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WORLDWIDE CHANGES IN EVAPORATIVE DEMAND

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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 $\approx$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.

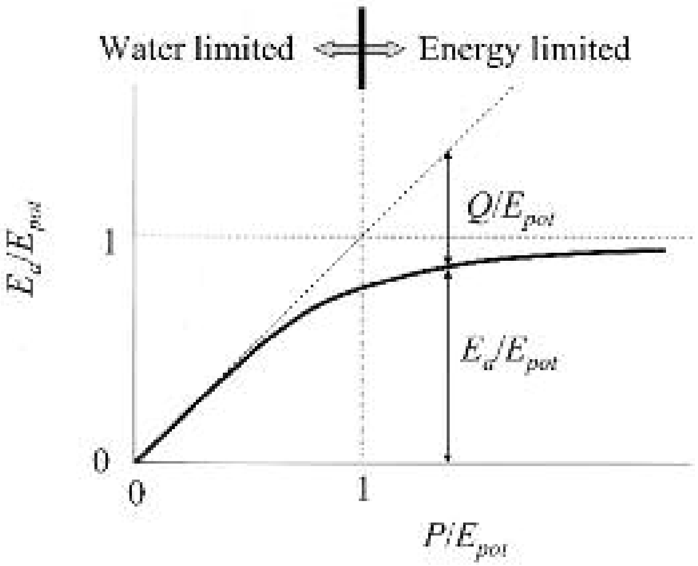

Figure 1. Inter-relationship between annual average precipitation (P), actual (E_a) and potential (E_{pot}) evaporation and runoff (Q). The full curve is known as the Budyko curve (Budyko, 1974).

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 $\approx$ -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 ($E_{\text{pan,R}}$) 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 $E_{\text{pan,A}}$. In short, Penman's combination equation is,

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

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.

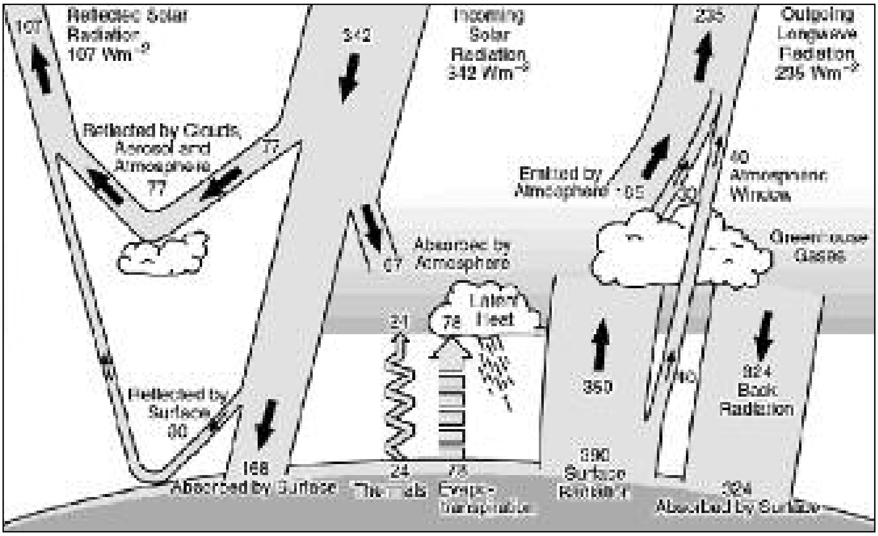

Figure 2. The Earth's annual and global mean energy balance. Source: Kiehl & Trenberth 1997 (and IPCC).

[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 $235/231 \times 519 = 528$ 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 $dF/dT = 5.4$ 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 $1.3/(1-0.4- \beta_{other})$, and for $\beta_{other}=0.1$, say, this would mean a 2.6 K 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 back-ground 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.

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