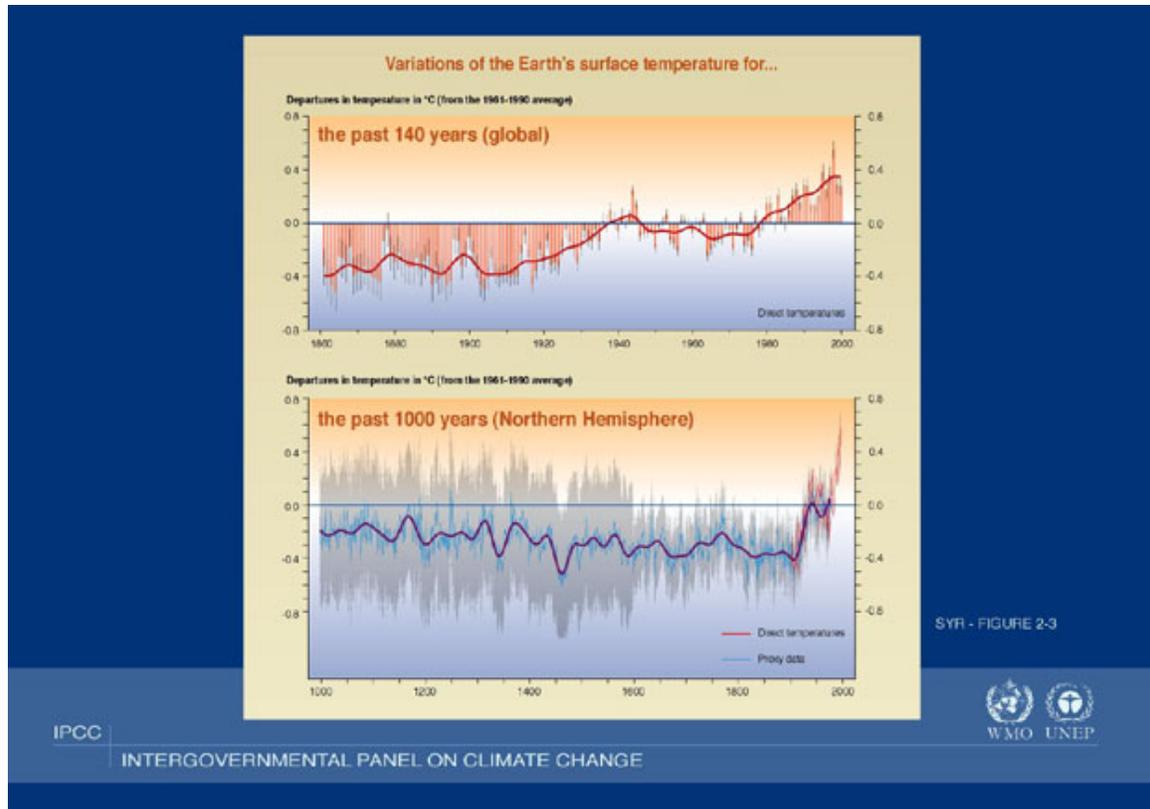


## Global warming and the acceleration of the hydrological cycle

### 1. Introduction

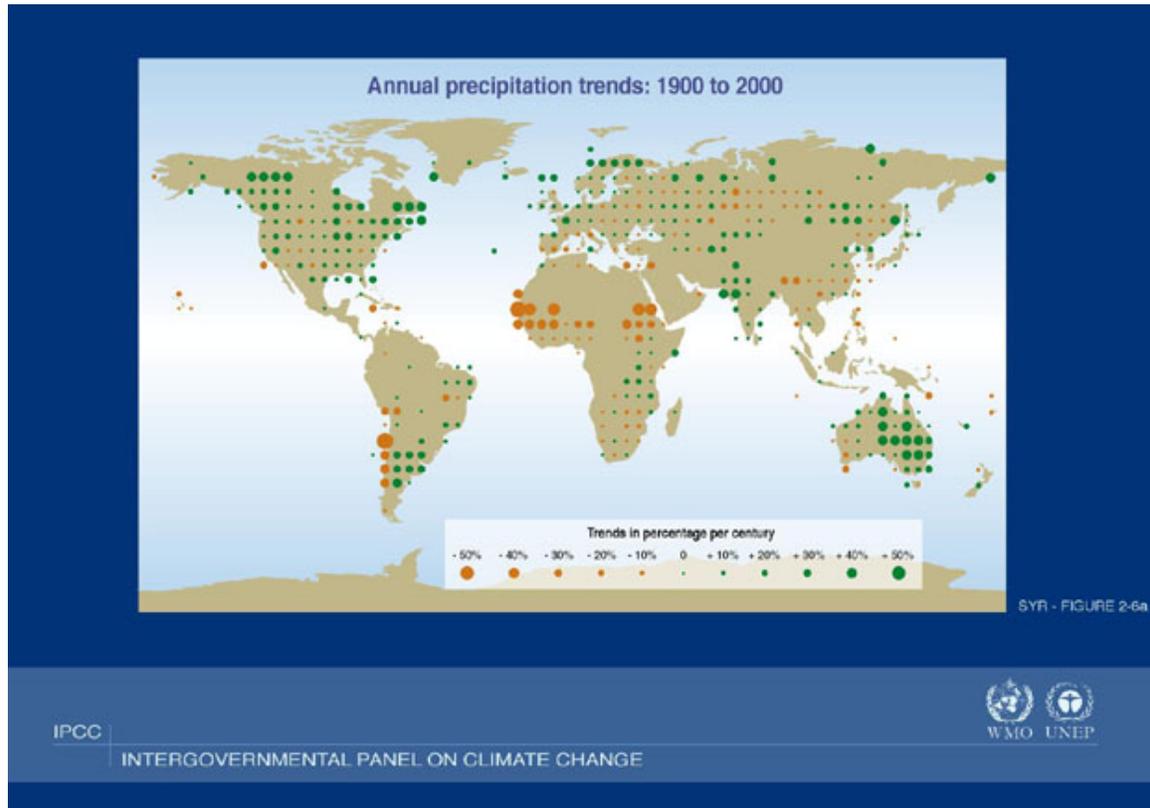
There is increasing evidence that the Earth's global-averaged surface air temperature has increased since the mid 19<sup>th</sup> century and that the rate and duration of warming of the 20<sup>th</sup> century has been much greater than in any of the previous nine centuries (Figure 1, IPCC TAR, 2001).



**Figure 1:** Variations of the Earth's surface temperature for the past 140 years (global) and the past 1000 years (Northern hemisphere) (*source: IPCC TAR, 2001*)

The climate of Earth and its global-averaged surface air temperature are the consequence of a balance between the amount of solar radiation absorbed by Earth's surface and atmosphere, and the amount of outgoing long-wave radiation emitted at the top of the atmosphere (TOA) (Charlson *et al.*, 2005). The buildup of greenhouse gases (GHG) during the past century has been held responsible for this global warming through an increased absorption of infrared radiation in the atmosphere. Changes in the energy balance of Earth are likely to affect other climatic factors besides temperature as well, such as precipitation (Figure 2) and evaporation. Therefore, a potential consequence of global warming is the acceleration of the hydrological cycle, which may manifest itself in the form of increased precipitation and land evaporation (Stocker and Raible, 2005). The

effects on the environment and society in terms of changes to hydrological extremes (e.g. floods and droughts) is unknown but potentially large and damaging.



**Figure 2:** Annual precipitation trends for the period 1900-2000 (*source: IPCC TAR, 2001*)

In this chapter we review our current empirical knowledge of the effects of climate change on the terrestrial water cycle over large areas. At the land surface the water balance can be written as:

$$\frac{dS}{dt} = P - E - R \quad (1)$$

where  $S$  is moisture storage,  $P$  is precipitation,  $E$  is evapotranspiration and  $R$  is net runoff (including surface and subsurface lateral redistribution of water in the landscape). Equation (1) is scale-invariant and can thus be applied for any spatial and/or temporal scale. At the river basin scale, the terrestrial water balance can be expressed as (*Peixoto and Oort, 1992*):

$$\left\langle \frac{\partial S}{\partial t} \right\rangle = \langle \overline{P - E} \rangle - \langle \overline{R} \rangle \quad (2)$$

The brackets  $\langle \rangle$  indicate the space average over the catchment, and the overbar denotes a temporal average (e.g. monthly means). In a similar fashion we can develop a vertically integrated atmospheric water balance equation applicable at the river basin scale:

$$\left\langle \frac{\partial \bar{W}}{\partial t} \right\rangle = \left\langle \overline{E - P} \right\rangle - \left\langle \nabla_H \cdot \bar{Q} \right\rangle \quad (3)$$

where the lhs represents the rate of change in atmospheric water storage, and the rhs terms are, respectively, the effective evaporation into the atmosphere, and the atmospheric horizontal water vapor flux divergence. Combining equation (2) and (3) leads to an alternative formulation of the terrestrial water balance:

$$\left\langle \frac{\partial \bar{S}}{\partial t} \right\rangle = - \left\langle \frac{\partial \bar{W}}{\partial t} \right\rangle - \left\langle \nabla_H \cdot \bar{Q} \right\rangle - \left\langle \bar{R} \right\rangle \quad (4)$$

Equation (4) shows how terrestrial water storage changes and runoff are coupled to atmospheric water storage changes (usually a small fraction of terrestrial storage dynamics) and large-scale circulation patterns of the atmosphere.

This terrestrial water balance is driven by the Earth's surface energy balance:

$$R_n = H + \lambda E + G \quad (5)$$

which in its turn is affected by the Earth's atmosphere energy balance. In (5),  $R_n$  is the net radiation,  $H$  is the sensible heat flux,  $\lambda E$  is the latent heat flux ( $\lambda$  is latent heat of vaporization), and  $G$  is ground heat flux. Over longer periods of time, the latter term becomes small compared to the other terms and can be safely neglected in the balance equation.

In the following we present an overview of recent literature reporting observational evidence of variations in solar radiation at Earth's surface and changes in the terrestrial water balance (evaporation, precipitation, runoff, and soil moisture storage), in an attempt to understand and quantify the effects of Earth's energy balance change on the terrestrial water balance.

## 2. Trends in land surface radiation and Earth's albedo

Widespread measurements of solar radiation at the land surface began in the late 1950s (*Wild et al.*, 2005). Several studies have reported a decline in solar radiation at land surfaces from the beginning of the measurements until 1990, a phenomenon known as global dimming (e.g. *Gilgen et al.*, 1998; *Liepert*, 2002). The largest decrease was found in observations in parts of the former Soviet Union (*Russak*, 1990), but also data from Europe, the US and China show significant reduction (*Pinker et al.*, 2005; *Liu et al.*, 2004). These trends are associated with the effect of cloud cover and aerosols on solar radiation. Aerosols increase the reflection of short-wave radiation to space, whereas their

effect on long-wave radiation is relatively minor (*Ramanathan et al.*, 2001). Aerosols also absorb solar radiation which further enhances the reduction in solar radiation absorbed by the Earth's surface. From space, the planet thus seems to be more absorptive, i.e. darker in the IR (due to GHG) and brighter in the visible wavelengths, during the period 1960-1990.

Aerosols have, besides the direct effect described above, also indirect effects on climate through their important role in cloud condensation and as ice nuclei. Increase in aerosols cause an increase in the droplet number concentration. The increase in the number of drops leads to an increase in the reflection to space of solar radiation from clouds (albedo changes). This is known as the first indirect radiative forcing (change in the radiation budget). If the condensed moisture inside the cloud is not altered by the increase in aerosols, the droplet radius will decrease resulting in a decrease in the precipitation efficiency. It can lead to an increase in cloud lifetime and in turn in the amount of clouds. The increase in cloudiness will lead to a further increase in the reflection of solar radiation, giving rise to the so-called second indirect radiative forcing (*Ramanathan et al.*, 2001).

Unlike the long-lived and uniformly distributed greenhouse gases, aerosol lifetimes are only a week or less, resulting in substantial spatial and temporal variations with peak concentrations near the source (*Ramanathan et al.*, 2001). As the competing effects of GHGs and aerosols on climate and the hydrological cycle depend on spatial and temporal scales, the cooling effect of aerosols could regionally exceed the global surface warming due to GHGs. This could be a key control on the observability of the regional effects of GHG-induced climate change on the hydrological cycle.

Newly available surface observations of solar radiation at Earth's surface from 1990 to the present show that the dimming does not persist into the 1990s (*Wild et al.*, 2005; *Pinker et al.*, 2005; *Liu et al.*, 2004). Instead, a widespread brightening has been observed since the late 1980s. This is found when considering the entire data set, as well as when analyzing only clear-sky conditions, pointing to an interplay of diminishing direct and indirect aerosol effects, possibly related to more effective clean-air regulations and, for the European area, the collapse of the Eastern European countries economy. The absence of dimming since the mid-1980s may profoundly affect climate and the hydrological cycle, as the increase in down-welling long-wave energy from the enhanced greenhouse effect may no longer be counterbalanced by the decline in solar energy at the land surface.

The fraction of the total solar radiation absorbed at Earth's surface is function of the albedo of Earth. Measurements from space since the 1970s estimate the global annual Earth albedo at  $\sim 0.29$ . The average incident solar radiative flux is  $340 \text{ Wm}^{-2}$ , so that a change in albedo of 0.01 (1%) represents a global energy balance change of  $3.4 \text{ Wm}^{-2}$ , similar in magnitude to the impact of doubling carbon dioxide in the atmosphere (*Wielicki et al.*, 2005). Based on observations (that cover the entire Earth and the entire solar spectrum from 0.3- to  $4\text{-}\mu\text{m}$ ) from 2000 to 2003 with the broadband CERES (Clouds and the Earth's Radiant Energy System) instruments from the NASA Terra

spacecraft, *Wielicki et al.* (2005) found that Earth's albedo has decreased by 0.006, resulting in a small decrease of  $\sim 2 \text{ Wm}^{-2}$  in shortwave reflected flux. These findings are very different from those reported by *Pallé et al.* (2004) who found a large increase in albedo of 0.017 between 2001 and 2003, with a corresponding increase of  $\sim 6 \text{ Wm}^{-2}$  in shortwave reflected flux. Their results are based on earthshine measurements and are primarily for visible wavelengths and represent about half of Earth's surface. Earthshine is light reflected by Earth's sunlit hemisphere towards the Moon, and then reflected from the lunar surface. Both studies therefore are difficult to compare, since they use different wavelengths to determine albedo and have different spatial coverage. If the first findings are correct and the albedo changes are related to land use changes, aerosols and snow and ice cover, than the decreasing albedo will warm the Earth. If the latter report is correct a global cooling twice the level of the  $\sim 0.25^\circ\text{C}$  of the Pinatubo eruption would be expected, even over short time periods. For further discussion we refer to the papers by *Pallé et al.* (2004) and *Wielicki et al.* (2005).

### 3. Trends in precipitation

The global mean value of precipitable water (column-integrated water vapor amount) is about 1 inch or 25 mm. The efficiency of rainfall mechanisms in drying the air is about 30%, leaving behind air with 70% relative humidity after a rain storm. So about 7.5 mm of the precipitable water is available for precipitation. The global average precipitation rate (including non-rainy days) is about  $2.8 \text{ mm day}^{-1}$ , which is also the global evaporation rate. The average rain rate when it rains is much higher, about  $45 \text{ mm day}^{-1}$ . So the moisture supply for most storms does not come directly from local evaporation, but has to be transported towards the region (convergence of low-level moisture from elsewhere in the atmosphere). It is therefore important to accurately measure and track moisture availability in the atmosphere to understand the link between how precipitation changes as the climate changes (*Trenberth et al.*, 2003).

Atmospheric moisture amounts (and thus precipitable water values) in the Northern hemisphere are generally observed to be increasing after 1973 (*Ross and Elliott*, 2001). Most of the increase is related to temperature and hence atmospheric water holding capacity. The change in water holding capacity of the atmosphere is governed by the Clausius-Clapeyron equation:

$$\frac{de_s}{e_s} = \frac{\lambda dT}{RT^2} \quad (6)$$

where  $e_s$  is the saturation vapor pressure at temperature  $T$  [K],  $\lambda$  is the latent heat of vaporization (here assumed to be constant at  $40.7 \text{ kJ mol}^{-1}$  but in reality the value changes with temperature), and  $R$  is the gas constant ( $8.3144 \text{ J mol}^{-1} \text{ K}^{-1}$ ). Global mean temperatures at 850 and 700 mbar are about 281 and 273 K, so  $7\% \text{ K}^{-1}$  is a reasonable estimate of the increase in water holding capacity of the atmosphere related to a unit increase in temperature.

An increase of a few percent of atmospheric moisture amounts, all things being equal, will lead to stronger rainfall rates when it rains, because low-level moisture convergence will be enhanced by that amount (*Trenberth et al.*, 2003). There is evidence that rainfall rates have changed in the United States (*Karl et al.*, 1996; *Groisman et al.*, 2004). *Groisman et al.* (2004) show that the nationwide precipitation increase in the US is 7% per century, and that during the past three decades the increase in heavy and very heavy precipitation has been most noteworthy.

#### 4. Trends in land evaporation

At the surface and over longer time periods, there is a balance between radiation, latent heat flux, and sensible heat flux (Equation 4). The observed reduction in surface solar radiation between 1960 and 1990 is therefore expected to result in a decrease of one or all of these components. On a global annual mean basis, 60 to 70% of the absorbed solar radiation is balanced by evaporation. *Peterson et al.* (1995), based on data from a network of pan evaporimeters in the US and the former Soviet Union, found indeed a decrease in pan evaporation between 1950 and 1990. This seems contradictory as in a warming atmosphere the air can contain more vapor and therefore, an expected consequence is a global increase of evaporation to match the global increase in precipitation. The contradiction between observed pan evaporation and the latter expectation is known as the evaporation paradox. *Brutsaert and Parlange* (1998) explained this paradox by interpreting the decreasing pan evaporation signal as an indication of an increasing evaporation from the water-limited environment surrounding the pan, through the complementary relationship between actual evaporation and apparent potential evaporation (*Bouchet*, 1963). *Roderick and Farquhar* (2002) showed, based on the energy balance (4) and when land-surface moisture is in ample supply (then the evaporation from a pan is a good indicator of the actual evaporation from the surrounding environment), that the decrease in evaporation from pans is consistent with the observed decrease in solar radiation at the land surface. Figure 3A-B illustrates this point using data from China for the period 1955-2000 (*Liu et al.*, 2004).

The issue of land evaporation changes in a changing climate is far from settled (*Ohmura and Wild*, 2002). Even though a very robust finding in all climate models with global warming is for an increase in potential evapotranspiration (IPCC TAR, 2001), the above cited references indicate there is still a debate about the question that land evaporation must increase under a warming climate. *Budyko* (1963) already demonstrated that the hemispheric evaporation is much more substantial in winter than in summer, indicating that a warmer atmosphere does not necessarily produce more evaporation. This expectation is in fact based on an implicit assumption that, as the air temperature increases, everything else stays constant. However, data reported by the IPCC TAR (2001) show that as the average surface temperature has increased there has also been a marked increase in the vapor pressure. Accordingly, the average water vapor pressure deficit near the surface appears to remain nearly constant (*Roderick and Farquhar*, 2002). Figure 3C illustrates that the average water vapor pressure deficit,  $D$ , for China, 1955-

2000, shows no significant trend. Given the fact that pan evaporation is generally much more sensitive to variations in net irradiance and  $D$  than to variations in wind speed, than with  $\delta D$  being small, a change in pan evaporation must result from a change in net irradiance. But how could  $D$  remain constant despite increases in average surface temperature? This question was answered by *Roderick and Farquhar* (2002) and is summarized here.

Note that  $D$  is defined by:

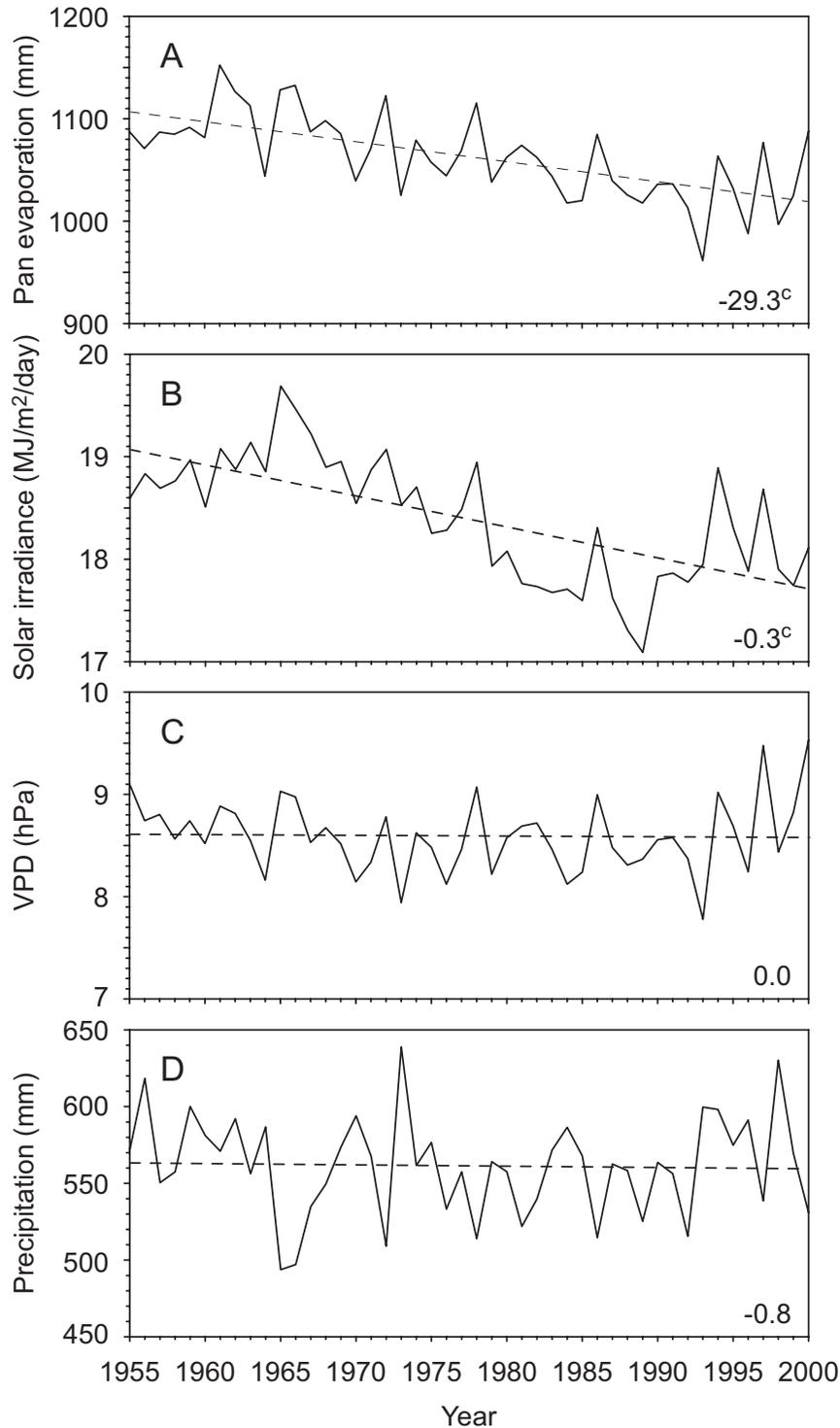
$$D = e_s(T) - e(T) = e_s(T) - e_s(T_d) \quad (7)$$

where  $T_d$  is dew point temperature. To first order, the change in  $D$  is given by:

$$\delta D = s\delta T - s_d\delta T_d \quad (8)$$

Where  $s$  and  $s_d$  are the slopes of the saturation vapor pressure-temperature relationship at  $T$  and  $T_d$ , respectively.  $T$  is larger than  $T_d$ , and  $s$  is larger than  $s_d$ . The change in  $D$  would be zero if  $\delta T_d / \delta T$  were equal to  $s/s_d$ . Averaged over a day,  $s/s_d$  depends on both the average  $T$  and the diurnal temperature range (DTR). Taking a typical value of 2 for this ratio, it follows that  $\delta D$  would be zero provided that  $\delta T_d$  is double of  $\delta T$ . Globally averaged measurements over the past 50 years show that while the average  $T$  has been increasing at  $\sim 0.15^\circ\text{C decade}^{-1}$ , the average minimum  $T$  generally has been increasing twice as fast at  $\sim 0.2^\circ\text{C decade}^{-1}$  as the average maximum  $T$  ( $\sim 0.1^\circ\text{C decade}^{-1}$ ) (IPCC TAR, 2001). When above the freezing point, the dew point will in general set a lower limit on the minimum  $T$ . Thus, the observed increase in minimum  $T$  implies that the dew point must also be increasing faster than the average  $T$ . Data from the US show that the average dew point has generally increased much faster ( $\sim 0.3^\circ\text{C decade}^{-1}$ ) than the average  $T$  (*Roderick and Farquhar*, 2002). Consequently, over the United States at least,  $\delta D$  should be very close to zero because  $\delta T_d / \delta T$  is about the same as  $s/s_d$ . This would explain why the average  $D$  has remained virtually constant in the US over the past 50 years. More generally, the widespread observed decline in the DTR suggests that the change in  $D$  should be very small in many place, as is illustrated in Figure 3C for China (*Liu et al.*, 2004).

In any case, a reduction in or an augmentation of the global terrestrial evaporation, combined with the increasing trend in global precipitation, will have to be balanced by changes in runoff and soil moisture, and this will effectively spin down or accelerate the hydrological cycle (*Ramanathan et al.*, 2005).



**Figure 3:** Temporal dynamics of warm season (May-September) pan evaporation (mm) (A), solar irradiance (B), vapor pressure deficit (C) and precipitation (D) for China, 1955-2000. The thick line represents the trend with the rate (units decade<sup>-1</sup>) shown in the lower right corner of the graph. Superscript indicate significance (c, significant at the 99% confidence level) (*Liu et al.*, 2004)

## 5. Trends in streamflow

Streamflow integrates over the considered drainage area the effects of the local imbalance between precipitation, evaporation and storage changes, and forms therefore the perfect signal to explore possible climate change effects on the terrestrial hydrological cycle. Unfortunately, the detection of anthropogenically forced changes in streamflow is difficult because of the substantial natural variability. *Milly et al.* (2002) investigated the changes in risk of great floods (i.e. floods with discharges exceeding 100-year levels from 29 basins larger than 200,000 km<sup>2</sup>) using both streamflow observations and numerical simulations of anthropogenic climate change. They found that the frequency of great floods increased substantially during the twentieth century, and that this trend will continue into the 21<sup>st</sup> century. However, the frequency of floods with shorter return periods did not increase significantly. *Groisman et al.* (2004) report that total and base streamflow in the US has increased during the past 60 years. Most of this increase occurred in the eastern part of the contiguous United States, where regional changes of heavy precipitation and high streamflow frequencies are in agreement. *Wu et al.* (2005) used ensemble simulations to study the climate over the past 140 years and derived from those simulations estimates for the mean discharge from Eurasian rivers. Their results suggest an increase in Arctic river discharge since the mid-1930s of about  $1.8 \pm 0.6$  mBe yr<sup>-1</sup>, which compares well with the observation-based estimates of  $2 \pm 0.7$  mBe yr<sup>-1</sup> (1 Be (Bering) is a convenient unit for water flux for large-scale hydrological studies, and equals 10<sup>3</sup> km<sup>3</sup> yr<sup>-1</sup>). Freshwater delivery to the ocean in the high northern latitudes is expected to increase by 20 to 70% by the end of the century (*Stocker and Raible*, 2005).

*Déry and Wood* (2005) investigated trends in freshwater discharge in 64 Canadian rivers with outlets into high-latitude oceans from 1964 to 2003. They found that the total annual discharge of these rivers decreases during the observation period at a rate of 3 mBe yr<sup>-1</sup>, and conclude that this is consistent with the 21 mm yr<sup>-1</sup> decline in observed precipitation over Northern Canada. They also find evidence of statistically-significant links between the Arctic Oscillation, El Niño/Southern Oscillation, and the Pacific Decadal Oscillation to the total annual discharge at interannual-to-decadal timescales (see also *Déry and Wood*, 2004).

## 6. Trends in soil moisture storage

Despite the importance of soil moisture in land surface, atmospheric boundary layer and climate processes, there are very few long-duration soil moisture data sets available. Regular gravimetric observation of soil moisture was started in the 1930s in the former Soviet Union, and several neighboring countries (Mongolia, China, India, and a few eastern European countries) adopted the Russian method shortly after. In the United States, the Illinois State Water Survey started the collection of soil moisture observations in the 1980s. More recently, a network of 100 stations has been set up as part of the Oklahoma Moistnet (*Robock et al.*, 2000). *Robock et al.* (2005), based on 45 years of 1-m soil moisture observations, averaged over 141 stations from fields with winter or spring cereals from the Ukraine, found a positive trend for the entire period (1958-2002), with the trend leveling off in the last two decades. This runs counter to predictions of summer

desiccation in a greenhouse-warming world. The authors observe that, while the region has been warming-up for the entire period, the observed downward trend in solar radiation reaching Earth's surface may have produced a downward trend in evaporation and may have contributed to the upward soil moisture trend. It will be interesting to see what the data for the next few decades will tell us about the hydrological cycle in that area.

## 7. Conclusions

The issue of how the hydrological cycle will change as the climate changes is complicated. However with warming, the main prospect is for increased water holding capacity of the atmosphere and associated increased water vapor. The expected rate of increase of 7% K<sup>-1</sup> is greater than current-day projected rates of increase in overall evaporation and precipitation, which are more like 1-2% K<sup>-1</sup> (Trenberth, 2004). Hence the prospects are for increases in precipitation intensity but decreases in duration or frequency of precipitation. The changes directly impact partitioning into soil moisture and runoff, and make both floods and droughts more likely. On top of these general tendencies are large regional changes associated with teleconnections.

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