covering up to 5 orders of magnitude) are extracted from digital terrain maps remotely collected and objectively manipulated. Raw data consist of discretized elevation fields z_i on a lattice. The drainage network is determined assigning to each site i a drainage direction through steepest descent at i, i.e. along ∇z_i. Multiple flow directions in topographically convex sites, and their derived hydrologic quantities, are also easily tackled. Many geomorphological features are then derived and analyzed. To each pixel i (the unit area on the lattice) one can associate a variable that gives the number of pixels draining through i i.e. following the flow directions. This quantity represents the total drainage area (total contributing, or accumulated, area) A_i at the point i, expressed e.g. in pixel units, via

$$A_i = \Sigma_j \, w_{j,i} \, A_j + 1$$

where $w_{j,i}$ is the element of an adjacency matrix, i.e. it is 1 if $j \rightarrow i$ and 0 otherwise. Here 1 represents the unit area of the 'pixel' unit that discretizes the surface. In the case of uniform rainfall injection, a_i provides a measure of the flow at point i.

Drainage directions determine uniquely network lengths. Downstream lengths (i.e. from a site to the outlet following the largest topographic gradient, i.e. steepest descent) can be computed easily to derive their distributions which clearly show the characters of finite-size scaling (Maritan *et al.*, 1996). The upstream length is defined as the distance, measured along the stream, from the farthest source draining into i. Overall, channelized patterns are now reliably extracted from topographic fields through the exceedence of geomorphological thresholds, and have thus much improved our ability to describe objectively natural forms over several orders of magnitude. Large-scale observations have allowed thorough comparisons across scales defining fractal river basins. One outstanding example of fractal relation is Hack's law relating the upstream length l_i at a given position i to the total cumulative area a_i at that position, seen quite early as a signature of the fractal geometry of nature. Contributing area A_i at any point is related to the gradient of the height (the topographic slope) of the landscape at that point: $\nabla z_i \sim A_i^{g-1}$ with a numerical value of g around 0.5 (e.g. Montgomery and Dietrich, 1992). This slope-discharge relation proves a powerful synthesis of the local physics. The distributions of cumulative areas a and upstream lengths l are characterized by power law distributions (with the expected finite size corrections) with exponents in the narrow and related (Rinaldo *et al.*, 1999) ranges 1.40-1.46 and 1.67-1.85, respectively. It is particularly revealing, in this context, that the finite-size scaling ansatz provides a most stringent observational proof of self-similarity.

Figure 5 (see page 233) shows a typical case of finite-size scaling analysis for total contributing areas within a natural river basin. Details are in the caption.

Scaling in the river basin has been documented in many other geomorphological indicators and exact limit scalings identified (Banavar *et al.*, 1999), making the case for the fractal geometry of Nature particularly compelling (Rinaldo *et al.*, 1999). Further proofs have been found by the striking invariance of probability distributions of length and area under coarse graining of the elevation field (Rodríguez-Iturbe and Rinaldo, 1997). The case of rivers is thus a solid starting point for other queries about the possible consilience of natural mechanisms that involve the signatures of complex adaptive systems.

4. OPTIMAL CHANNEL NETWORKS, LOOPLESS STRUCTURES & THE DYNAMICS OF FRACTAL GROWTH

It has been suggested (Rodríguez-Iturbe *et al.*, 1992) that optimal networks are spanning loopless configurations only under precise physical requirements that arise under the constraints imposed by continuity. In the case of rivers, every spanning tree proves a local minimum of total energy dissipation. This is stated in a theorem form applicable to generic networks, suggesting that other branching structures occurring in Nature (e.g. scale-free and looping) may possibly arise through optimality to different selective pressures.

In this section we review the basis for the claim that tree-like fluvial structures are a natural by-product of some optimization of form and function peculiar to the physics of rivers (Rodríguez-Iturbe *et al.*, 1992 a-c) and its implications (Rinaldo *et al.*, 1992, 1996, 1999). The OCN model was originally based on the ansatz that configurations occurring in nature are those that minimize a functional describing the dissipated energy and on the derivation of an explicit form for such a functional. A major step was the later proof (Banavar *et al.*, 1997, 2001) that optimal networks are exactly related to the stationary solutions of the basic landscape evolution equation. In particular, any configuration that minimizes total energy dissipation, within the framework of general dynamical rules, corresponds, through the slope discharge relation, to an elevation field that is a stationary solution of the basic landscape evolution equation. Thus spanning, loopless network configurations characterized by minimum energy dissipation E are obtained by selecting the configuration, say s, that minimizes:

$$E(s)=\Sigma_i A_i^\gamma$$

where i spans the lattice and a_i and γ are as defined above. It is crucial, as we shall see later, that one has $\gamma<1$ directly from the physics of the problem.

The global minimum (i.e. the ground state) of the functional for E(s) is exactly characterized by known mean field exponents (Maritan *et al.*, 1996b), and one might expect to approach this mean field behavior on trying to reach stable local minima on annealing of the system. This is in fact the case. The proof of the above is not trivial. We thus maintain, following proper analyses based on observational data, that the drainage basin can be reconstructed using the rule of steepest descent i.e. the flux in a point has the direction of the maximum gradient of the elevation field (the direction towards the lowest among all its nearest neighbors). Moreover, the channelized part of the landscape is necessarily (but not sufficiently) identified by concave areas where the above assumption holds strictly. One can thus uniquely associate any landscape with an oriented spanning graph on the lattice, i.e. an oriented loopless graph passing through each point. Identifying the flux in a point with the total area drained in that point, one can reconstruct the field of fluxes corresponding to a given oriented spanning graph. From the fluxes, a new field of elevation can be defined (Rinaldo *et al.*, 2006). It should be noted that we must limit our attention to patterns embedded in runoff-producing areas within the above framework to confine the problem within tractable limits. As we shall see, theoretical matters are already complex enough even in this oversimplified framework, and the patterns produced surprisingly similar to those observed in nature.

Note also that we wish to emphasize the dependence on the configuration s, an oriented spanning graph associated with the landscape topography z through its gradients ∇z. An interesting question is how networks resulting from the erosional dynamics are related to the optimal networks arising from the minimization of the dissipated energy. Specifically, we require that any landscape reconstructed from an optimal configuration using the slope-discharge relation is a stationary solution of the evolution equation. Superficially, this may seem to be a trivial fact because the relation between gradients and flows is verified by construction, but one should notice that the slope discharge relation alone does not implies stationarity, because the flow may not be (and in general is not) in the direction of the steepest descent in the reconstructed landscape. Thus optimal channel networks consist of the configurations s which are local minima of E(s) in the sense specified below: two configurations s and s′ are close if one can move from one to the other just by changing the direction of a single link (i.e. the set of links $s \subset s'$ represent a graph with a single loop). A configuration s is said a local minimum of the functional E(s) if each of the close configurations s′ corresponds to greater energy expended. Note that not all changes are allowed in the sense that the new graph again needs to be loopless. Thus a local minimum is a stable configuration under a single link flip dynamics, i.e. a dynamics in which only one link can be flipped at a given time, and is flipped only when the move does not create loops and decreases the functional E. Any elevation field thus obtained by enforcing the slope-area relation to a configuration minimizing at least locally E(s) is a stationary solution, i.e. the landscape reconstructed from an optimal drainage network with the slope-discharge rule is consistent with the fact that the flow must follow steepest descent.

The OCN model has been thoroughly analyzed (Maritan *et al.*, 1996b; Banavar *et al.*, 2001). In particular, the scaling behavior of the global minimum has been worked out analytically and it has been found to yield mean field exponents. Interestingly, local minima also exhibit critical behavior but are characterized by different nontrivial scaling exponents of key probability distributions describing e.g. drained area, channelled length, elongation (e.g. Rodríguez-Iturbe and Rinaldo, 1997).

Figures 6 a-c, that complement Figure 1c, show examples of local and global minima of OCNs (here chosen in a multiple-outlet configuration). Figure 6a shows the result obtained by 'Eden' growth generated by a self-avoiding random walk, which is known to lead to suboptimal structures (Rodríguez-Iturbe and Rinaldo, 1997). It is interesting to use Eden structures as benchmarks because their chance-dominated selection principle (no necessity is implied by the random-walk dynamics, and tree-like structures are selected because of the self-avoiding nature imposed on the process) because such structures were initially thought of as capturing the essentials of natural selection. That turned out to be an artifact of non-distinctive tests of the network structure, nicely termed the 'statistical inevitability' of Horton's laws. Indeed if topological measures alone (e.g. Horton numbers, Tokunaga matrices) are used to sort out the fine properties of networks, one can be hugely misled into finding spurious similarities with natural forms, as one would sometimes safely conclude even at eyesight: compare e.g. Figure 6a with b – topological features like e.g. those based on Strahler's ordering like Horton ratios or Tokunaga's matrices are indistinguishable in the two cases shown (Rinaldo *et al.*, 1999). Yet these are very different networks, as (linked) scaling exponents of areas, lengths and elongation clearly reveal. If eyesight and common sense would not suffice, exact proofs are available, like in the case of Peano's basin (Figure 1e) where topological measures match perfectly those of real basins and of OCNs, but fail to satisfy the strict requirements of aggregation and elongation. More subtle but equally clear is the failure of random walk type models or topologically random networks to comply with exhaustive comparisons (Rinaldo *et al.*, 1999). Notice that the latter models were extremely influential in suggesting that chance alone was behind the recurrence of natural patterns, because of the equal likelihood of any network configurations implied by the topologically random model. Instead their purported similarity with natural patterns is now seen as an artifact of lenient comparative tools, and the statistical properties and 'laws' derived in that context are almost inevitable for spanning trees.

Necessity is instead at work in the selection of natural networks. Figure 6b shows a local minimum of E(s), whose fine features match perfectly those found in Nature (Rinaldo *et al.*, 1999) including a power law in the distribution of cumulative areas with exponent $g=0.43 \pm 0.01$ (compare e.g. with Figure 5). These results, (b), are obtained moving from an initial configuration s. A site is then chosen at random, and the configuration is perturbed by disconnecting a link, which is reoriented to produce a new configuration s′. If the new configuration lowers total energy dissipation i.e. $E(s') < E(s)$, the change is accepted and the procedure is restarted. Figure 5 (c) is obtained through the same procedure used to obtain (b), where an annealing procedure has been implemented, i.e. unfavorable changes may also be accepted with probability proportional to $e^{-(E(s)-E(s'))/T}$ where T assumes the role of temperature in a gas or a spin glass. It is rather instructive to compare Figure 5(b) with (c), where a ground state is reached by very careful annealing using a schedule of slowly decreasing temperatures. This state is characterized by mean field scaling exponents (here matched perfectly), and overall all too regular and straight to reproduce, even at eyesight, the irregular and yet repetitive vagaries of Nature.

Several random constructs have been thoroughly analyzed, in a few cases through exact results, comparing them with optimal ones obtained through minimization of total energy dissipation (e.g. Rinaldo *et al.*, 1999). Random network forms range from self-avoiding random walks like Eden growth patterns, topologically random or Leopold-Langbein constructions, to the so-called Scheidegger network (Figure 1) which is a directed random aggregation pattern with injection. Deterministic fractals like Peano's networks have been also exactly analyzed. Thus many misleading similarities are inferred from the matching of topological measures like Horton's ratios. These turn out to be too lenient measures, as they occur almost inevitably for spanning loopless networks and thereby do not distinguish the structure of the aggregations patterns. On this basis alone it was shown that topolog-

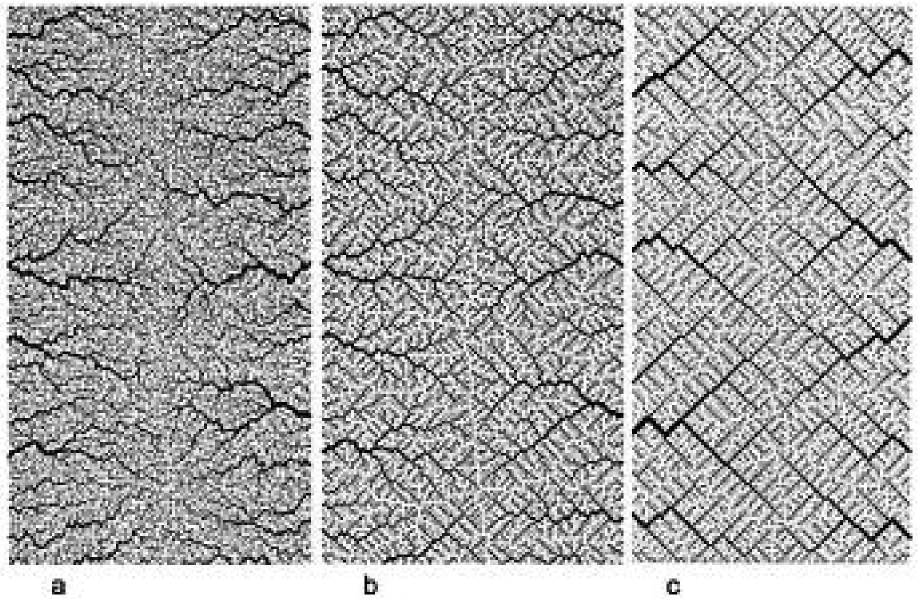

Figure 6. Multiple-outlet networks obtained in the same rectangular domain by: (a) Eden growth patterns of self-avoiding random walks filling the domain; (b) an imperfect optimal channel network (OCN) leading to a local minimum of total energy dissipation. Note that OCNs bear long-lived signatures of the initial condition owing to the myopic search procedure, but actually reproduce perfectly the aggregation and elongation structure seen in real river landscapes; and (c) ground-state OCNs obtained through simulated annealing using a very slow schedule of decreasing temperatures. The reaching of the ground state is confirmed by the matching of the exact mean field exponents with those calculated for (c) (Rinaldo *et al.*, 2006).

ical similarities are to be interpreted as necessary, rather than sufficient, conditions for comparison of network structures. A distinctive comparison of network structures stems from the matching of several scaling exponents which characterize the finite-size scaling forms of the distributions of length, aggregated area and elongation. At times perfect matching of aggregation (underlined by Horton's ratios of bifurcation, length and area indistinguishable from those observed in natural structures) proves inconsistent with the structure of channelled lengths, like in the case of self-avoiding random walks. Moreover, suboptimal networks, that is, those derived by imperfect search of the type perceived as dynamically feasible, match all the features of the networks observed in the fluvial landscape, and thus pass the most thorough screening differently from all chance-dominated constructs. The hydrologic context thus suggests a case for optimal selection of network structures in Nature.

I shall now finally define precisely the selective advantags of trees in the fluvial physics (Banavar *et al.*, 2001). Consider a square lattice. Fix an orientation for all lattice bonds. On each bond b a flux J_b is defined. Assume that $J_b > 0$ if it is flowing along an assigned orientation. Uniform (unit) injection is equivalent to the set of constraints $\nabla \cdot J = 1$, i.e. a discrete version of the divergence, and is a measure of the net outflow from a site:

$$\nabla \cdot J = \Sigma_{b \in x} J_b \, \theta(b,x) = 1$$

where: the unit value is the model injection, constant for every node in the simplest case; b spans all bonds (links) concurring on node x, and q(b,x)=1 (-1) if b is oriented outward (inward) node x. Any local minimum of the function:

$$E = \Sigma_b J_b^{\gamma}$$

when $0 < \gamma < 1$, corresponds to $J_b \neq 0$ only on the bonds of a spanning tree. Note that the assimilation $J \sim A$ is commonplace in hydrology, for a variety of empirical and theoretical reasons (Rodríguez-Iturbe and Rinaldo, 1997) – thus the above equation is exactly that defining an OCN. The main point is in the proof that the networks that correspond to local minima of the dissipated energy are loopless and tree-like. The tree must be spanning due to the above constraints: one cannot have $J_b = 0$ for all b's connected to a site so that there must be at least one outlet from each site x. Some site (or sites) must also be declared to be the global outlet.

Figure 7 illustrates an extremely simple example with just four sites: (a) shows the setup for the elementary 4-bond network. The dot is the outlet. Here the current a is taken as the parameter regulating the entire distribution of fluxes owing to continuity; (b) illustrates the only loopless configurations of the system generated by integer values of a; (c) shows the plot of the function E vs a from the following Equation with g=0.5:

$$E = a^{\gamma} + (a+1)^{\gamma} + (1-a)^{\gamma} + (2-a)^{\gamma}$$

which is derived from the above equations. In particular, (b) shows the plot E(a) where one notices that there are local minima in correspondence with one of the four currents being zero (a=2, 1, 0, -1), corresponding to the four trees shown in Figure 3c. The proof for the general case is elsewhere (Banavar *et al.*, 2001).

Figure 7 (c) shows the function E versus a plotted for various values of γ (specifically, for γ=0.25, 0.5, 1 and 2). Note that for γ=1 all directed (with the currents going in the positive directions) configurations, loopless or not, have the same energy. The case γ=2 corresponds to the resistor network case for which there is just one minimum at a=1/2. Note that since there is one unknown current for each bond and one continuity equation for each site the number of independent variables is given by the number of bonds minus the number of sites (excluding the outlet), which for the simple topologies considered is equal to the number of elementary loops (this is a particular case of the Euler theorem).

The general proof is beyond the scope of this paper and given elsewhere (Banavar *et al.*, 2001) for an arbitrary graph, where the number of independent loops is given by the number of bonds minus the number of sites plus the number of connected components. Note that for the particular case where the graph must be a spanning structure the number of connected components is unit.

Obviously, for the set of dynamical rules postulated above, the energy landscape is riddled with a large number of local minima characterized by

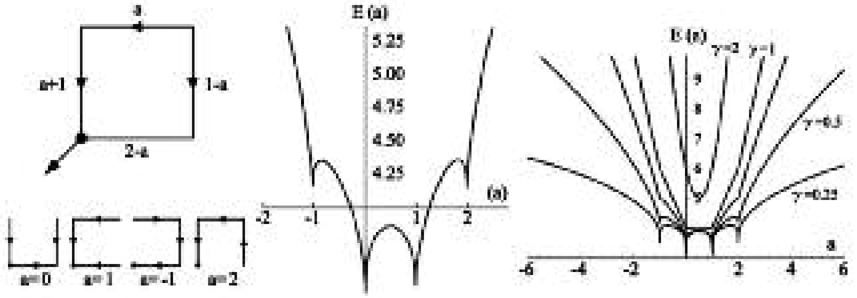

Figure 7. The 4-bond lattice. (Top left) the 4-node arrangement, with indications on the currents that respect continuity (note that a unit flux is injected at each node); (bottom left) the only for possible trees correspond to the cases a=0, -1, 1, 2. (Center) The energy function E(a) vs. a; (Right) Energy functions E(a) vs. a for the cases g=0.5, 0.75, 1, 2 (after Banavar *et al.*, 2001).

a range of similar values of E. In single realizations, boundary and initial conditions affect the feasible (i.e. dynamically accessible) optimal state to different degrees depending on their constraining power. This fact matches the observation that scaling exponents are coherently linked in a range of values, narrow enough but significantly different from the ground state (see e.g. Rodríguez-Iturbe and Rinaldo, 1997). The truly important implications are twofold: one one side, in fact, all local optima are trees; on the other, imperfect optimal search procedures are capable of obtaining suboptimal networks which nevertheless prove statistically indistinguishable from the forms observed in nature and quite different from the absolute minima. Indeed we believe that the worse energetic performance and yet the better representation of the patterns of Nature are thought of as mimicking the myopic tinkering of evolutionary processes.

The rules investigated above also suggest that the convexity of the function defining the selective advantage of different hydrologic network structures matters. In the case of fluvial basins, the basic concavity of the energy E is provided directly by the physics of the landscape evolution problem. It has been studied whether similar principles apply to the selection of different network structures by natural processes of different nature. While a detailed account is given elsewhere (Rinaldo *et al.*, 2006), suffice here to mention that a class of optimal models evolved by local rules and chosen according to global properties of the aggregate yields unexpected behavior in the transition from different types of optimal topologies. Random or scale-free arrangements (and a variety of in-betweens like small-world constructs) are then seen as particular cases emerging from selective pressures towards connectivity and/or directedness.

8. Conclusions

The results I have analyzed here show consistently that selective criteria blend chance and necessity as dynamic origins of recurrent network patterns seen in the river basin. The role of selective pressures as a possible cause of emergence of observed features has been reviewed both in the cases of loopless and of looping networks. In the latter case we show why Nature distinctively favors tree-like shapes in the particular dynamic environments of which landscape evolution carved by water is a particular case.

My main conclusion is that the emergence of the structural properties observed in natural network patterns may not be necessarily due to embedded rules for growth, but may rather reflect the interplay of dynamic mechanisms with an evolutionary selective process. This has implications, of course, for hydrologic research because many landforms originated by the collection or the distribution of hydrologic runoff (from riverine to tidal or deltaic patterns) might indeed be classified according to the compliance to the above mechanisms. Whether the above has somewhat more general relevance to Nature's mechanisms, it remains to be seen as more and more we need to understand how the complex biosphere has emerged from natural selection and other forces operating at small scales.

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HEADING TOWARDS BASIN-LEVEL HYDROSOLIDARITY GOAL FOR LAND/WATER/ECOSYSTEM COORDINATION

MALIN FALKENMARK

INTRODUCTION

Human interaction with the life supporting web of living matter has recently been assessed in the Millennium Ecosystem Assessment (MA 2025). The outcome of the assessment was summarised in four findings:

- over the past 50 years, ecosystems have been changed more extensively than ever before in human history;
- the changes have contributed to substantial gains for society, achieved however at growing costs in terms of degradation of many ecosystem services and increased risk of sudden non-linear changes;
- the degradation could grow significantly worse in the first half of the present century;
- reversing the degradation while meeting increasing human needs will involve significant changes in policies, institutions and practices.

This raises the question to what degree ecological changes can be repaired or avoided, and to what degree they must be seen as the unavoidable outcome of more or less aware trade offs.

The water cycle has the function of bloodstream of both biosphere and society (Falkenmark, 2005). People live on land where water is a key livelihood component. More or less irregular rainwater pulses rinse the land and generate runoff in aquifers and within river systems. During this movement, water has many parallel functions, Figure 1. Humans depend on clean water but pollute it during use. Since water is a unique solvant, it also tends to pick water soluble pollutants along its pathways, polluting the habitats of aquatic ecosystems in the rivers and coastal waters. The result is proceeding losses of biodiversity in these ecosystems.

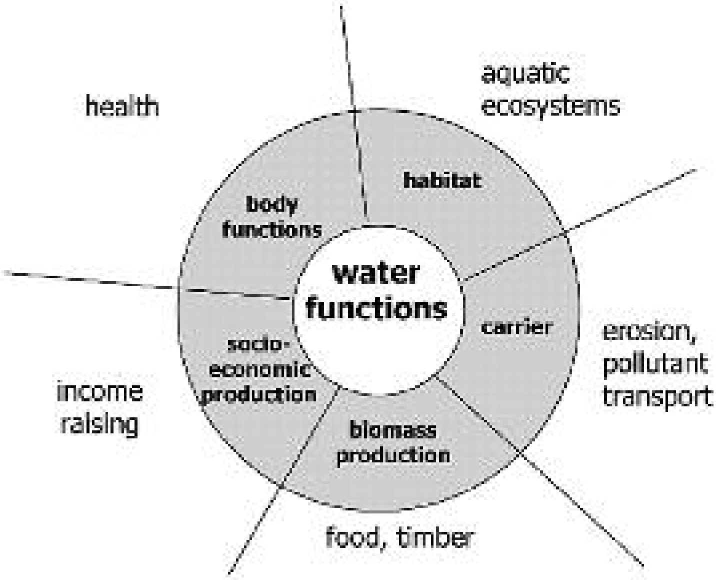

Figure 1. Five central functions of freshwater. From Falkenmark, 2005.

The focus of the Vatican Seminar is scientific frontiers regarding links between hydrology and ecology and the need for increasing disciplinary convergence. The current biodiversity loss makes a more science-based approach to humanity's water dependence urgent: while many river basins are already closed or closing (Smakhtin *et al.*, 2004, Falkenmark & Lannerstad, 2005), pollution continues to escalate, and aquifers are being overexploited, driving forces remain strong. A real dilemma is that the scientific and conceptual development needed to address these huge challenges has remained surprisingly slow. The Seminar aims at analysing scientific issues in terms of eco-hydrological links of relevance for future engineering and political problems. Especial attention is to be paid to the strong driving forces related to achieving the Millennium Development Goals (MDGs).

The aim of this paper is to clarify a number of interactions of hydrological and ecological phenomena in a river basin context. It will address the interpretation of the concept of ecosystem approach, building on the author's earlier studies on the links between water and ecosystems (Falkenmark & Folke, 2002, 2003; Falkenmark, 1997, 2003a, 2003b; Falkenmark & Rockström, 2004). It will analyse the water perspective of the MDGs and the particularities of the global hot spot regions. Integration opportunities in ecohydrological basin management will be discussed and conclusions drawn on the urgent need for better bridging of ecological and hydrological phenomena.

WATER AND THE MILLENNIUM DEVELOPMENT GOALS

Need for Additional Landscape Modifications

The scientific community has to base its future-oriented considerations on anticipation of the considerable changes related to water, land and vegetation. Such changes will be more or less unavoidable in order to *eradicate poverty* by income generating production activities (cash crop production, small scale industrial activities), to *alleviate hunger* by increased agricultural production among small scale farmers (SEI, 2005, Figure 2, see page 234), to expand *safe water provision* (a large number of additional raw water sources), and to organise *sanitation* (e.g. a large number of water-table vulnerable latrines).

Particularly the MDG-oriented activities aimed at eradicating poverty and hunger and securing societal water supply will necessarily involve modification of landscape components (Falkenmark, 1997). Examples are deepened wells and groundwater withdrawals, pipelines and surface water withdrawals, irrigation and consumptive/evaporative water use, clearing of additional agricultural land etc. Such landscape manipulations will influence water phenomena in the landscape and thereby alter abiotic conditions in terms of habitats of ecosystems, terrestrial as well as aquatic.

In altering abiotic conditions, thereby influencing ecosystems, it will be essential to secure *environmental sustainability*, defined as 'meeting current human needs without undermining the capacity of the environment to provide for those needs over the long term' (Melnick *et al.*, 2005). Environmental sustainability related constraints will have to be identified. It has to be clarified in what way landbased manipulations of vegetation, soil and water will have to be constrained, in other words define the degrees of freedom for MDG-driven landscape-related alterations. Abiotic alterations can originate both from *biophysical alterations* of landscape components, influencing evapotranspiration, groundwater recharge and runoff generation, and from *chemical alterations*, in particular introduction of pollutants directly through waste products disposed of to the atmosphere (leached out and carried back to the land by rainout or fallout), to the land (carried to the river by runoff), or as wastewater directly to the river. In addition, pollutants originate from agricultural chemicals, leached out to the river system.

Thus, it may be foreseen that MDG-driven modifications may influence the ecosystems both directly and indirectly. The alterations will vary between different MDGs. When *direct* and visible, they can be minimised and managed by for example a natural reserve approach through protection of particular landscape elements. When *indirect* and/or invisible, the response options are more uncertain. Some alterations may even generate moisture feedbacks, altering drought patterns, or the rainfall, influencing a rainforest. Specific considerations call for attention to the resilience of particular ecosystems, and how to avoid that they degrade into unwanted states.

Resilience protection refers to the fact that humanity, through its activities, tends to alter disturbance regimes with which organisms have evolved over time. There is therefore a need to secure enough 'elasticity' (resilience) of ecosystems to change in the surrounding conditions (storms, fire, drought, pollution events, or creeping pollution). What has to be protected is the capacity of the ecosystem to absorb continuous change *without loss of the dynamic capacity to uphold the supply of ecological goods and services.*

Hot Spot Regions

A fundamental factor to consider in analysing how to eradicate hunger is the hydroclimate. There is an unfortunate congruence between the zone where the majority of the hunger-prone countries are located and the zone with savanna climate (Figure 3, see page 234). Typical for this zone is that considerable challenges will have to be overcome:

- seasonal rainfall with intermittent dryspells, making the rainfall unreliable;
- recurrent drought years linked to large-scale fluctuations in the intercontinental water vapour flow system;
- high evaporative demand so that most of the rainfall evaporates, leaving only a limited fraction to generate runoff;
- often vulnerable soils with low permeability and low water-holding capacity which limits the amount of water available to the root system.

In that climate, rainwater partitioning is highly vulnerable to land cover change, altering the consumptive water use involved in food production and forestry. The result may be surprising effects on groundwater and streamflow. In vaste irrigation-dependent regions river flow is already over-appropriated beyond estimated needs of aquatic ecosystems (Smakhtin *et al.*, 2004). Overexploited groundwater, increasing water pollution and salinisation are other serious water-related problems that will demand great human ingenuity to be succsssfully coped with.

HYDROLOGIC-ECOLOGICAL INTERACTIONS

Global Scale Interactions

Water circulates through the biosphere and thereby links atmosphere, terrestrial ecosystems, freshwater flows, and aquatic ecosystems. In this system, water has three fundamental global scale tasks (Ripl, 2003):

- distribute solar energy over the planet (by balancing evaporation and condensation);
- distribute water soluble substances (by balancing dissolution and crystallisation), in particular nutrients and vital minerals;
- provide one of the two key raw materials for the photosyntesis, the other being carbon dioxide from the atmosphere (by balancing splitting and reassemblage of the water molecule).

When striving towards environmental sustainability, the starting point is the interaction between the network of nested ecosystems and the social system (Figure 4, see over). Humans try to manage the complex of living organisms and their non-living surrounding – the ecosystem – since it provides essential goods and services on which human welfare is based. Human needs are driven by population growth and wealth expectations. In trying to meet those human needs, waste is introduced and various biophysical disturbances are produced, together degrading the life supporting web of ecosystems (Falkenmark, 2003b).

The life support system on the landscape scale has generally one single water source: the precipitation. All water-dependent human activities and ecosystems are enclosed in the water delivery system of the catchment. In its contacts with the land surface, the water input is partitioned between the naturally infiltrated *green water* in the soil and the surplus producing runoff in rivers and aquifers (*blue water*). Since the former evaporates and the latter forms liquid water flow, the distinction has been extended into vapor form green water flow and liquid form blue water flow.

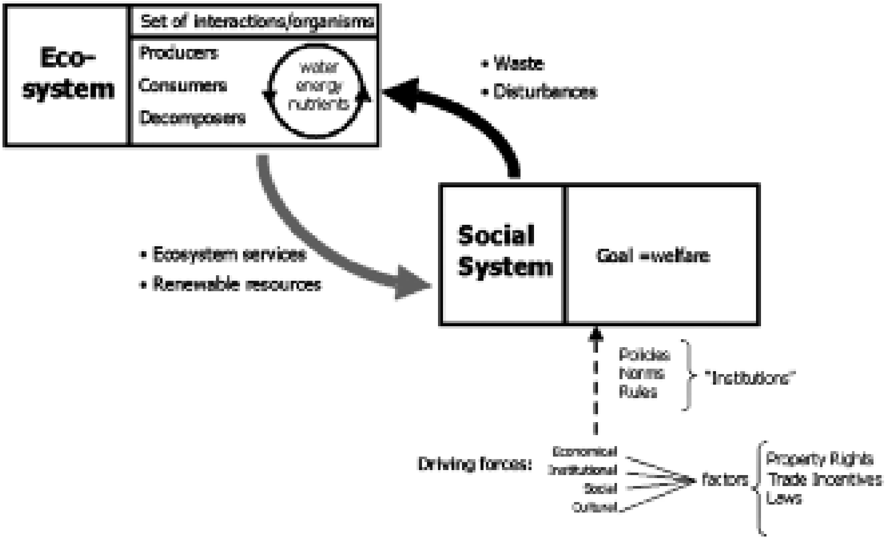

Figure 4. Humanity critically depends on ecological links between nature and society. Because driving forces are acting on the social system, ecosystem management is a question of living with change while securing long-term ecosystem productivity. From Falkenmark 2003a.

This division between green and blue water flows (cf. Figure 5, page 186) is useful in a closer analysis of water balance alterations, linked to terrestrial ecosystems, which are green water dependent, and aquatic ecosystems, which are blue water dependent. The green water flow system incorporates the consumptive water used by forests, grasslands and rain-fed croplands. The blue water system provides the water resource directly available to and 'harvested' by humans. Water is in other words being withdrawn from rivers and aquifers for use in the social system, and after use returned to the water cycle by two complementary pathways: as vapour flow after consumptive/vapourising water use, or as blue water return flow back to the river system, often carrying pollutants (Falkenmark, 2003b).

Both irrigation and deforestation are activities, altering vapour flows. Gordon *et al.* (2005) have studied the large-scale redistribution of global water vapour flows; they found that irrigation has increased the vapour flow by some 2,600 km^3/yr, which has been more or less compensated by an almost equal reduction from global scale deforestation. Different patterns were shown to dominate in different regions.

Interactions in the River Basin

As already stressed, human needs for food, water, energy, minerals etc. cannot be met without manipulating the life support system with its natural resource base and its incessant biomass production processes (Falkenmark, 1997, 2003b). These interventions involve alterations of three key water processes, crucial for the generation of ecosystem impacts: water partitioning at the land surface, influenced by land use change; water as a carrier of pollutants to the ecosystems, linked to waste production and use of agricultural chemicals; and consumptive blue water use (mainly in irrigation), involving a blue-to-green redirection.

Since ecosystems are water-dependent they are easily impacted when water's activities in the life support system are being disturbed. The manipulations mentioned aim at meeting human needs, but are through the biosphere bloodstream system translated into ecological side effects, most of them mediated by water multifunctionality. The resulting environmental degradation influences the capacity of ecosystems to produce goods and services.

In analysing possible countermeasures against ecosystem degradation, it is useful to distinguish whether the causes in terms of manipulations are *avoidable or unavoidable*. The former (erosion, pollution etc.) include uncautious land use changes, containable waste loads, use of toxic chemicals that will escape to the life support system etc. The latter (biologically controled consumptive water use etc.) include consumptive/evaporating water use linked to the photosynthesis process (Falkenmark & Lannerstad, 2005).

In meeting the ecological side effects of the alterations needed to meet societal needs, there are principally two alternative approaches involved (Falkenmark, 2003a):

- for the former type *minimisation*;
- for the latter type *striking of trade offs*.

In managing the trade offs it is useful to distinguish also between *known trade offs* and *unknown trade offs*. The former call for analysis, ability to balance different interests, stakeholder involvement etc. The latter have to be met by clarifying resilience conditions and by an adaptive management, that is flexible and supported by monitoring of slow indicators that can provide early warning about unacceptable ecosystem change.

Ecosystem Approach

A fundamental tool often referred to for the response to unacceptable effects of hydrology-ecology interactions is the so-called *ecosystem* *approach*. Since ecosystems may be of very different scales this concept is somewhat unclear. The concept may be interpreted on different scales (Falkenmark, 2003a).

It may on the one hand be seen in a local scale, and refer to *living components in the local landscape* that are of particular interest from societal and/or scientific perspectives, such as iconic sites (a certain local forest with high biodiversity, a beautiful lake, a groundwater-dependant wetland with particularly high biodiversity due to the shifting mix of groundwater seepage and inundating surface water, etc.). It may also be understood on the overall catchment scale, and refer to the conglomerates of ecosystems, internally linked by water flows into a *catchment ecosystem.* This is the way that GEF has used the concept when stressing the need for 'land-water integration in a catchment-based ecosystem approach' (GWP, 2000). When looked at in this scale, we might think of the catchment as a biological fabric linked by flows of water and nutrients.

In a good ecosystem governance, environmental sustainability will as already indicated have to remain in focus, implying that the life support system may not be undermined (Melnick *et al.*, 2005). This means that ecological bottomlines have to be defined. What this would mean in terms of terrestrial ecosystems remains rather unclear. In terms of aquatic ecosystems, such bottomlines have been formulated in terms of minimum residual streamflow ('environmental flow', Tharme, 2003), referring to the minimum seasonal flow to remain in the river. Also water quality must evidently be a key component of such minimum flow characteristics.

Thus, the concept ecosystem approach will differ depending on what ecosystem is under scrutiny. Whereas for an ecosystem in the sense of a local landscape component, iconic site, or downstream aquatic ecosystems, focus has to be put on the water determinant of that particular ecosystem, it is less clear what should be meant by a catchment-based ecosystem approach.

But the concept ecosystem approach is even more complex. At the recent international symposium in South Africa on 'Good ecosystem governance', it became clear that the concept 'ecosystem approach' tends to have basically *two interpretations*: a biophysically based one in line with the approach in this paper, and a rhethoric, socio-politically based one with very unclear meaning, referring back to the WCED report in 1977.

INTEGRATION OPPORTUNITIES IN MANAGEMENT

The water-related linkages in a catchment provides a basic rationale for the integrated, basin-wide approach taken within IWRM, Figure 5. Currently, attention is being paid to the need of expanding the approach from blue water only, to incorporating also the consumptive water use linked to plant production and green water. Land use needs in other words to be included by entering an L for 'land' into the integrated approach, turning IWRM into ILWRM (Duda, 2003).

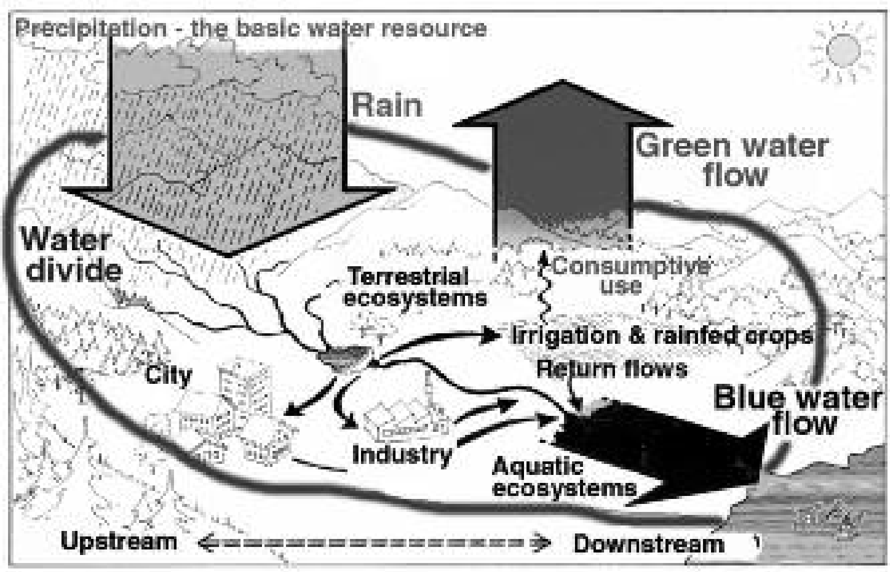

Figure 5. The catchment allows an integrated approach to all water-related phenomena at work within the water divide. All the rain falling within the water divide is being partitioned between humans and nature, between land use/terrestrial ecosystems and water use/aquatic ecosystems, and between upstream and downstream uses and phenomena. From Falkenmark, 2003a.

Water is thus increasingly being seen as a resource to be shared between human society and ecosystems. It is both the bloodstream of the biosphere, and a fundamental base for a multitude of human activities, and therefore a common denominator of the two systems. But these complementary functions are not always compatible: consumptive water use removes water from the catchment and therefore withholding it from the aquatic ecosystems. Pollution load degrades the habitat for aquatic ecosystems and therefore contributes to biodiversity loss. According to the comparison, within the Living Planet Index study, of the biodiversity loss in three major types of ecosystems during the last 30 years (marine ecosystems, freshwater ecosystems and forest ecosystems), the biodiversity loss was largest in the freshwater ecosystems. This is of course a natural consequence of their lying in the bottom end of river basins, cumulating all the human influences to the water arriving from upstream.

The goal for a good governance can be described as reaching an *eco-hydrosolidarity*, where the rainwater input to a catchment is wisely orchestrated between all different water-dependent and water-impacting activities and ecosystems. An introductory analysis will have to clarify the water-related links between major land uses, water uses and ecosystem services (Falkenmark & Rockström, 2004). The crucial resilience capacity of the ecosystem to absorb change without loss of stability must be established. There has also to be a broad realisation of the fact that a land use decision is also a water decision, and that all ecosystems are genuinely water-dependent.

A pragmatic approach taken in Australia is the concept 'healthy working river', defined as the negotiated compromise 'struck between the level of work and the loss of naturalness, depending upon the values the community places on any river' (Whittington, 2002). This type of approach is currently under discussion also for the Yellow River in China.

CONCLUSIONS

It has been stressed that water is a permeating phenomenon in the landscape with a circulation governed by biological and physical laws and moving by gravity through river basins, linking human activities with ecosystems, land based activities with streamflow and groundwater, and upstream activities with downstream opportunities and systems. However, science fragmentation inherited from the time of the 17th century philosopher Descartes, adds to the difficulties of a science-based coping with the looming water crisis.

The *urgency* of an effective bridging between hydrology and ecology is evident from the fact that the overappropriation of streamflow has already gone very far, involving 15 percent of the global land area with a gross population of 1.5 billion.

In spite of this urgency, the concept 'ecosystem approach', although having been around for several decades, still remains unclear. There are two interpretations:

- one biophysical, demanding attention to the protection of the resilience against change that might lead to the ecosystem flipping towards a lower state where some of the ecological services provided may not be available any more;
- one socio-political, based on WCED-originating rhethorics with focus on environmental impacts and supported by international, unidimensional conventions.

A *basin-level eco-hydrosolidarity* will have to involve an ecosystem approach, with proper attention to the linkages between ecosystems and different human activities, performed by the water flows above and below the land surface, from the water divide to the mouth. Such an approach will have to be based on current understanding of water/humans/ecosystem linkages.

It will be essential to further develop the mode of research of human interaction with the life support system from monodisciplinarity to interdisciplinarity. It is urgent to proceed from advocacy-oriented ecological studies and from focus on the intricacies of different local ecosystems to the clarification of possible trade-off-based pathways on the route towards an ecologically sustainable future, based on realistic assumptions of basic human rights as expressed by the MDGs, and proper awareness of the many different functions of water in the life support system.

It will be essential to give much more focus to near-future problems to complement the massive amount of longer term climate-change research. It is only when superimposing the water-related changes, linked to human driving forces, and the altering climate that we get an idea of the real challenges during the next few decades (Vörösmarty, 2000). The SEI-study on the water implications of meeting the MDG goal of eradicating hunger shown in Figure 2 is thought-provoking (SEI, 2005): to alleviate hunger, *massive amounts of additional water will be needed for consumptive water use linked to food production*.

Further delays in linking ecology and hydrology are unacceptable: their price will have to be paid in terms of even further degradation of ecosystems and loss of biodiversity, even in terms of human lives. Attention is therefore needed to *ethics of science*, as discussed by Lubchenko (1998) and to the social contract of science, interpreted as the *duty to address priority issues*.

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OTHER CONTRIBUTIONS

FROM THE PHYSICS OF THE SMALL TO LARGE BASIN SYNTHESIS

LUCIO UBERTINI

In spite of all the scientific and technological efforts exerted in the past decades towards data collection, analysis and modeling of hydroclimatic processes, there is still a large amplitude of uncertainties in the prediction of the so-called leading precursors of climate such as temperature and precipitation, let alone the prediction of the resultant runoff. The most recent analysis of the Intergovernmental Panel on Climate Change (IPCC) indicates a series of possible effects greenhouse warming might have on the supply of water and the hydrological balance, based on predictions of climate change from GCMs. The results suggest that a 1.5 to 4.5°C rise in global mean temperature would increase global mean precipitation about 3 to 15% with very divergent results according to different scenarios. Translating such precipitation predictions into annual runoff has become an upbeat task. For example, prediction of annual runoff with different models for northern South America shows considerable discrepancies varying from 93.3% increase to 49.1% decrease of regional runoff.

Even though the introduction of remote sensing techniques was heralded as decisive, their contribution towards understanding climate dynamics and their ground effects is still minimal. Satellite data for example have been accumulated and interpreted at least in the past three decades but still not much seems to have been achieved in terms of predicting climate change and/or climate modifications, necessary for adapting water resources management strategies.

Couldn't it be the case to 'study' the 'artificial' planet (or part of the planet) through physical models instead of the study of the planet from satellite data being considered as a laboratory by itself? Alternatively, it could be a scaling laboratory comprising part of the atmosphere. Is this approach more expensive than the satellites or is it much more uncertain? I do not know. The Japanese have always been on this path and, among other things, they have, for example, developed a complex simulation installation for atmospheric processes and their resultant ground effects under different weather scenarios from physical models to real world installations and thereby creating many exciting scientific facilities in Tokyo. Is it only a question of money or is it a promising road?

Hasn't the time come to think about something else, perhaps, or to go back to Nature through nature's own system construction of the river network? The law of conservation of mass and energy is well observed within the system boundaries of the river network. It is well known that the river network itself is a definite product of climatic, soil, and hydraulic processes and changes in the triggering processes can therefore be monitored through the basin response at different time scales. The river basin has a unique property of having a very stable structure in time (skeleton) which does not lend itself to instantaneous changes and hence can monitor the changes in the mass and energy balance within its system.

Recourse to Hydraulics can therefore 'explain' many things! The discharge of a river at a section (and hence the volume of water passing during at a given time interval: month, year, multiyear) is an integration (in both physical and mathematical senses) of a series of processes occurring in the channel network and therefore emerges as the resultant synthesis of all! I therefore think that a big project on large basins with or without atmospheric 'boundary' but rather with land boundary could better 'explain' a series of questions connected to the climate and/or climate changes. This could lead to a necessary synthesis which can be derived from hydraulics of large basins (eg. Amazon River, Mississippi, Danube, etc.). A special discussion on the Mediterranean basin can also be initiated and formulated, within a global framework. The alternative road could be from the 'physics' of the small to arrive at deriving information at a larger scale but presently much has been left at the level of the 'small'.

Such projects could go a long way towards monitoring climatic processes and modifications and also climate changes through actual measurements of discharges at controlled sections (basin response) which could lead to a continuous verification of the relations between surface and ground water responses to precipitation modifications from the basin water balance. This approach could lead to the quantitative monitoring of the effects of the ongoing frequency/magnitude modifications of precipitation and the consequent necessity for adapting water management strategies to them.

WATER AND THE ENVIRONMENT
CONCLUDING COMMENTS

HOWARD S. WHEATER

The Pontifical Academy of Sciences has created a unique meeting of the world's most distinguished scientists. The Theme of Water and the Environment is multi-faceted – it includes some of the most challenging areas of science, and areas where there is exciting progress to be reported, but also some of the world's most pressing and difficult problems of environmental management.

The meeting has operated on a variety of levels and addressed each of these aspects. At one level, the bringing together of leading experts in adjacent disciplines has provided a unique opportunity for interaction. Individuals will have seen the meeting from different perspectives, but all will have learnt new things and gained new insights and perspectives; for some new collaboration will have begun. This in itself is an important contribution to the development of science.

At another level, the meeting has presented a feast of science. It has focussed on global scales and global issues, and reported important developments in theory and the understanding of earth systems. We have seen the maturing of interactions between hydrology and ecology, represented for example in global models that encompass hydrology, ecosystem response and geochemical cycling.

One of the world's most pressing and politically controversial issues is that of global warming. Here the science presented to the meeting encompassed the assessment of the nature of global warming and the associated global change. On this, the meeting has been unanimous. The clear and unequivocal message is that anthropogenic emissions of greenhouse gases are giving rise to global warming. Climate change is a reality and we have to face the consequences, and adopt appropriate management strategies to mitigate the effects. The major uncertainties concern the magnitude of future response, 50-100 years hence. Action now will only have benefits on that timescale. And other important policy implications emerged in discussion. For example, it is likely that the single most effective short term contribution to reduction in CO_2 emissions is the reduction of tropical deforestation.

The meeting began with an address by Prof. Ardakanian that highlighted some of the important socio-economic aspects of water, including recognition of the provision of water as a human right. And the closing address by Prof. Falkenmark returned to this theme, stressing the challenge of meeting the Millennium Development Goals for the provision of water and food, and the potential conflict between human socio-economic development and ecological protection. These were management themes highlighted by the meeting, but not addressed in detail. They raise important issues of science, for example the impacts of human activity on changing land use and land management. But these issues of land and water management cannot be resolved without considering the social and economic context. The meeting heard of the deforestation within a generation of 620,000 km^2 of the Brazilian Amazonian rainforest. To resolve these issues raises major social and economic issues. My own current work in the UK focuses on the effects of changes of agriculture on flooding. These changes have occurred in response to agricultural policy and socio-economic forces. Clearly where science informs management, the social sciences are also required to effect solutions.

And finally, to balance the potential conflict between socio-economic development and ecosystem protection, a much closer dialogue is required between hydrology and aquatic ecology. Here important disciplinary differences exist, and the development of an effective common language and the meeting of methodologies has far to go. Interestingly, these challenges are being forced by the European Union through the recent Water Framework Directive. At the European scale, hydrologists are having to recognise the need to communicate with ecologists and to develop effective strategies to balance the conflicts of integrated management.

Much remains to be done to integrate the disciplines of physical, biological and social sciences to meet the challenges of water management and the Millenniums Goals. Perhaps this is one more area where the Pontifical Academy of Sciences can play a leading role.

CONTRIBUTION TO FINAL DISCUSSION

JAMES DOOGE

I join with those who have already expressed their appreciation of the organisation of the workshop and for the personal invitation to take part. It has been an excellent illustration of the possibility and of the fruitfulness of dialogue between those concerned with hydrologic processes or atmospheric or ecological processes.

In considering the possibility of a further step in relation to water and the environment, the Pontifical Academy should consider carefully what is the type of role best suited to promotion of its special objectives. In my opinion this role should combine interdisciplinarity and outreach.

The promotion of interdisciplinarity in relation to the problems facing humanity in regard to water and the environment has been a feature over the past few decades of a number of important international organisations both non-governmental and inter-governmental. For example the International Council for Science (ICSU) initiated a key break with the traditional reductionist approach of concentrating on research in a single discipline by establishing the International Geosphere Biosphere Programme (IGBP) to bridge the gap between the earth sciences and the biological sciences. The water science division of UNESCO widened the scope of successive phases of their International Hydrological Programme. Recent initiatives of the Water Science Division of UNESCO have included the establishment of a Research Centre for Ecohydrology in Poland and the publication of a series of 12 essays on aspects of water and ethics in order to promote an interdisciplinary dialogue with the social scientists on this topic. In dealing with climate, the World Meteorological Organisation (WMO) has widened the dialogue from the First World Climate Conference (1979), attended only by scientists, to the Second World Climate Conference, attended by both scientists and ministers and their advisers to the Intergovernmental Panel on Climate Change (IPCC) to the U.N. Convention on Climate.

It would not be appropriate for the Pontifical Academy of Sciences to seek to rival these large-scale initiatives but rather to seek a niche of its own that would be complimentary to them. The selection of such a niche would be a suitable focus for a second workshop in relation to water and the environment. There is a wide range of possible topics for special study with varying degrees of interdisciplinarity and outreach. If a specific science-based topic in desired, a number of areas could be considered. Studies in recent years have shown that in both hydrological analysis and ecological analysis difference in the scale being investigated may result in quite different approaches in each case. There is room for further work on the matching of the critical scales in hydrology and in ecology and of the relationship between them. If a greater emphasis or outreach is required, consideration should be given to a more general exploration of cooperation between natural scientists and social scientists in relation to the problem of water and the environment and human development.

In either case, we should be prepared for the difficulties in any transdisciplinary dialogue. The conditions of success in such development involve overcoming three key obstacles: (1) the difficulty in choosing and defining a sharply focused topic of interest to all participants; (2) a recognition that the supposed common language of science includes many different dialects; and (3) the need for the skill and humility to listen to scientific strangers with the some efficiency as that with which we seek to express our own viewpoint.

STATEMENT OF THE WORKSHOP ON WATER AND THE ENVIRONMENT

IGNACIO RODRÍGUEZ-ITURBE

A scientific workshop on 'Water and the Environment' was held at the Pontifical Academy of Sciences on 12-14 November 2005. Underlying the programme of the workshop was the basic premise that the survival of humanity and all species on earth depends upon the fate of water. Where water is absent, life is absent. The common symbol of life for mankind and all species, valued and respected in all religions and cultures, today water is symbolic of social equity.

There are two facets to the question of 'Water and the Environment'. The first belongs strictly to the natural sciences and centres on the understanding of the hydrologic cycle and its interactions with the living and non-living components of the earth and its atmosphere. The second facet pertains more to the social sciences and focuses on the fair distribution of water, considering both quality and quantity aspects, as well as the impact of these issues in the economical and spiritual growth of people around the world. These two facets are inextricably linked, with scientific knowledge providing a basis for well-informed decisions expected from the policymakers involved, decisions that will affect all humanity over many generations to come.

The main emphasis of the workshop was on the first of the abovementioned facets. It dealt in particular with up-to-date scientific research bearing on the impact of hydrologic dynamics on issues concerning sustainable development, in which water resources are of paramount importance. Contamination, ill-planned industrial development, mega cities, are just a few of many threats to these vital resources. Some hope of success in countering these threats is provided by concepts such as the so-called Integrated Resources Management, a (management) process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.[1]

Such coordinated development and concomitant decision-making need firm scientific underpinning, in which the science of Hydrology – with its intimate links with Ecology and with its geophysical sister sciences, Geomorphology, Geology, Climatology and Meteorology – has a key role to play. In the words of Hedin *et al.*,[2]

> this disciplinary convergence will over the next several decades transform our understanding of basic processes that control the stability and sustainability of natural environmental systems. The ensuing findings will have extraordinary implications for our abilities to predict and manage how humans impact the health of ecosystems across local, regional, and global scales. Such knowledge is a critical component of a safe, sustainable and prosperous future.

The workshop was organized around recent advances in research in five main areas – Biodiversity, Global Hydrology, Climate Change, Land-Atmosphere Interactions, and River Basins – with hydrologic dynamics providing the unifying theme to the discussions. Particular emphasis was placed on the investigation of feedbacks and interactions between the five areas, with the goal of identifying some of the main scientific challenges that need to be faced in the immediate future.

The presentations and discussions of the different topics took place in the Casina Pio IV in an environment which could be described by the eloquent words of Paul VI characterizing the attitude of a scientist:

> On the one hand, he must honestly consider the question of the earthly future of mankind and, as a responsible person, help to prepare it, preserve it, and eliminate risks; we think that this solidarity with future generations is a form of charity to which a great many men are sensitive today, in the framework of ecology. But at the same time, the scientist must be animated by the confidence that nature has in store secret possibilities which it is up to intelligence to discover and make use of, in order to reach the development which is in the Creator's plan. This hope in the Author

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[1] Global Water Partnership, TAC Background Paper, No. 4.

[2] Report to the U.S. National Science Foundation, 2002.

> of nature and the human spirit, rightly understood, is capable of giving new and serene energy to the researcher who is a believer.[3]

In order to keep the overall perspective and deal with the range of implications of the scientific topics, the workshop was opened and closed with two presentations providing a link between the science aspects and the social impacts of the themes under study. These presentations were entitled 'The Fair Distribution of Water' and 'Heading Towards Basin-level Hydrosolidarity: Goal for Land/Water/Ecosystem Coordination'. Thus the workshop opened with a strong message that access to sufficient and healthy water is a human right which has to be taken into consideration by governments without discriminations of any kind. It is essential to consider the fair distribution of water when applying concepts like 'sustainable development', 'globalization' and 'food security'. All these need to be discussed considering the challenges and obstacles of geographical, social, cultural and political nature that impact any effort towards a world-wide fair distribution of water. The workshop then ended with the discussion of a road map towards hydrosolidarity framed on the scale of the multiple uses by different geographical regions of the water resources of a river basin. It involves a plea that it is an ethically demanding duty for the scientific community to prepare wisely for the water related challenges involved in the Millennium Development Goals over the next half century. Thus it will be crucial to develop a scientifically sound and ethic-based vision, that will stimulate new optimism and involve people in striving towards hydrosolidarity-based balances of interests and activities in river basins.

The five general themes of the workshop presented a challenging perspective of the scientific aspects of some of the most crucial areas related to water and the environment. Thus, in Biodiversity and Hydrologic Dynamics, the extremely important role of water was made clear in the preservation of biodiversity and in the temporal and spatial patterns that biodiversity exhibits. The main causes of accelerating extinction rates are habitat destruction and degradation, the introduction of exotic species, pollution, overexploitation and global climate change. In all key aspects of biodiversity, hydrologic dynamics play a crucial role and it was clearly shown that natural or human-caused fluctuations of the water cycle are fundamental drivers of the vegetation dynamics. The different characteristics

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[3] Paul VI, *Papal Addresses*, The Pontifical Academy of Sciences, Scripta Varia 100, Vatican City 2003, p. 208 f.

of the interaction between vegetation and climate were discussed in-depth for both savannah and river basin ecosystems. In the case of savannahs, the dynamic grass cover enhances the degree to which the savannah vegetation is optimal with respect to its use of the stochastic water input. In the case of river basins the deep coherence was made apparent between the geomorphological organization of the watershed and the vegetation patterns that exist around the river network.

In the session on Global Hydrology and Hydrologic Dynamics, special emphasis was placed on the fact that the impact of climate change will be felt most strongly through changes in surface hydrology (e.g., changes in the frequency of floods and droughts), which affect ecosystems and agriculture, as well as the water available for direct human use. The key drivers of contemporary changes in river flow (land use change, climate change, solar dimming and direct CO_2 effects) were assessed by comparing model simulations to continental-scale runoff records. These comparisons suggest that direct CO_2 effects can already be detected, with important consequences for water availability in the 21st century. Our ability to meet the water resources requirements of this century demands a coordinated scientific agenda at the international level and a review was provided of the progress towards addressing the above requirements for an integrated water resources management system.

The topic discussed above continued with the study of Climate Change and Hydrologic Dynamics where it was pointed out that anthropogenic climate change is expected to affect the hydrologic cycle in many ways and it is not unlikely that changes in precipitation will be more serious than those in temperature. Of particular concern are long-term changes in precipitation stretching over multiple years. Worldwide changes in evaporative demand are also of fundamental importance in this topic and received extensive discussion especially in what concerns the apparent paradox between global warming and decreased evaporative demand. Aerosols are another important factor impacting the hydrologic cycle since they change cloud characteristics in many ways. Human emissions of aerosols cause a reduction of solar radiation at the surface (e.g., solar dimming). This has important consequences for the surface energy budget and for the hydrologic cycle.

Land-Atmosphere Interactions are a key component of the intimate interdependence between water and the environment. A particularly important region for this mutual feedback is the Amazon River basin which contains the largest, contiguous extent of tropical forest on earth.

Over the past 30 years almost 600,000 km^2 have been deforested in Brazil alone due to the rapid development of Amazonia. There are observational evidences of regional changes in the surface energy budget, cloudiness and lower troposphere radiative transfer due to biomass burning aerosol loadings. Observational evidence of changes in the hydrologic cycle includes reductions of streamflow and modelling studies of large scale deforestation indicate a likely drier and warmer post-deforestation climate. Precipitation suppression by anthropogenic air pollution is likely to lead to a major loss of water resources where we need them most. The study of the physical mechanisms responsible for suppressing the precipitation forming processes provides the scientific basis for corrective actions that were discussed. The need to quantify the linkage between plant hydraulics and leaf biochemistry was also shown for understanding how the biosphere-atmosphere exchange of water and carbon occurs under current and projected climate conditions.

River Basins play a fundamental role in all aspects of water and the environment and they constitute complex adaptive systems where the action of water is central to the dynamic origin of their scaling characteristics. They also constitute fascinating laboratories for the study of how nature works across a wide range of scales. Of particular importance is the discussion of the dynamic origin of their scale-invariant forms which lies at the core of the organization and evolution of river networks and their associated ecosystems. How does biology affect landscape form and evolution? How do biotic processes influence weathering, erosion, and sediment transport mechanisms, and how could such influences be manifest in landscape-scale morphology? Is there a topographic signature of life? These questions are intimately linked to the basic premise of the workshop underlying all presentations: the survival of humanity and life depends on the fate of water. The preservation of earth as a planet that nurtures life crucially depends on the understanding of the hydrologic cycle and its interactions with the living and non-living components of the earth and its atmosphere.

All the above topics need measurements from space which have provided information on the water cycle with unprecedented accuracy. This new information provided by satellite shows that when comparing Mars, Venus and Earth, which are all of the same geological age, only Earth has liquid water whose dynamics is controlled by the hydrologic cycle. If we do not conserve the equilibrium of this cycle the singularity of Earth and the life it sustains are very much at risk and the Earth could become like other planets. Furthermore, given the global nature of the processes involved any effective action will benefit immensely if it is planned within an international framework.

The workshop provided a truly unique opportunity for leading scientists of different disciplines to find a common ground in a problematic area that is of fundamental importance for mankind. The cross-fertilization and links that took place in a climate of free scientific discussion are bound to have a lasting impact.

TABLES

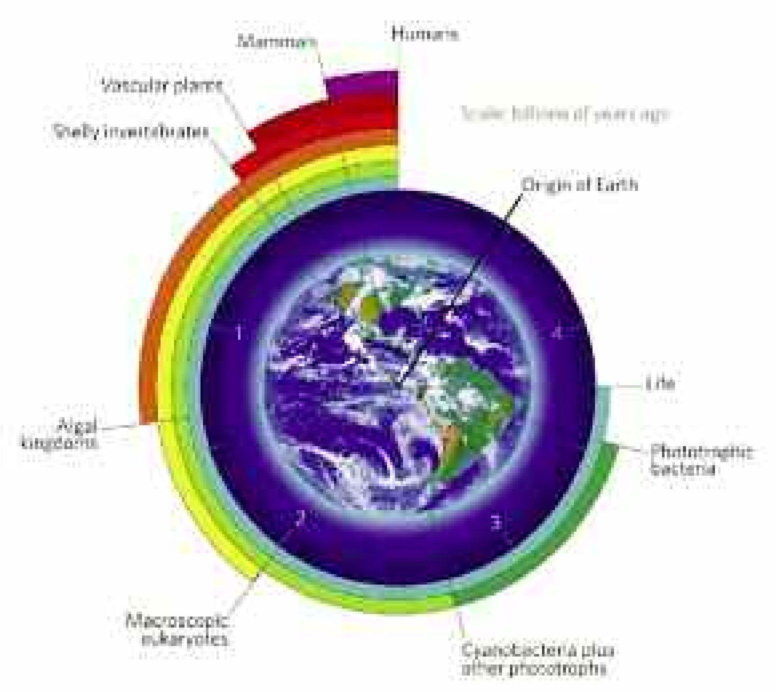

Figure 1. Reprinted with permission from Des Marais (2005). A diagrammatic clock sketching the ages of life on Earth.

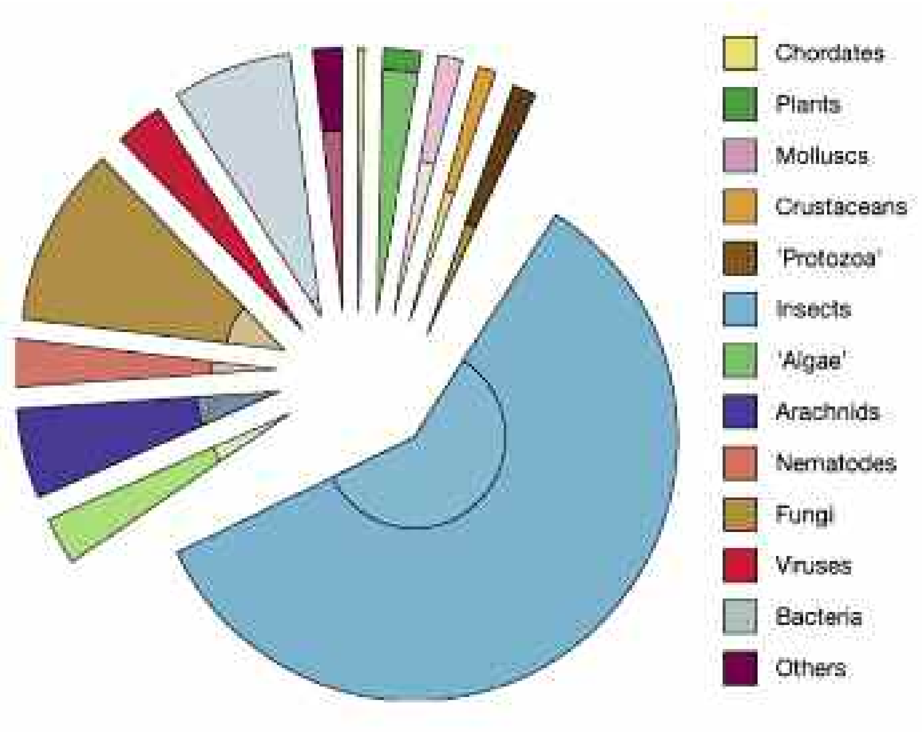

Figure 2. Reprinted with permission from Purvis and Hector (2000). How the world biodiversity is probably subdivided across different taxonomic groups. The area of each slice of the pie represents the number of species estimated to exist in each group; the inner sectors show the proportion that have been formally described.

Figure 3. Reprinted with permission from Myers *et al.* (2000). Hotspots of biodiversity. They are defined as 'areas featuring exceptional concentrations of endemic species and experiencing exceptional loss of habitat'.

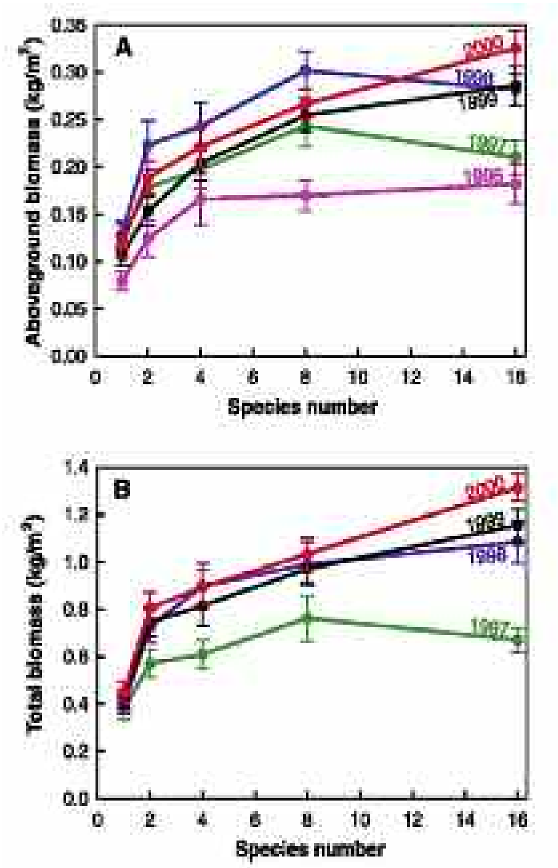

Figure 5. Reprinted with permission after Tilman *et al.* (2001). Results of experiments in a north-American grassland (A) The plant aboveground biomass and (B) the total biomass, i.e., aboveground plus belowground living plant mass, as functions of the number of planted species. Data are shown as the mean ± SE.

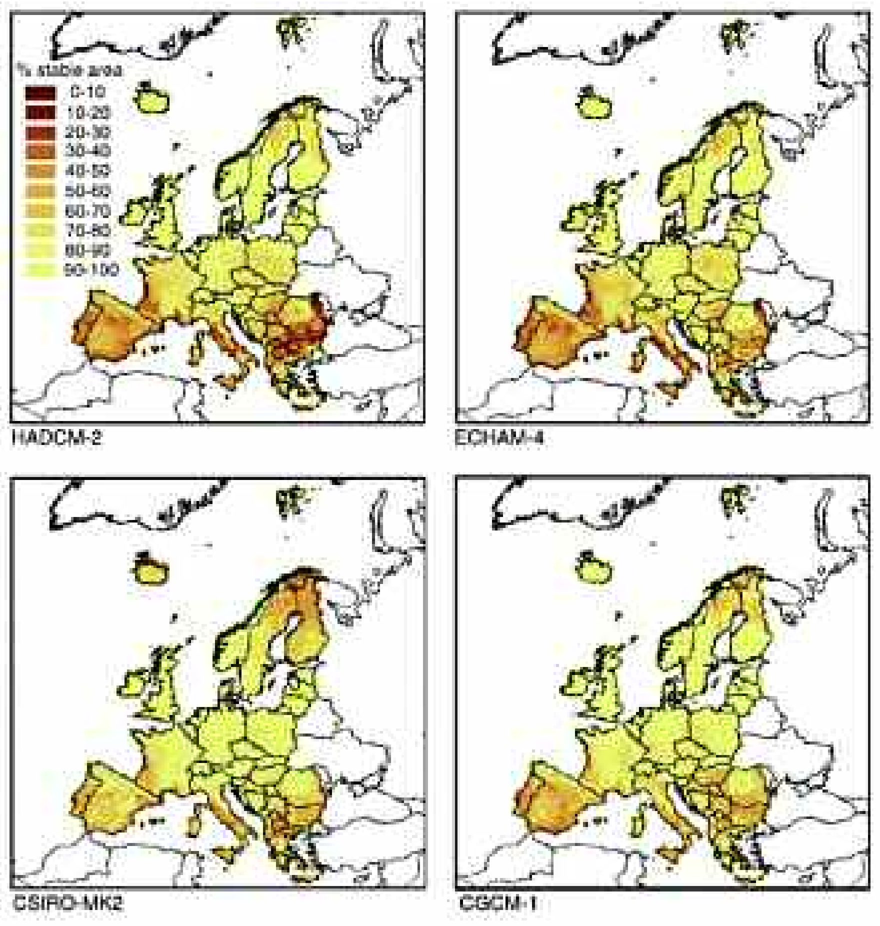

Figure 9. Reprinted with permission after Bakkens *et al.* (2006). Biodiversity changes in Europe by 2100 in the baseline climate scenario (namely with business as usual emissions, Van Vuuren *et al.*, 2003) according to four different Global Circulation Models. For each grid cell, % stable area is defined as the percentage of vascular plant species for which the cell will remain suitable with respect to 1995.

Figure 10. Hotspots of species richness (in green), hotspots of threatened species (in yellow) and hotspots of endemic species (in red). Modified after Orme *et al.* (2005).

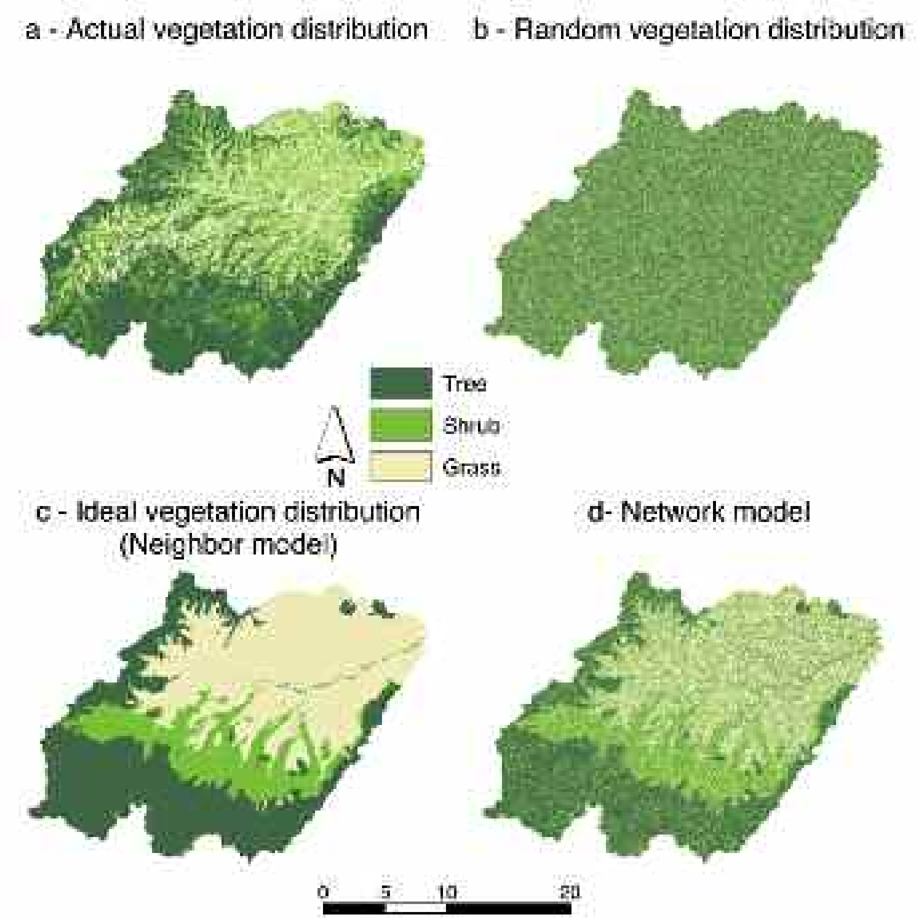

Figure 3. Spatial distribution of land cover within the Rio Salado basin. (a) Actual vegetation distribution in the upper Rio Salado river basin. (b) A random distribution of vegetation representing equal amounts of each land cover type. (c) The pattern of land cover corresponding to an ideal (optimal) pattern that minimizes water stress at each location. (d) A feasibly optimal pattern of vegetation that arises from local optimization within the network flow paths starting from an initially random condition. Scale bar measures distance in kilometers. Figure reproduced with permission from Caylor *et al.* (2004b).

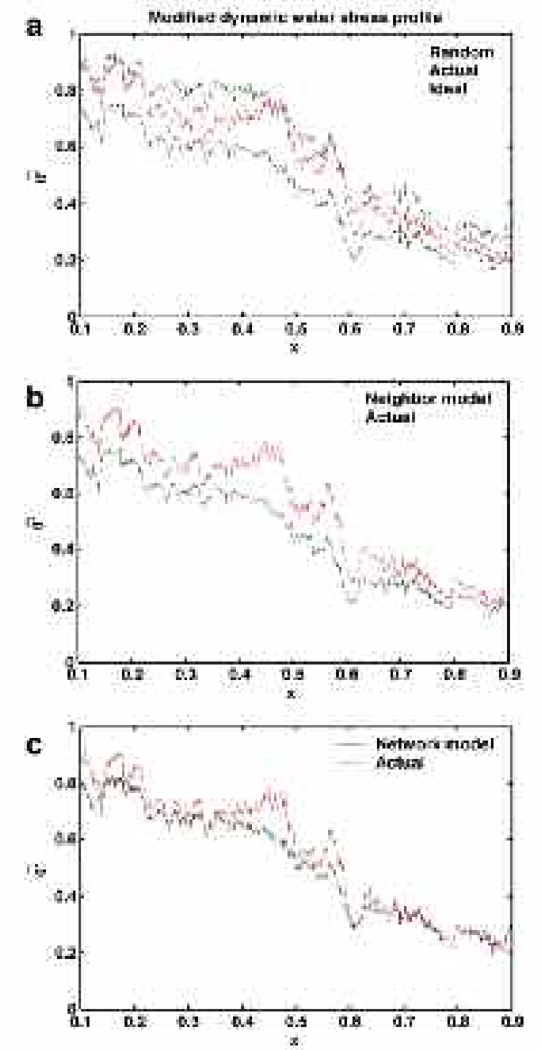

Figure 4. Modified dynamic water stress profiles for the Rio Salado basin, which measures water stress, $\overline{\Theta'}$, in the basin according to the normalized flow path distance from the basin outlet, x. (a) Modified dynamic water stress profile for the actual vegetation pattern (red line), a random vegetation pattern (dashed line) and the optimal vegetation pattern (solid line). (b) Modified dynamic water stress profile for the actual vegetation pattern (red line) and the neighbor model at statistical steady state (solid line). (c) Modified dynamic water stress profile for the actual vegetation pattern (red line) and the network model at statistical steady state (solid line). Figure reproduced with permission from Caylor *et al.* (2004b).

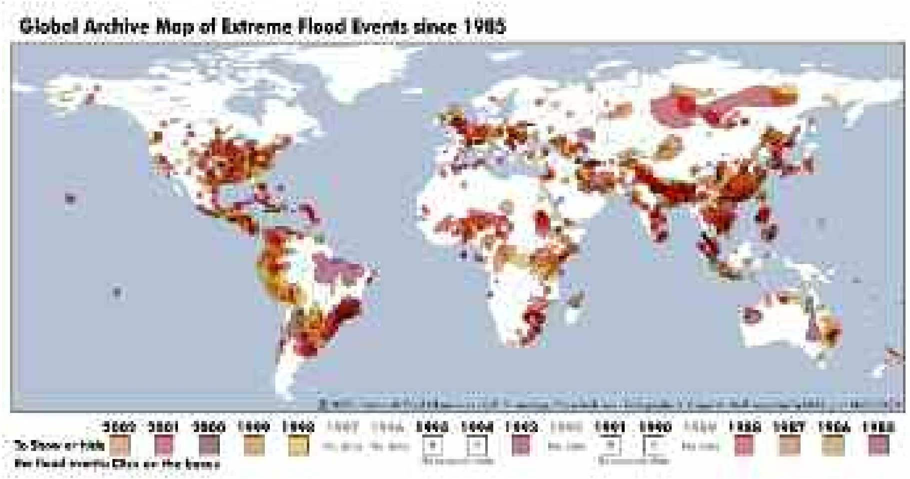

Figure 3. Dartmouth flood observatory mapping of severe floods since 1985. constructed using online application at http://www.dartmouth.edu/~floods/. (Brakenridge *et al.*, 2003).

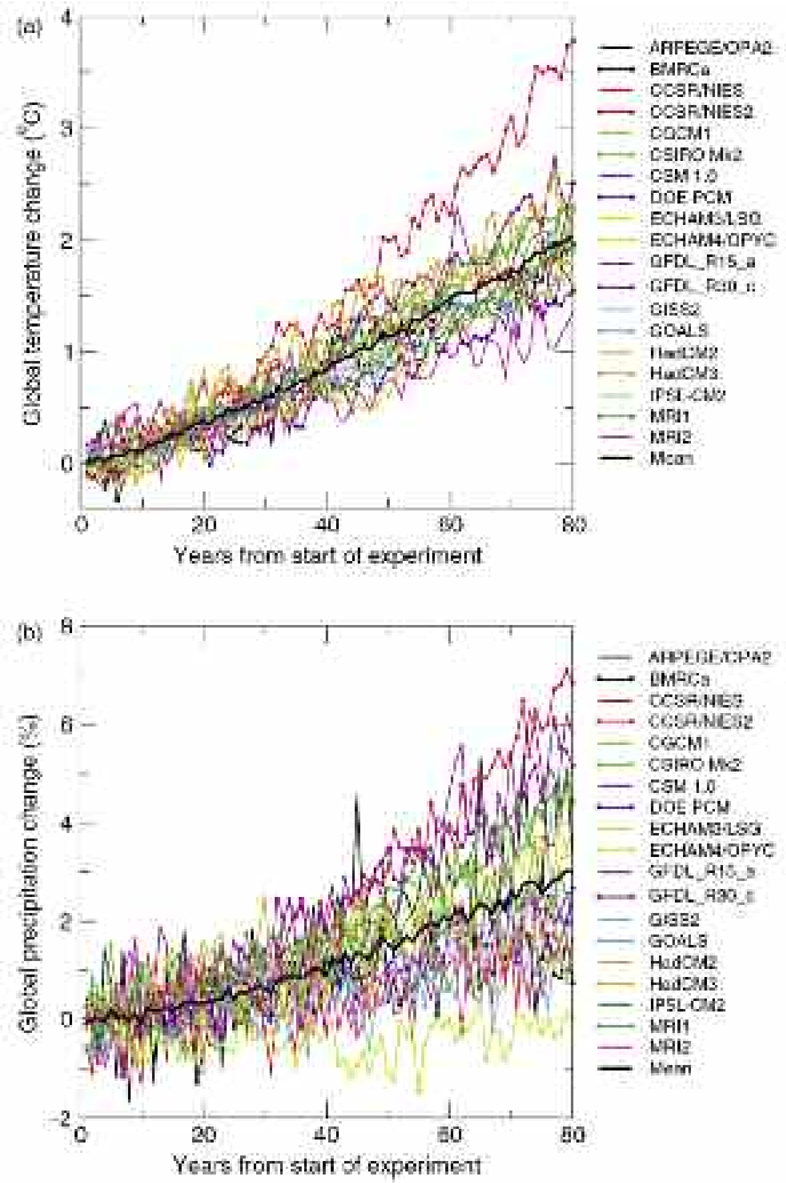

Figure 4. Future climate predictions of temperature (upper panel) and precipitation (lower panel). Notice the wide range of uncertainty in both variables among models and scenarios. (After IPCC, 2001).

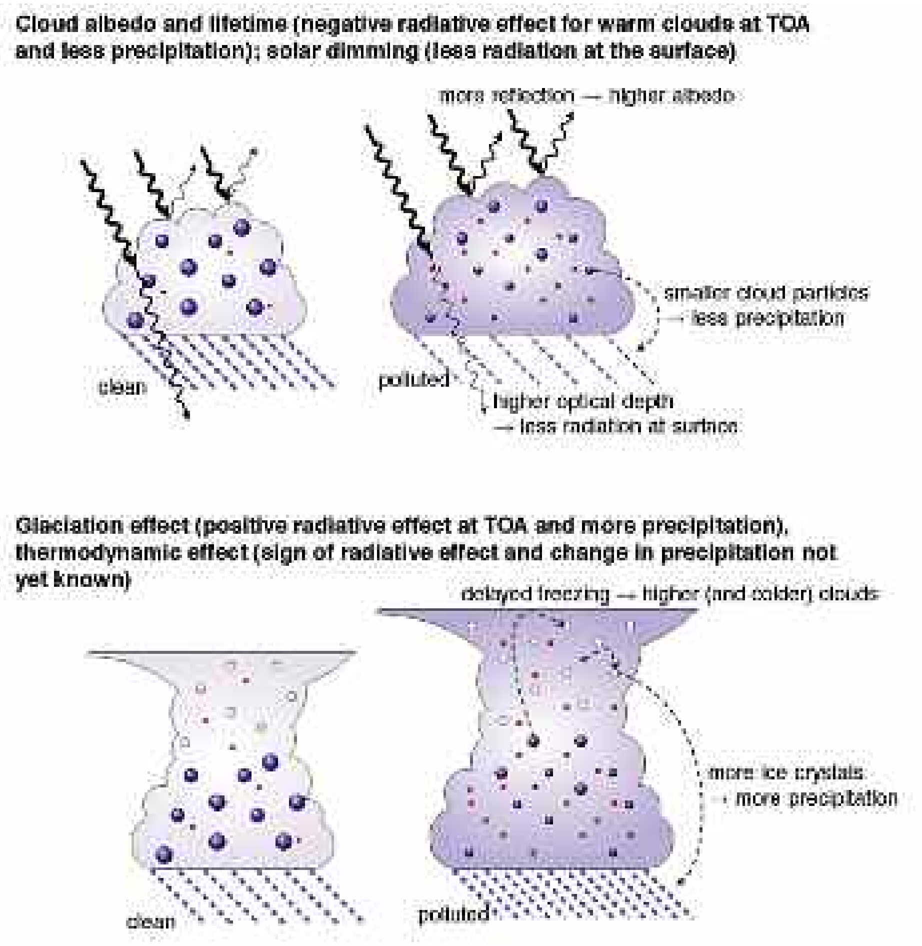

Figure 1. Schematic of the aerosol effects discussed in Table 1 (page 105).

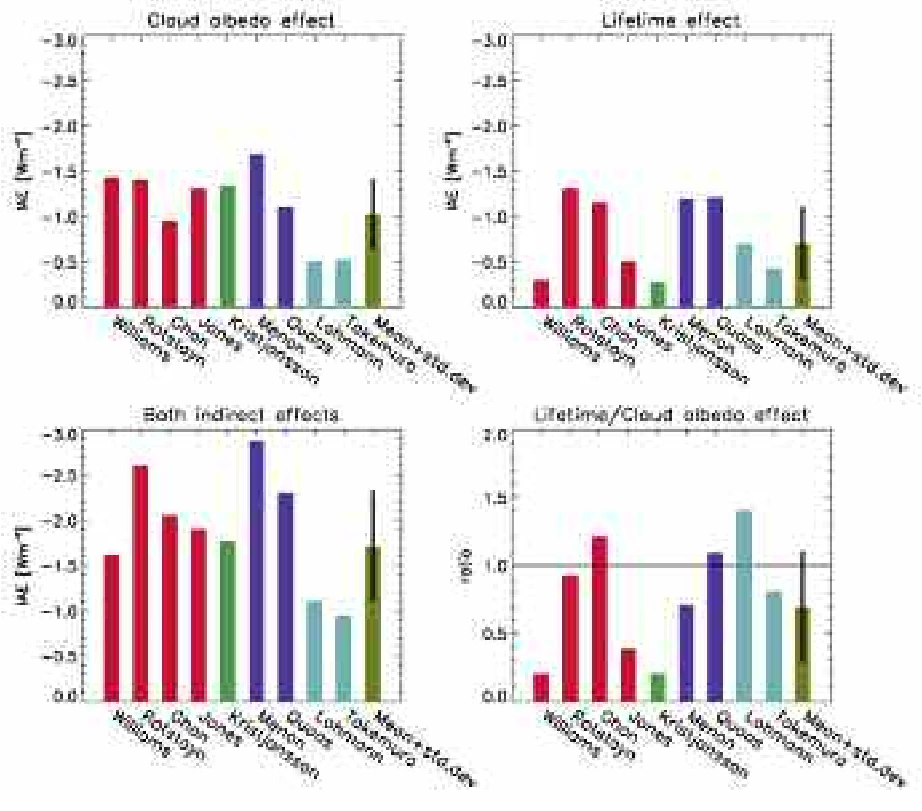

Figure 2. Global mean cloud albedo effect, lifetime effect, both effect and the ratio lifetime effect/cloud albedo effect for different models considering only anthropogenic sulfate aerosols (red bars), of anthropogenic sulfate and black carbon (green bars), of anthropogenic sulfate and organic carbon (blue bars), of anthropogenic sulfate and black, and organic carbon (turquoise bars) and the mean plus standard deviation from all simulations (olive bars), adapted from Lohmann and Feichter (2005).

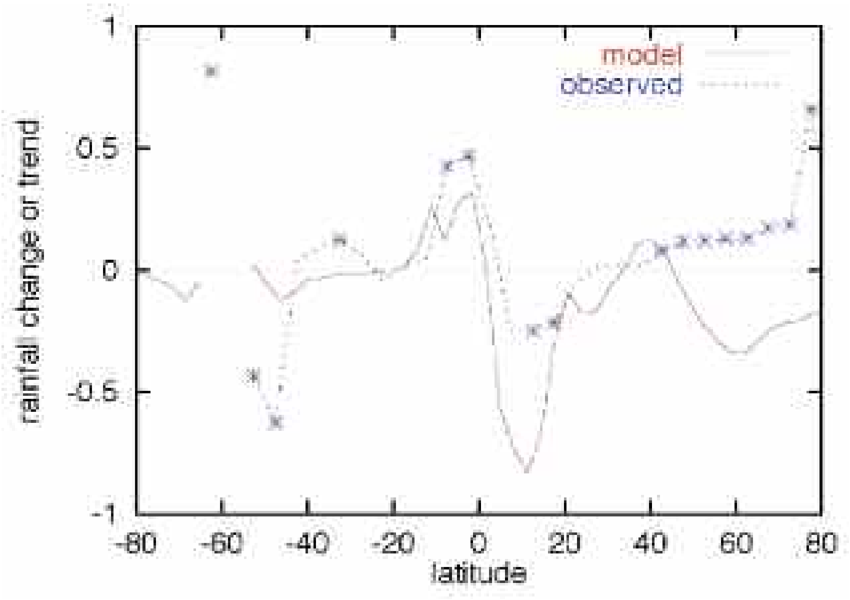

Figure 3. Zonally averaged trend in observed annual-mean precipitation over land for the period 1901-1998 after Hulme *et al*. (1998) in mm day^{-1} per century (blue dotted line) and zonally averaged difference in annual-mean precipitation over land between the present-day and pre-industrial simulations in mm day^{-1} (solid red line). Points at which the observed trend is (is not) significant at the 5% level are shown as asterisks (pluses). Courtesy of Rotstayn and Lohmann (2002).

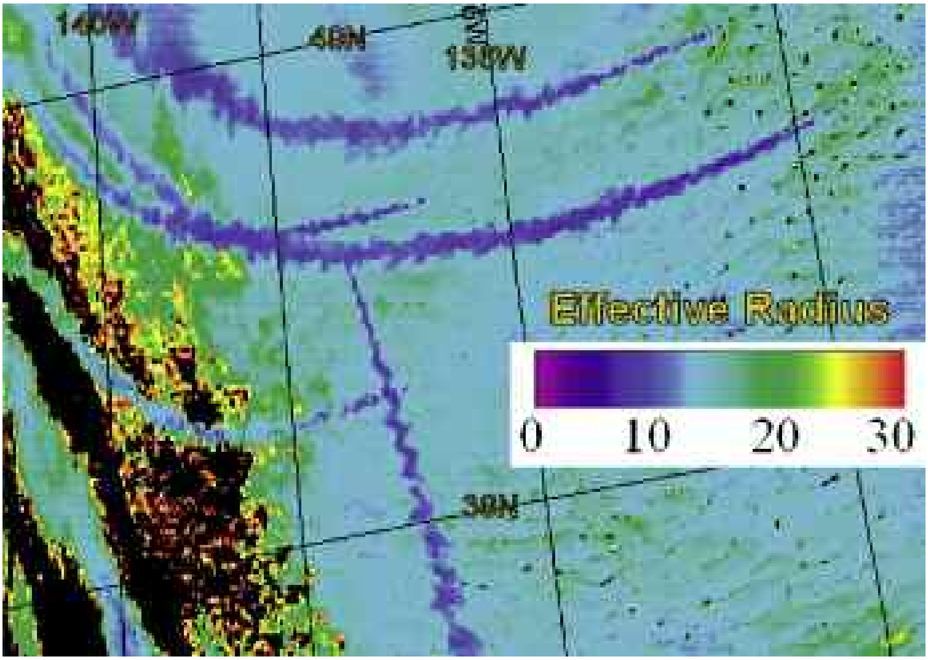

Figure 1: Ship tracks in marine layer clouds, manifested as linear features with reduced cloud drop effective radius. Clouds with effective radius > about 15 µm are partially dissipated due to loss of water by precipitation. The ship tracks are manifested as lines of solid cloud cover with small drops that prevent their dissipation by raining out. From Rosenfeld *et al.* (2006a).

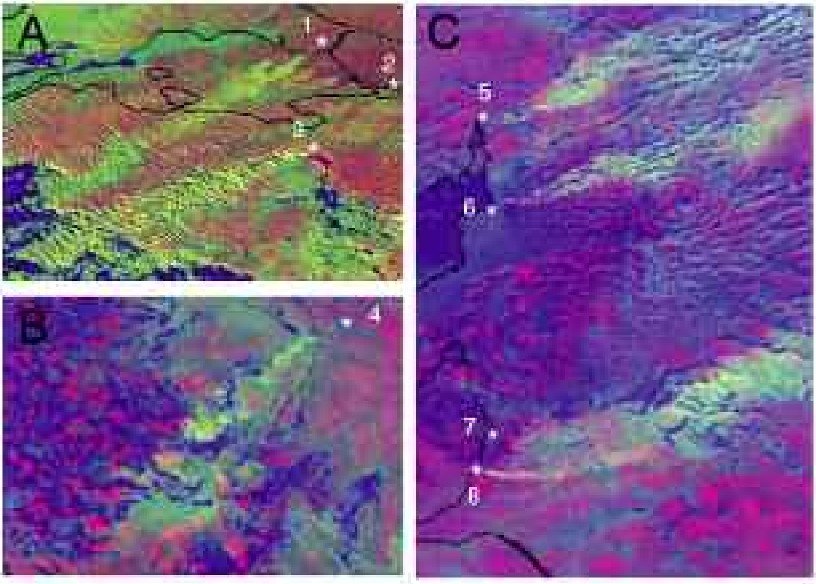

Figure 2. Satellite visualization of NOAA/AVHRR image, showing the microstructure of clouds with streaks of visibly smaller drops due to ingestion of pollution, originating from known pollution sources, marked by white numbered asterisks. The yellow streaks in panel A (about 300×200 km) originate from the urban air pollution of Istanbul (*1), Izmit (*2) and Bursa (*3), on 25 Dec 1998 12:43 UT. Panel B (about 150×100 km) shows the impact of the effluents from the Hudson Bay Mining and Smelting compound at Flin Flon (*4), Manitoba, Canada (54:46N 102:06W), on 4 June 1998 20:19 UT. Panel C (about 350×450 km) shows pollution tracks over South Australia on 12 Aug 1997, 05:26 UT, originating from Port Augusta power plant (*5), Port Pirie lead smelter (*6), Adelaide port (*7) and the oil refineries (*8). All images are oriented with north at the top. The images are color composites, where the red is modulated by the visible channel, blue by the thermal IR, and green is modulated by the solar reflectance component of the 3.7 μm channel, where larger (greener) reflectance means smaller droplets. That determines the color of the clouds, where red represents clouds with large drops, and yellow clouds with small drops. The blue background is the ground surface below the clouds. A full description of the color pallets and their meaning was provided by Rosenfeld and Lensky (1998). From Rosenfeld (2000).

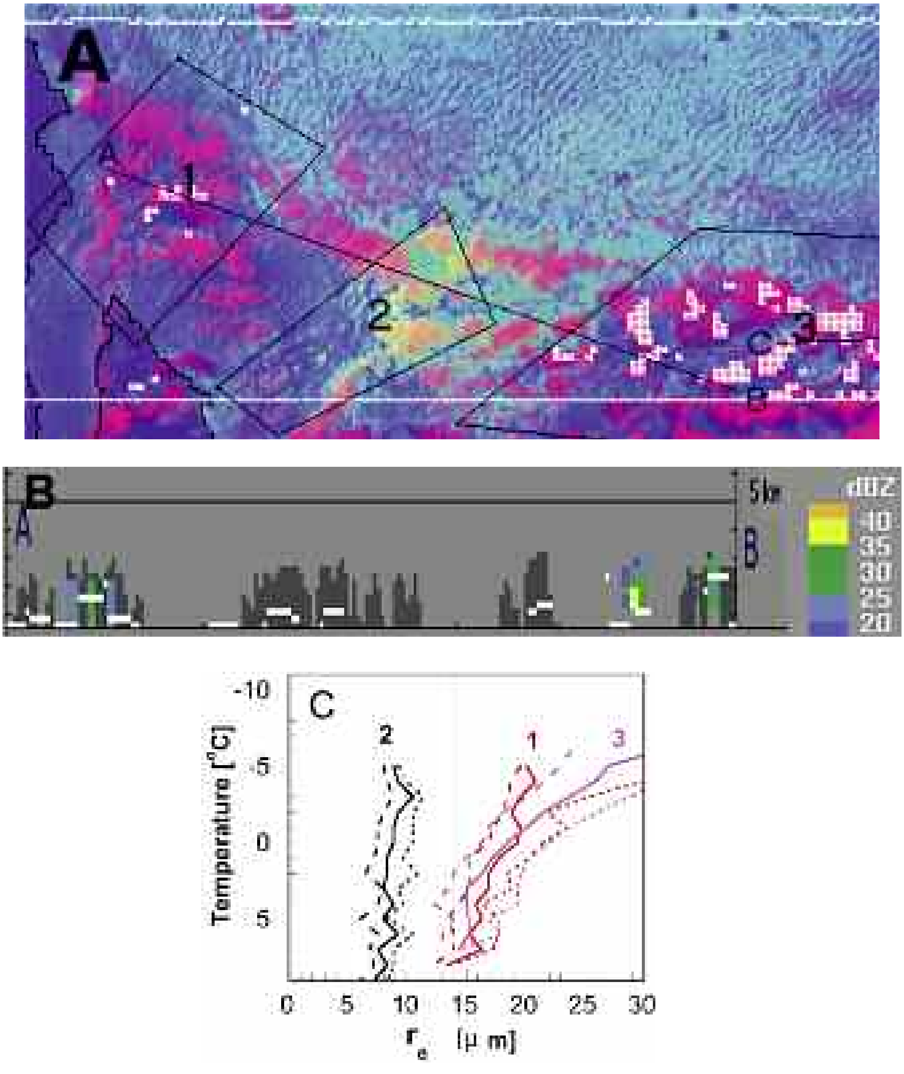

Figure 3 (a) Pollution tracks (yellow) detected by AVHRR satellite imagery in clouds over South Australia. The higher reflectivity is due to reduced droplet sizes. Radar shows precipitation as white patches outside pollution tracks, although these clouds have the same depth as adjacent non-polluted clouds, as shown in the vertical cross section (b). The gray clouds are the silhouettes obtained from the TRMM VIRS. The colors represent the radar echo intensities. No radar echoes occur within the clouds with reduced effective radius in Area 2. (c) Average effective radius of particles (probably water drops) at cloud tops in these regions (1, 2, and 3). The dashed lines represent the 15th and 85th percentiles of the distributions. From Rosenfeld (2000).

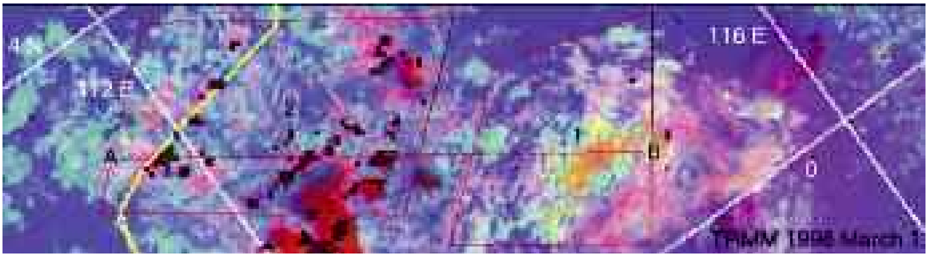

Figure 4. The TRMM VIRS image of fires, smoke and clouds over Kalimantan, Indonesia, from 1 March 1998, 02:50 UT. The color is composed of: red for visible reflectance, green for 3.7 mm reflectance (approximating the cloud drop effective radius, r_e), and blue for the inverse of 10.8 μm brightness temperature. The northwest coast of the island is denoted by the yellow line. The small orange areas on the upper right (east) corner are hot spots indicating the fires. The smoke, streaming from the hot spots south-westward, is indicated by the fuzzy purple color of the background. The smoke-free background is blue. This color scheme (see full detail in Rosenfeld and Lensky, 1998) shows clouds with small droplets ($r_e<10\,\mu$m) as white, becoming yellow at the supercooled temperatures. Clouds with larger droplets ($r_e>15\,\mu$m) are colored pink, and cold ice clouds appear red. The black hatching marks the areas in which the TRMM radar detected precipitation. From Rosenfeld (1999).

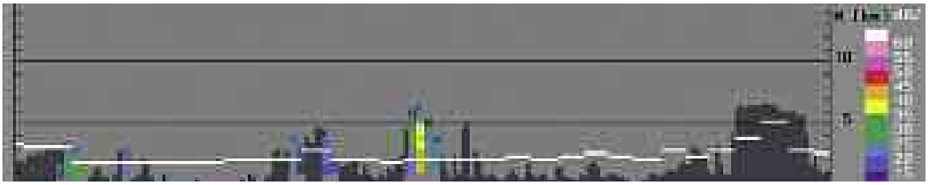

Figure 5. Vertical cross section along the line AB in Fig. 2, where the left end is point A and the right end correspond to point B in Fig. 2. The gray area is the clouds, as measured by their top temperature. The colors represent the precipitation reflectivity, in dBZ, as measured by the TRMM radar. The white line is the brightness temperature of the TRMM Microwave Imager 85 GHz vertical polarization, plotted at the altitude of that temperature. Please note that the 85 GHz brightness temperature and actual cloud top temperature have different physical meaning. From Rosenfeld (1999).

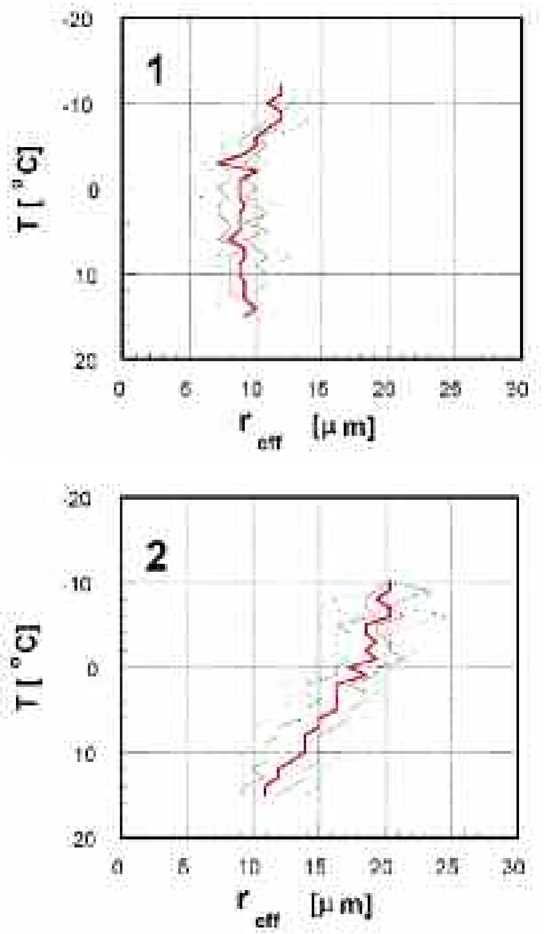

Figure 6. Analysis of the temperature (T) – droplet effective radius (r_e) relationship, for the clouds in the two boxes plotted in Fig. 4, respectively. Area 1 is smokey (on the right of Figure 4, whereas Area 2 is smoke-free. Plotted are the 10% 25% 50% 75% and 90% percentiles of the re for each 1°C interval. The median is indicated by the thick red line. From Rosenfeld (1999).

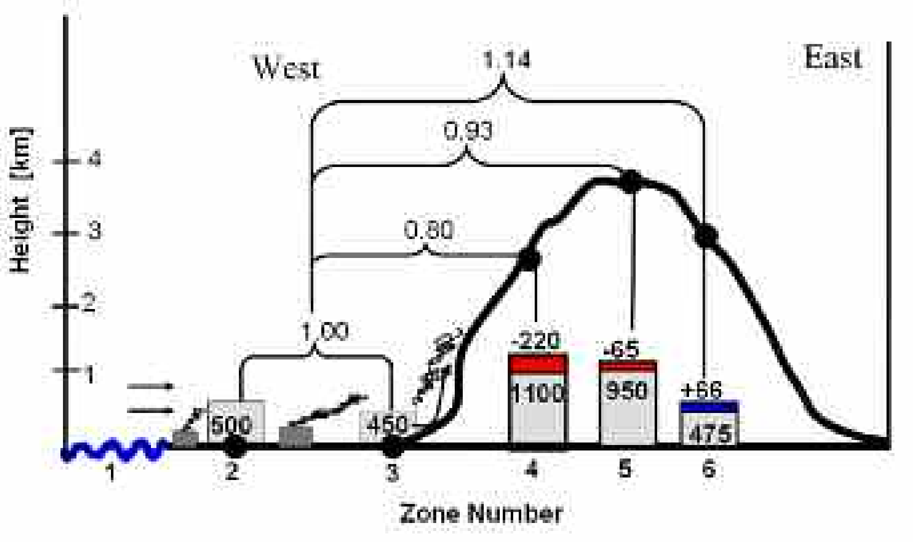

Figure 9. The effects of pollution on rainfall in the Sierra Nevada Mountains in California. The figure is a schematic topographic cross section showing the effects of urban air pollution on precipitation as the clouds move from west to east from the coast to the Sierra Nevada and to the eastern slopes. The boxes show the amount of the annual precipitation (mm yr^{-1}) in each topographic location, and the numbers above them show the loss or gain of precipitation (mm yr^{-1}) at each site. Maritime air (zone 1) is polluted over coastal urban areas (zones 2, 3), with no decrease in precipitation. The polluted air rises over mountains downwind and forms new polluted clouds (zone 4), with decreases of ~15%–20% (losses of 220 mm yr^{-1}) in the ratio between the western slopes and the coastal and plain areas (appears as 0.80 above the line connecting zones 4 and zones 2-3). The clouds reach to the high mountains in zone 5. All of the precipitation is snow, with a slight decrease of ~5%–7% (loss of 65 mm yr^{-1}) in the ratio between the summits and the plain areas (appears as 0.93). The clouds move to the high eastern slopes of the range (zone 6), with an increase of ~14% (gain of 66 mm yr^{-1}) in the ratio between the eastern slopes and the plain (appears as 1.14). From Givati and Rosenfeld (2004).

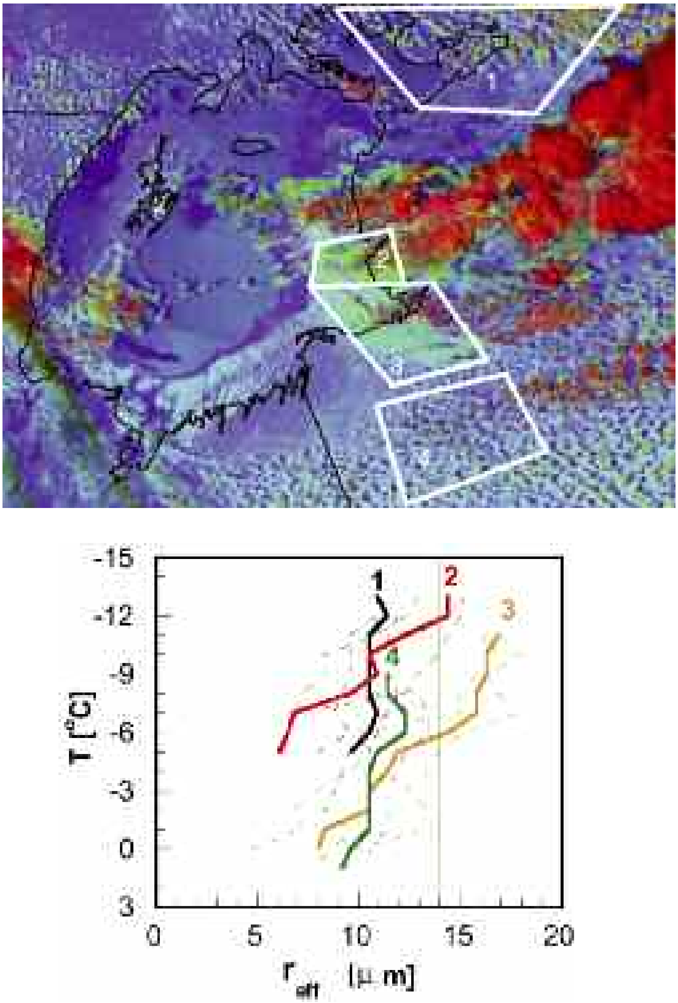

Figure 10. Left: NOAA – AVHRR satellite image (11 May 1998 09:32 UT) showing clouds forming in salt-dust plumes off the eastern shores of the Aral Sea (frames 2 and 3). Clouds outside the dust storm are shown in frames 1 and 4. Right: T-r_e relationship for the clouds in the 4 areas shown in the left panel. T is the temperature and r_e is the cloud particle effective radius. The solid lines show the median r_e for a given T, and the broken lines show the 15th and 85th percentiles. The vertical green line marks the 14-mm precipitation threshold. Curves 2 and 3 for clouds forming in heavy salt-dust show smaller near-cloud-base re and much larger cloud-top r_e compared to background clouds of comparable depths (curves 1 and 4). This analysis shows the fast growth of cloud droplets with height above cloud base. From Rudich *et al.*, (2002).

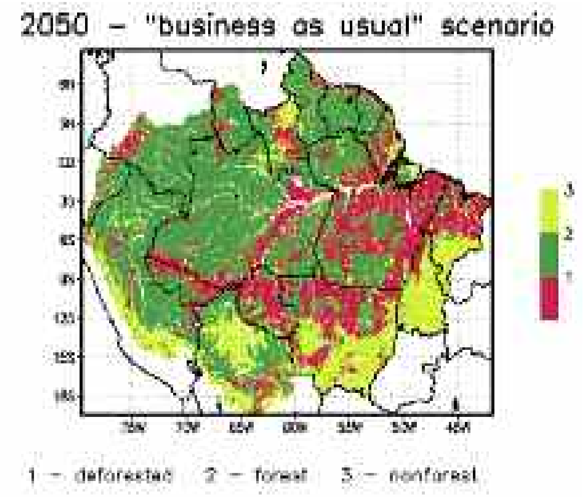

Figure 1. Projected land use change for Amazônia in 2050 for a 'business-as-usual' scenario. Areas in red represent deforestation, in green, forest areas and areas in yellow and white are non-forest (Courtesy of Soares-Filho, Federal University of Minas Gerais, Brazil).

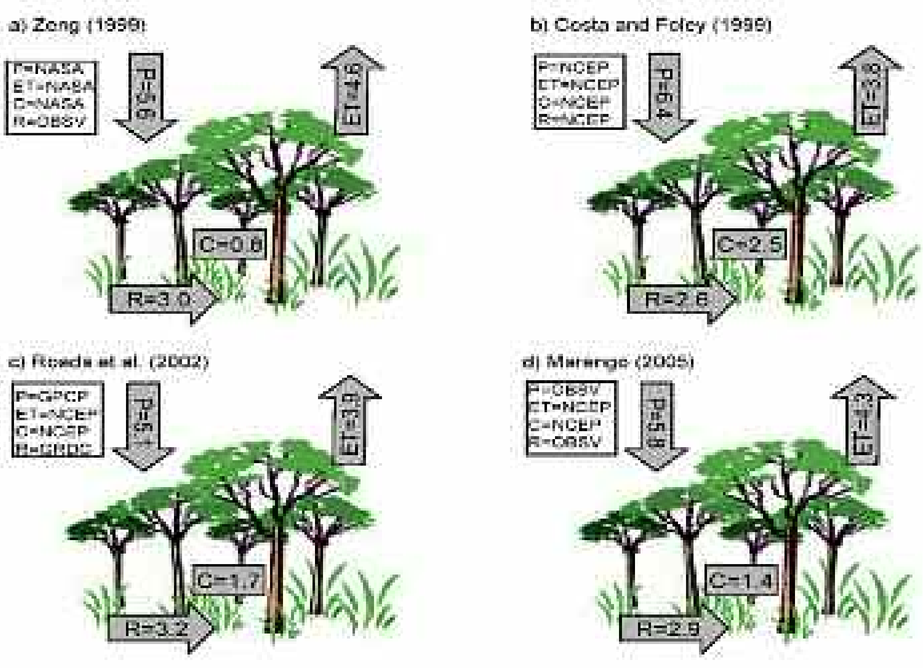

Figure 2. Summary of surface and atmospheric water balance calculations for the Amazon Basin based on four studies: (a) Zeng (1999), (b) Costa e Foley (1999), (c) Roads *et al.* (2000) e (d) Marengo (2005). P = precipitation; E = evapotranspiration; C = atmospheric moisture convergence; R = surface runoff. Units = mm/day (Marengo *et al.*, 2006).

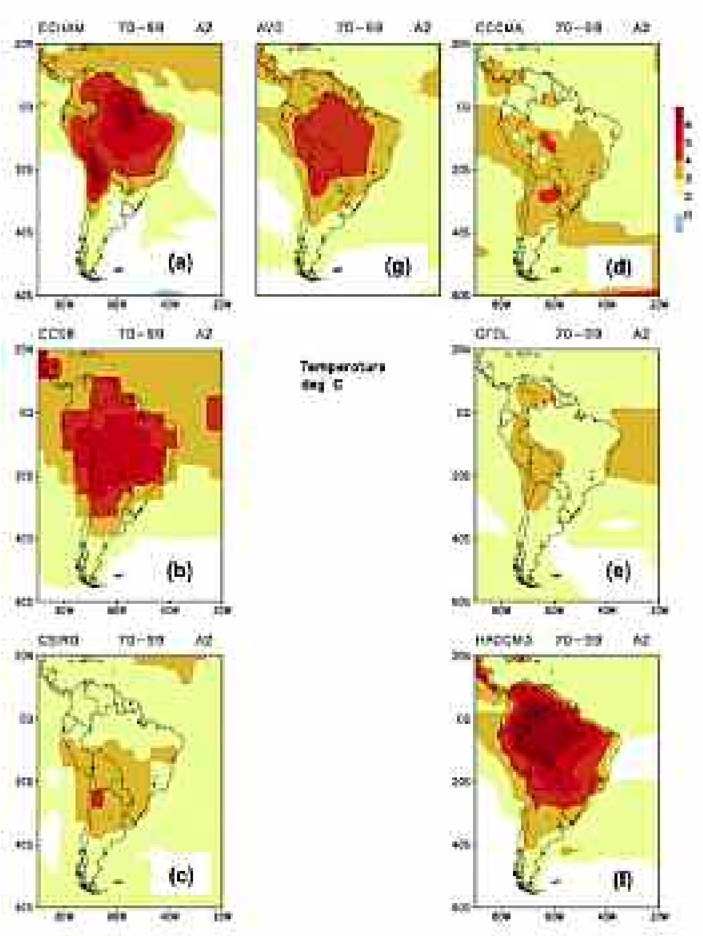

Figure 3. Climate change projections for 2070-2099 of surface temperature anomalies (C) for 6 Global Climate Models (a-f) (with respect to each model's average temperature for the base period 1961-1990) for emissions scenario A2. The top, center panel (g) shows the average of the 6 model anomalies for the same period (Nobre *at al.*, 2005).

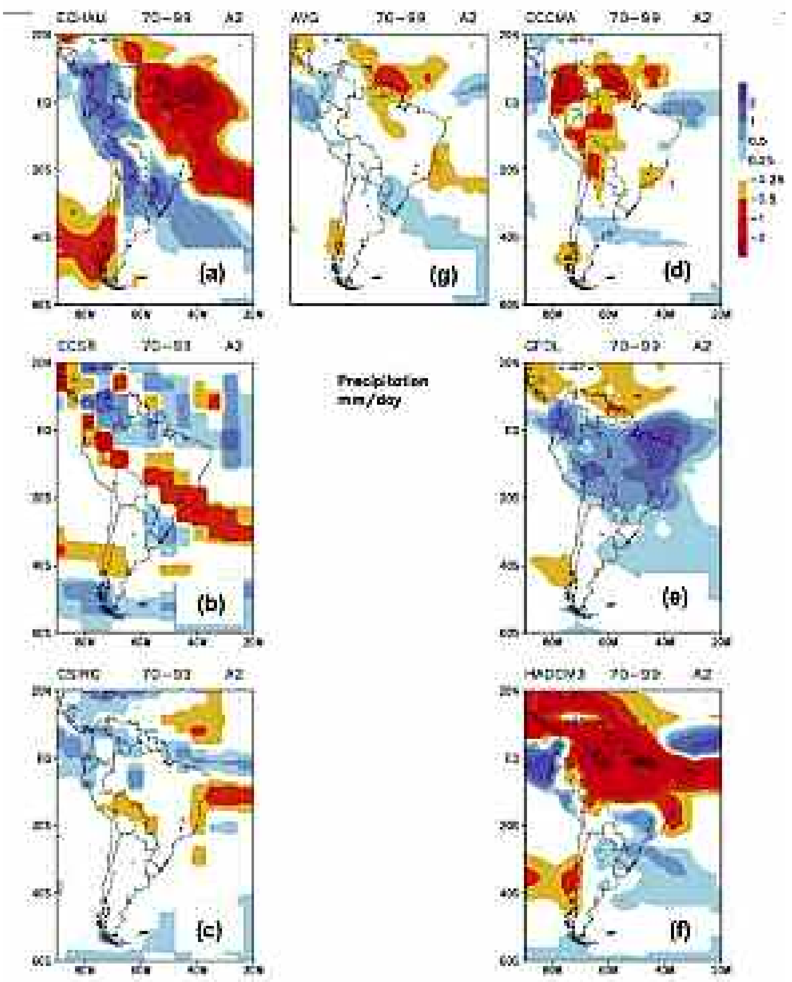

Figure 4. Climate change projections for 2070-2099 of precipitation anomalies (mm/day) for 6 Global Climate Models (a-f) (with respect to each model's average precipitation for the base period 1961-1990) for emissions scenario A2. The top, center panel (g) shows the average of the 6 model anomalies for the same period (Nobre *at al.*, 2005).

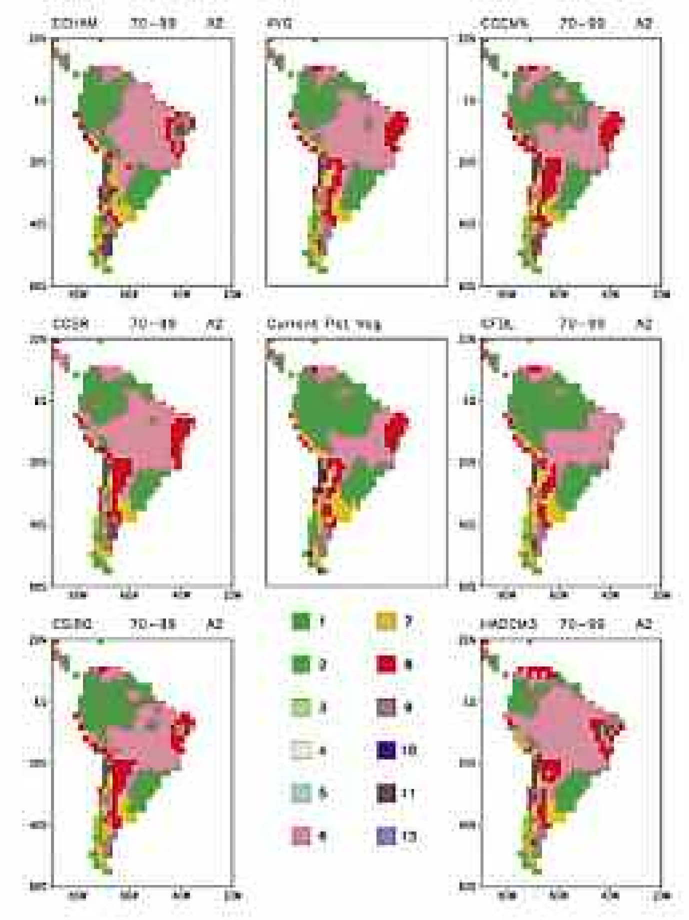

Figure 5. Projected distribution of natural biomes in South America for 2070-2099 based on the climate scenarios of Figures 3 and 4 from 6 Global Climate Models for the A2 emissions scenarios. The calculations of the biomes in equilibrium with the new climate were carried out with the use of CPTEC Potential Vegetation Model (PVM). PVM associates the main world's biomes to 5 climate variables, derived from monthly distribution of surface air temperature and precipitation. The main biomes for South America are represented by the following color code: green = tropical forest; pink = savanna; red = dry shrubland; yellow = extratropical grasslands; light brown = semi-desert; dark brown = desert; light green = deciduous Forest. The center panel labeled 'current pot veg' represents the natural biomes in equilibrium with the current climate. Notice that they represent the potential biomes, but not the actual vegetation distribution, which is a result of historical land use and land cover change. The upper, central panel labeled 'avg' represents the projected biome distributions for the averaged temperature and precipitation scenarios of Figures 3 and 4, respectively.

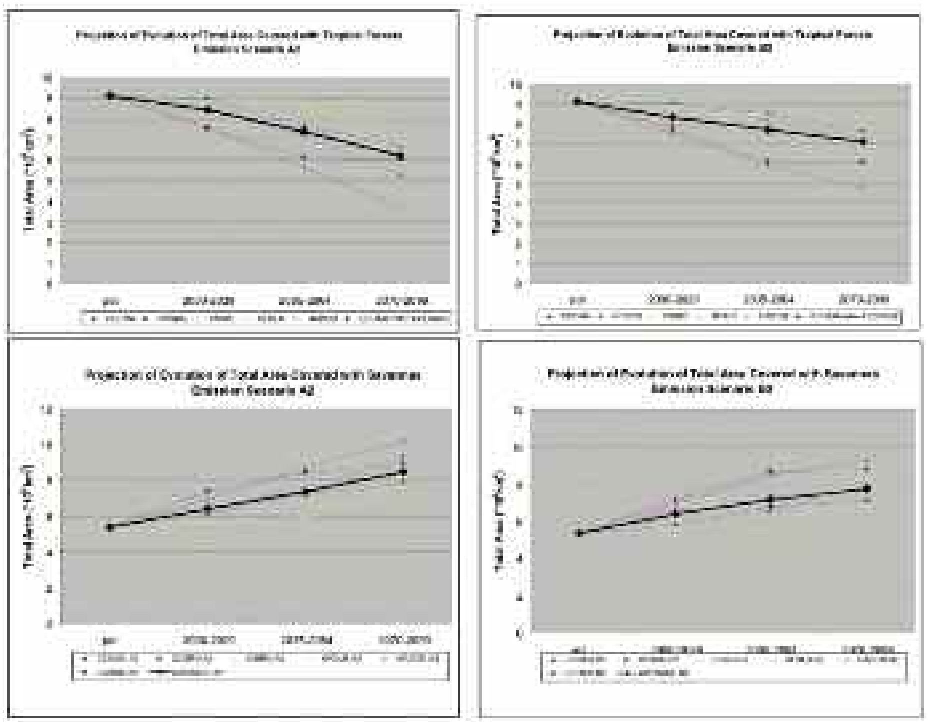

Figure 6. Projections of evolution of total area (in million km^2) covered with tropical forests (upper panels) and savannas (lower panels) for the period 2000 through 2100 for two emissions scenarios (left-hand panels for A2 and right-hand panels for B2). The black line represents the average for the 6 different projections.

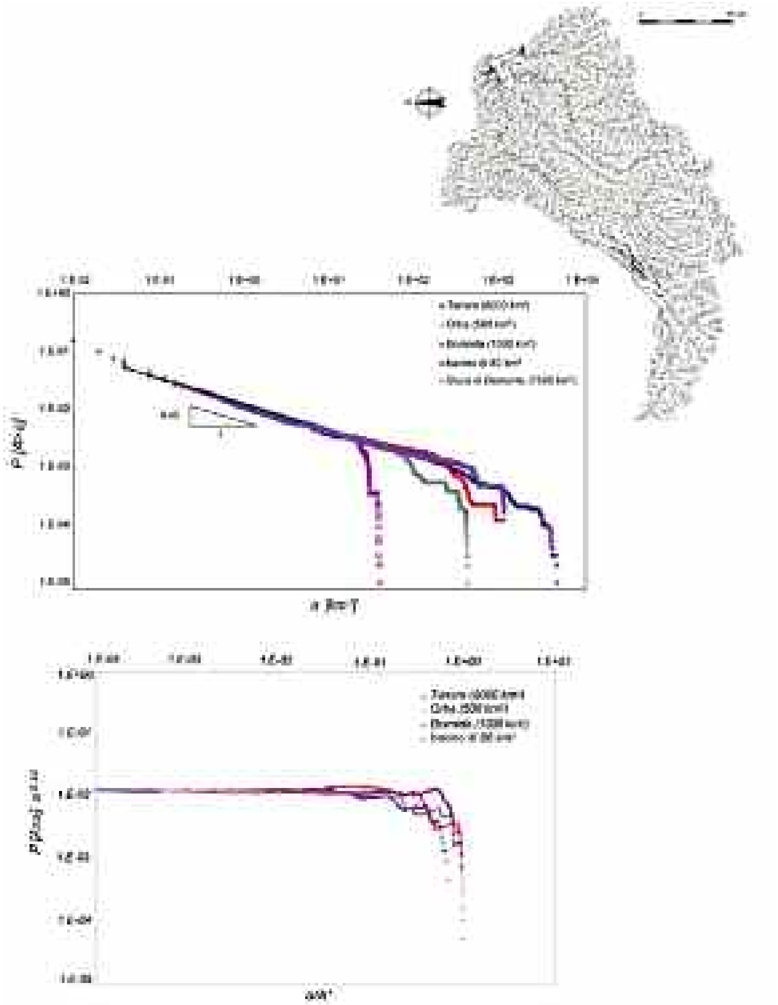

Figure 5. Power-law distribution of total cumulative area (top left) for the 8000 km^2 Tanaro river basin (top right). Here the cumulative distribution $P(A \varnothing a) \sim a^{g-1}$ (which, of course, implies that the pdf scales like a power law with exponent g) is computed for 4 subbasins of different maximum size A* (Tanaro, 8000 km^2; Orba, 500 km^2; Bormida 1300 km^2; and a small unnamed basin, 80 km^2). The similarity of the basins insure that in the range of areas where no cutoff effect is perceived, one obtains a remarkably coherent estimate of g~0.45. The distributions collapse into a single curve, however, once plotted as $P(A \varnothing a)\ a^{0.45}$ vs a/A* (bottom). This suggests a finite-size scaling ansatz for the area distribution, and a strong empirical proof of self-similarity of form in the river basin. Needless to say, the above observation is confirmed by ubiquitous empirical evidence regardless of geology, climate, vegetation and exposed lithology (Rodríguez-Iturbe and Rinaldo, 1997).

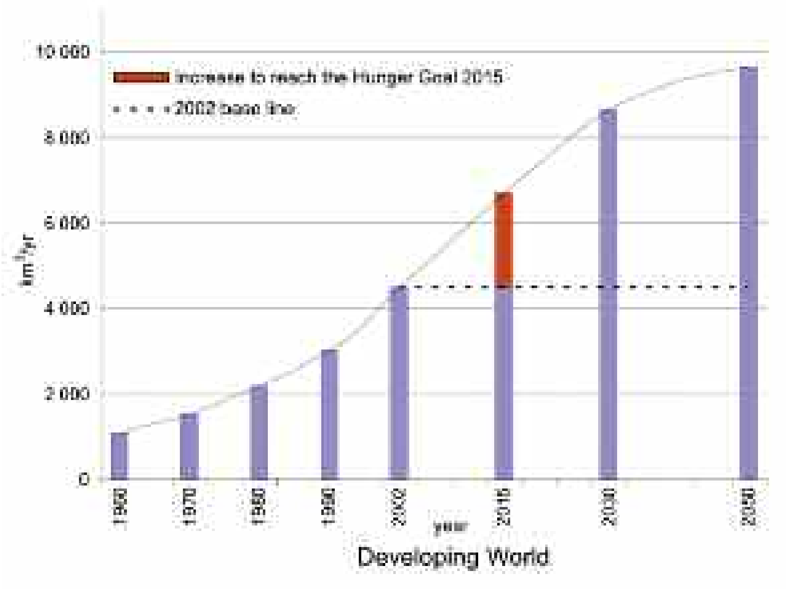

Figure 2. Consumptive water use for food production in 92 developing countries 1960 to 2002 and future requirement to fulfill the Hunger Goal Target 2015 of halving the number of undernourished and to eradicate hunger 2030 and 2050. From SEI 2005.

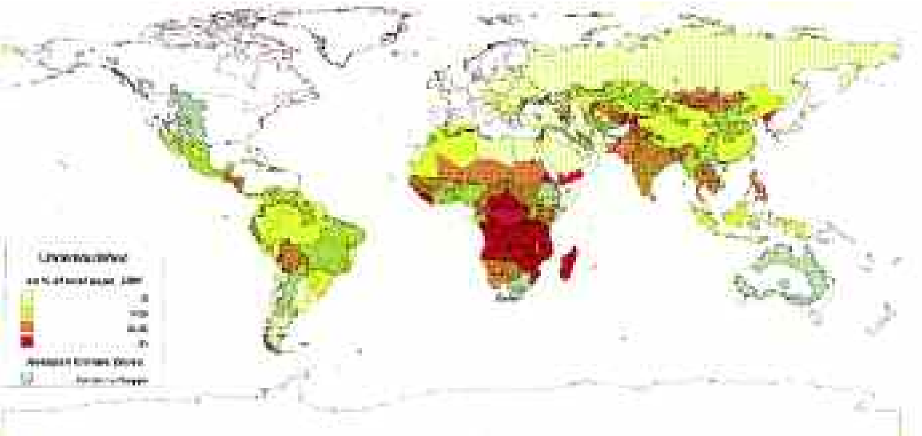

Figure 3. Most of the poor countries with large hunger eradication challenges are located in the zone with savanna and steppe type hydroclimate. From SEI 2005.