CHAPTER ONE

Climate Warming-Induced Intensification of the Hydrologic Cycle: An Assessment of the Published Record and Potential Impacts on Agriculture

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Contents

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Abstract

Climate warming is expected to intensify and accelerate the global hydrologic cycle resulting in increases in evaporation, evapotranspiration (ET), atmospheric water-vapor content, and precipitation. The strength of the hydrologic response, or sensitivity of the response for a given degree of warming, is a critical outstanding question in climatology and hydrology. In this review chapter, I examine the published record of trends in various components of the hydrologic cycle and associated variables to assess observed hydrologic responses to warming during the period of observational records. Global and regional trends in evaporation, ET, and atmospheric water-vapor content and several large river basin water-balance studies support an ongoing intensification of the hydrologic cycle. Global trends in precipitation, runoff, and soil moisture are more uncertain than the trends in the variables noted above, in part because of high spatial and temporal variability. Trends in associated variables, such as systematic changes in ocean salinity, the length of the growing season, and the rate of precipitation recycling are generally consistent with intensification of the hydrologic cycle. The evidence for an increase in the frequency, intensity, or duration of extreme-weather events like hurricanes is mixed and remains uncertain. The largest potential impacts to agricultural systems depend greatly on the responses of hydrologic variables that are the most uncertain; for example, intensity and duration of heavy rainfall events; frequency, intensity, and duration of major storms and droughts; and rates of erosion. Impacts on agriculture will depend greatly on how insects, diseases, weeds, nutrient cycling, effectiveness of agrichemicals, and heat stress are affected by an intensification of the hydrologic cycle.

1. Introduction

1.1. The hydrologic cycle

The Earth's hydrologic cycle is driven by solar energy that provides the heat necessary for evaporation (E), transpiration, and sublimation. Over land areas, the sum of evaporation and transpiration is defined as evapotranspiration (ET). Water flux associated with evaporation over the oceans is estimated to be about 413×10^3 km^3 a^{-1}and ET over land is estimated to be about 73×10^3 km^3 a^{-1} (Trenberth *et al.*, 2007a; Fig. 1). Water vapor in the atmosphere derived from these sources is estimated to be about 12.7×10^3 km^3. Water vapor condenses and precipitation (P) falls as rain or ice (e.g., sleet, snow, hail). Over land P is then either evaporated, transpired, sublimated, or eventually flows back to the oceans as surface water or submarine groundwater discharge, thus completing the hydrologic cycle. The fluxes shown in the hydrologic cycle (Fig. 1) from Trenberth *et al.* (2007a) are constrained to balance; for example, P − E over land (40,000 km^3 a^{-1}) is equal to E − P over the oceans. The estimates of

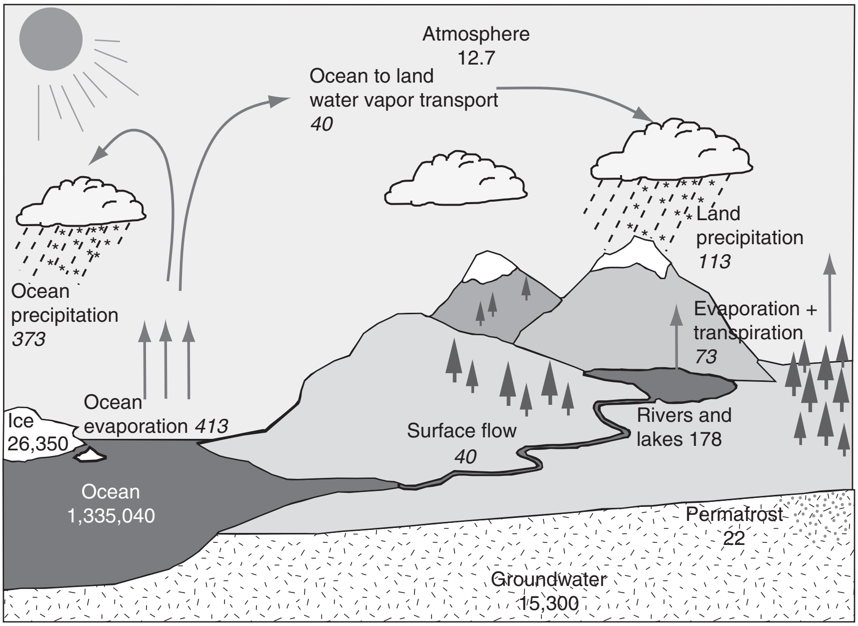

Figure 1 The hydrologic cycle. Estimates of the main water reservoirs, given in plain font (10^3 km^3), and the flow of moisture through the system, given in italic font (10^3 km^3 a^{-1}). Modified from Trenberth *et al.* (2007a), and used with permission.

individual fluxes are not well constrained and recent hydrologic budgets differ in various fluxes and stores (e.g., Oki and Kanae, 2006; Shiklomanov and Rodda, 2003). Evaporation is larger than P over the oceans and this difference is the water vapor that is transported from the oceans to land, resulting in an excess of P over ET over land. To balance the global water budget, the excess (or positive P − E) over land must be equal to total continental runoff + groundwater discharge to the oceans − the net change in storage terms. Changes in net storage, including in surface water, groundwater, and in the mass of ice and snow on land (Greenland and Antarctic ice sheets and non-ice-sheet glaciers (e.g., ice caps, ice fields, mountain glaciers)), and precipitation recycling over land complicate this simple cycle, but are ignored in this depiction of the global water cycle.

Climate change can affect all aspects of the hydrologic cycle through its effect on the Earth's energy budget (Bates *et al.*, 2008; Kundzewicz *et al.*, 2007; Trenberth *et al.*, 2007b). One of the most important consequences of climate warming on the hydrologic cycle is thought to be an intensification of the cycle itself. (DelGenio *et al.*, 1991; Held and Soden, 2000, 2006; Huntington, 2006; Loaciga *et al.*, 1996; Trenberth, 1999). There are many hydrologic responses to climate change, the potential impacts of these responses are far-reaching, and are likely to affect agriculture, forestry, availability of fresh water, habitat sustainability, forest-fire incidence and intensity, pests and pathogens (Bates *et al*., 2008; Kundzewicz *et al*., 2007). Another critically important impact of climate warming on the hydrologic cycle involves an increase in atmospheric water-vapor content and the consequent positive feedback on warming because water vapor is a radiatively active "greenhouse" gas in its own right.

1.2. Intensification of the hydrologic cycle

Intensification of the hydrologic cycle is here defined as an acceleration or increase in the rates of E, ET, and P. In other words, intensification is an increase in the flux of water between existing ocean, atmosphere, terrestrial, freshwater, and cryospheric pools. It is recognized that as the climate warms and the hydrologic cycle intensifies, it is likely that there will be an increase in the temporal and spatial variability of precipitation and in the intensity and duration of storms and droughts. It is likely that some regions will get wetter and some will get drier, but overall, on a global scale, the fluxes shown in Fig. 1 will increase. The scientific basis for a warming-induced intensification of the hydrologic cycle is that the rate of evaporation increases with increasing temperature and that warmer air will hold more moisture. The relation between surface air temperature and atmospheric water vapor is described by the Clausius–Clapeyron equation that indicates that water vapor will increase by about 7% K^{-1} (Held and Soden, 2000). Many scientists also conclude that an increase in the frequency, intensity, or duration of major storms would be another consequence of a warming-induced intensification of the hydrologic cycle (e.g., Knutson and Tuleya, 2004; Kundzewicz *et al*., 2007; Wetherald and Manabe, 2002). It is important to note that increasing P over land does not necessarily imply an increase in continental runoff because it is possible that increases in ET could balance increases in precipitation. Another way of looking at intensification is to consider the case where, for a given region, the net influx of water vapor from outside that region does not increase but P and ET do increase over that region. This would be the case if the P recycling ratio was increasing (e.g., Dirmeyer and Brubaker, 2006; Dominguez *et al*., 2006).

It is widely believed that climate warming has the potential to intensify the hydrologic cycle and increase the concentration of water vapor in the atmosphere, but there is considerable debate about whether the increase will scale according to the Clausis–Clapeyron equation, or at some substantially lower rate (e.g., Allen and Ingram, 2002; Wentz *et al*., 2007). Allen and Ingram (2002) noted that the mean sensitivity of precipitation to warming of a number of global circulation model (GCM) analyses was approximately 3.4% K^{-1}. Recent analyses of observational data on atmospheric water-vapor content, P, and ET support increases at rates that are more consistent with predictions based on the Clausius–Clapeyron equation of about 7% K^{-1} (Allan and Soden, 2007; Wentz *et al.*, 2007; Willet *et al.*, 2008; Zhang *et al.*, 2007). However, uncertainty remains in the sensitivity of this response to warming (e.g., John *et al.*, 2009). This discrepancy between GCM outputs and observations during the late twentieth century is critically important for understanding the sensitivity of the hydrologic response to future warming. This problem is graphically illustrated in an adaptation of Allen and Ingram's (2002) original figure that shows sensitivity of the GCMs versus these recent observations (Fig. 2).

Resolving this question of the sensitivity of hydrologic fluxes to climate warming may be one of the more fundamental questions in climatology and hydrology, because the potential impacts associated with intensification would be greatly amplified under a system with higher sensitivity, thereby necessitating more aggressive adaptation. The importance of this question is emphasized by historical observed and twenty-first century projected surface air-temperature increases (Trenberth *et al.*, 2007b). These projections reported by the IPCC in their Fourth Assessment report have recently been updated and now indicate that the upper ranges of the 2007 projections are increasingly likely (Rahmstorf *et al.*, 2007; Smith *et al.*, 2009; UNEP, 2009). The fact that atmospheric CO_2 concentrations are rising more rapidly than expected (Canadell *et al.*, 2007; Raupach *et al.*, 2007) and climate warming appears to be progressing more rapidly than thought likely in 2007 (e.g., Sokolov *et al.*, 2009) could be attributed to several processes, including ocean acidification, which results in decreased ocean uptake CO_2 (e.g., Moy *et al.*, 2009; Park *et al.*, 2008a; Wootton *et al.*, 2008); a possible decrease in land-based carbon sinks (Canadell *et al.*, 2007; Cramer *et al.*,

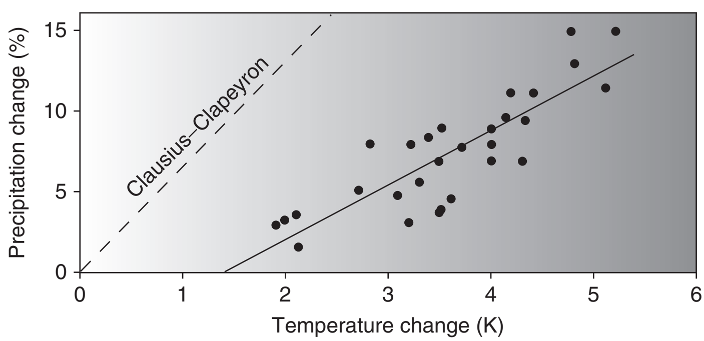

Figure 2 Global-mean temperature and precipitation changes in a wide range of equilibrium CO_2 doubling AOGCM simulations (scatter plots) with simple thermodynamic ("slab") oceans. The solid line shows the best-fit (least squares) linear relationship. All these points would lie on the dashed line if precipitation were to follow the Clausius–Clapeyron. Modified from Allen and Ingram (2002), and used with permission.

2001; Piao *et al.*, 2008); methane release from degrading permafrost (e.g., Heginbottom *et al.*, in press; Walter *et al.*, 2006); decreases in albedo from declines in Arctic Ocean sea-ice cover (Comiso *et al.*, 2008; Parkinson and Cavaliere, in press); stronger carbon-cycle feedbacks than once thought (Scheffer *et al.*, 2006); poleward migration of vegetation (ACIA, 2004; McGuire *et al.*, 2009) and associated decrease in albedo; higher than expected global CO_2 emissions (Auffhammer and Carson, 2008; Raupach *et al.*, 2007; UNEP, 2009); and increase in particulates in the atmosphere such as black carbon (soot) (Ramanathan and Carmichael, 2008). Some negative (cooling) feedbacks may not be as important as once thought; for example, nutrient or water limitations could minimize the capacity of vegetation to assimilate carbon at faster rates under conditions of higher atmospheric CO_2 (Leakey *et al.*, 2006, 2009; Long *et al.*, 2006; Thornton, *et al.*, 2009). Gains in water-use efficiency caused by higher atmospheric CO_2 concentrations (Gedney *et al.*, 2006) may not be as effective as previously hypothesized (Huntington, 2008). The direction of all of these trends and the implications of potential hydrologic responses add urgency to gaining a better understanding of the sensitivity of the hydrologic cycle to future warming.

One approach for gaining insight into this question has been to assess the published observational evidence for or against historical increases in rates of E, ET, P, and other related variables that might indicate hydrologic responses to warming during the twentieth century. This approach has distinct limitations because of a lack of data for comprehensive spatial and temporal coverage, differences in methodologies, and high natural interannual variability, which requires multidecadal time series to conclusively confirm trends detection (Ziegler *et al.*, 2003). There are also errors associated with measurement, estimation of missing data, and spatial averaging. There are large variations among regions (spatial variations) and, in some cases, trends that have reversed (temporal variations) during the period of record. Some of the studies cited in this review have not addressed the potential effects of decadal or multidecadal persistence associated with large-scale patterns of climate variability (climate indices) like the El Nino Southern Oscillation, the Pacific Decadal Oscillation, and the North Atlantic Oscillation. In spite of these concerns, assessments of this type complement modeling studies and lend insight to the problem through synthesis of relevant available data. One such study at the global scale suggested that the weight of evidence supported intensification during the twentieth century (Huntington, 2006). Wentz *et al.* (2007) examined short-term trends analyzed from satellite-sensor data and concluded that P, E, and atmospheric water-vapor content increased during 1987 through 2006. Regional studies have also substantiated evidence for intensification in Canada (Déry *et al.*, 2009) and the pan-Arctic region (Rawlins *et al.*, in press; Holland *et al.*, 2006, 2007; Zhang *et al.*, 2009).

The objective of this chapter is to review the published findings on global and regional trends in various components of the hydrologic cycle and associated variables that could lend insight into the sensitivity of the hydrologic cycle to future warming. Some of this information has been included in earlier IPCC and regional assessments and reviews (e.g., Huntington, 2006; Ziegler *et al.*, 2003), but many more recently published reports are now available that, taken together, provide a more comprehensive analysis. The majority of the studies reviewed involve analysis of historical observational data. In some instances, particularly where data are sparse either spatially or temporally, studies are included that have used modeling as a substitute for missing data. Some studies also include projections of future responses, although a thorough treatment of model forecasts is beyond the scope of this review. As a general rule, there is substantially more uncertainty in GCM projections regarding future rates of precipitation when compared with future temperatures given in prescribed emission scenarios (Bates *et al.*, 2008; Kundzewicz *et al.*, 2007; Trenberth *et al.*, 2007b). This review begins with a discussion of the significance of intensification of the hydrologic cycle, addressing the question "Why should we care about the sensitivity of this response?" This section is followed by the main body of the chapter in which trends in components of the hydrologic cycle and associated variables are reviewed. The next sections discuss the effect of the explosive 1991eruption of Mount Pinatubo, Philippines, on the hydrologic cycle (Trenberth and Dai, 2007), and the evidence for trends in extreme-weather events. The final section of the chapter addresses the implications of an intensification of the hydrologic cycle for agricultural systems.

2. Significance of an Intensification of the Hydrologic Cycle

Water vapor is the most important radiatively active "greenhouse" gas, accounting for approximately 60% of planetary atmospheric heat trapping (Kiehl and Trenberth, 1997). Significant changes in atmospheric water-vapor content would therefore have profound effects on the Earth's radiation budget and resultant surface air temperature. Surface air-temperature warming caused by an increase in other greenhouse gasses (e.g., CO_2, CH_4, CFCs, N_2O, etc.) will very likely result in an increase in atmospheric water-vapor, further amplifying climate warming in what is termed the "water-vapor feedback" process (Held and Soden, 2000, 2006). A lack of understanding of the sensitivity of water-vapor feedback to future warming is one of the reasons for the relatively large differences in GCM climate projections. The higher the sensitivity, the greater the water-vapor feedback and the greater the amplification of warming due to other greenhouse gasses.

Apart from the water-vapor feedback, there are many other concerns arising from an intensification of the hydrologic cycle. One of the chief concerns is the possibility that intensification will result in an increase in "extreme" weather events, including major storms, floods, and droughts (Bates *et al.*, 2008; Kundzewicz *et al.*, 2007; Tebaldi *et al.*, 2006). An increase could include an increase in intensity, frequency, and/or duration of extreme events, as well as an increase in overall variability in the magnitude, timing, and sequence of weather events. The implications of an increase in extreme events are many and varied; they range from increased risk of flood-related mortality and damage to infrastructure to more frequent and severe crop losses, increases in soil erosion, loss of forest productivity, increased risk of fire and disease, and stress caused by insect infestations. It is likely that some regions will get drier and the frequency of severe drought may increase. This has major consequences for the sustainability of water resources, especially in arid and semiarid areas. Regionally, there are likely to be large changes in the amount of freshwater stored in soils, aquifers, natural lakes and reservoirs, and in snowpack and glaciers that will also influence resource availability (e.g., Barnett *et al.*, 2008). Another concern is that changes in extreme events would adversely affect systems for the management of wastewater and storm runoff because conditions that were once considered to be extremely rare events, and, therefore, not properly engineered for, may become more common (Milly *et al.*, 2008).

In some areas (e.g., in the northeastern United States; Burakowski *et al.*, 2008; Hayhoe *et al.*, 2007), reductions in the seasonal duration that snow cover is on the ground will decrease albedo, which is a positive feedback that will amplify warming. An increase in winter precipitation, with more precipitation expected to fall as rain rather than snow would likely change the timing and volume of groundwater recharge and stream runoff. Although more runoff is likely to occur during winter and early spring, the size of the spring freshet (snowmelt) is likely to be reduced because the amount of snow cover at the beginning of spring is likely to decrease over time as more winter precipitation falls as rain rather than snow. If the ground is frozen, no groundwater recharge will occur during rainfall, and there will be an increase in runoff. If snow cover is absent when the ground does thaw, less infiltration will take place, and less groundwater recharge will occur.

Intensification-related increases in specific humidity could have adverse effects on human health and the health of crops and forests. Increases in specific humidity are likely to exacerbate the problem of heat stress (Gaffen and Ross, 1998). Although relative humidity is not expected to increase with increasing temperature, specific humidity is, and the human body's ability to dissipate heat is inversely proportional to specific humidity (Jendritzky and Tinz, 2009). Heat stress caused by increasing temperature alone is already a major concern associated with projections for increases in the number of days of extremely high temperatures (Trenberth *et al.*, 2007b), but projected increases in heat stress will be felt more acutely under conditions of higher specific humidity. Increases in specific humidity could result in increases in susceptibility of plants to diseases, in particular, less resistance to fungal infections (Hatfield *et al.*, 2008). Increases in specific humidity may adversely influence harvesting and susceptibility of harvested crops to fungal infections and insect damage (Hatfield *et al.*, 2008). Increases in specific humidity could increase stomatal conductance (Wang *et al.*, 2009) leading to a decrease in water-use efficiency and increases in plant-water stress.

To the extent that, in some regions and during some seasons, intensification will result in an increase in ET that is greater than any increase in P, soil-moisture content will decrease accordingly. Decreases in soil moisture could increase plant-water stress. It is important to note that these conditions can lead to seasonal short-term drought (soil-moisture deficits) in spite of increases in average annual precipitation (e.g., Hayhoe *et al.*, 2007). Seasonal decreases in soil moisture can also adversely affect sensitive biota. For example, pool-breeding amphibians have minimum soil-moisture requirements during the parts of their life cycles spent in soil burrows; decreases in soil moisture and decreases in pool hydroperiod could adversely affect their survival (Brooks, 2009; Semlitsch, 2000).

3. Trends in Hydrologic Variables

3.1. Evaporation and evapotranspiration

Solar radiation drives the hydrologic cycle by providing the energy for evaporation and ET. Long-term measurements of these components of the hydrologic cycle are excellent indicators of the intensity of the hydrologic cycle. However, direct measurements of these fluxes over large landscapes are not possible. This section will briefly describe direct measurements from evaporation pans, small plots using massive-weighing lysimeters, and eddy-covariance-flux towers, and will discuss in substantially more detail a number of indirect measurements or measurements of associated variables that can be used to infer trends in evaporation and ET. The indirect measurements include water-balance studies, land-surface modeling, ocean salinity, and satellite measurements. Associated variables include the length of the growing season.

3.1.1. Direct measurements

The original massive-weighing lysimeters employed in the former Soviet Union and United States beginning about 1950 could measure ET associated with a change in mass equivalent to 0.25 mm of water per hour in a monolith 8 m × 2 m and 2 m deep (Harrold and Dreibelbis, 1967). Golubev *et al.* (2001) reported increasing ET during the post-WWII to 1990 period at most sites in the former Soviet Union using these lysimeters. They reported significant increasing trends at two grassland (steppe) sites and one forest site; increasing, but not significant trends at another forest site, mixed trends at another forest/steppe site, and decreasing, but not significant trends at two taiga sites. These plots had native vegetation and received only natural rainfall.

Another method for direct measurement of the net exchange of water vapor between terrestrial landscapes and the atmosphere involves the use of the eddy-covariance-flux approach that can compute flux from high-temporal-resolution measurements of vertical wind speed and water-vapor-concentration gradients above the soil and the vegetation canopy. The two largest networks of sites with this type of data are EUROFLUX (Aubinet *et al.*, 2002) and Fluxnet (Law *et al.*, 2002). Although there are no long-term ET measurements with which to evaluate trends anywhere, measured ET is positively correlated with growing-season temperature (GST) for humid regions at the Fluxnet sites. In the Fluxnet program, water-vapor exchange has been measured continuously for several years over forest, grassland, and agricultural ecosystems. Plotting annual ET against GST reported by Law *et al.* (2002) results in a significant (p-value < 0.0001) positive relation (Pearson's $r^2 = 0.58$) (Fig. 3). Ordinary least-squares, simple

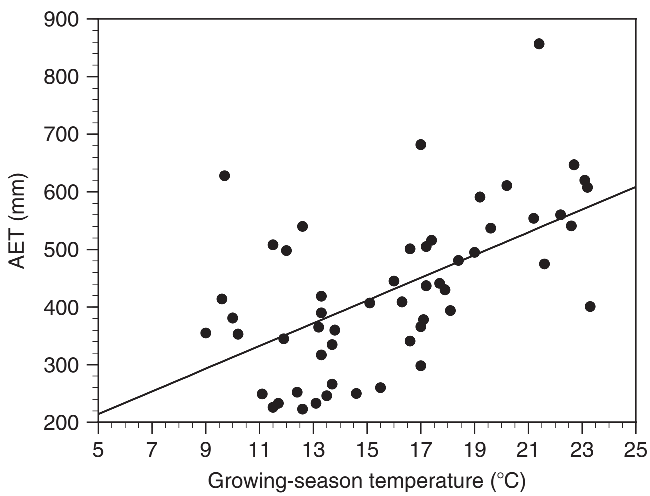

Figure 3 Annual actual evapotranspiration (AET) versus growing-season temperature for all Fluxnet data reported in Law *et al.* (2002), except for Aberfeldy, Scotland, in 1997 that was excluded because of a negative value for AET. Line shown is the ordinary least-squares simple linear regression. Modified from Huntington (2006), and used with permission.

linear regression gives a best-fit line of $ET_{mm} = 115 + 19.7 \times GST_{°C}$, indicating a sensitivity of 19.7 mm ET per °C across a broad range of forest ecosystems in Europe and North America and two grassland and two cropland sites in the United States (Huntington, 2006). This relation between ET and temperature suggests that observed temperature increases during the twentieth century may have resulted in increasing ET where moisture is not limiting.

Decreases in pan evaporation were observed over most of the United States and the former USSR between 1950 and 1990 (Peterson *et al.*, 1995). Such decreases were generally thought to be inconsistent with observed trends toward increasing temperature and precipitation, resulting in an "evaporation paradox" (Brutsaert and Parlange, 1998). Several analyses have suggested, however, that decreasing pan evaporation is consistent with increasing surface warming and an acceleration of the global hydrologic cycle (Brutsaert, 2006; Brutsaert and Parlange, 1998; Golubev *et al.*, 2001; Roderick and Farquhar, 2002; Szilagyi *et al.*, 2002). Various mechanisms have been suggested to explain the apparent paradox. For example, it has been suggested that decreases in solar irradiance (what some have called "global dimming," Wild, 2009) resulting from increasing cloud cover and aerosol concentrations, and decreases in diurnal temperature range (DTR) would cause the observed decrease in pan evaporation (Peterson *et al.*, 1995; Roderick and Farquhar, 2002). Brutsaert and Parlange (1998) concluded that increasing water-vapor concentration resulting from a warming-induced increase in ET would inhibit pan evaporation. Golubev *et al.* (2001) concluded that the observed opposing trends supported the mechanism proposed by Brutsaert and Parlange (1998). These analyses build on application of the principle of complementarity that pan evaporation (a surrogate for potential evaporation) is in a complementary relationship with actual evapotranspiration (AET) (Brutsaert and Parlange, 1998; Kahler and Brutsaert, 2006). The complementary relation states that for fixed radiation inputs in water-limited environments (i.e., excluding land surfaces where free water is exposed to the atmosphere; e.g., wetlands, swamps, rice paddies), as aridity increases, measured pan evaporation will increase, but actual AET will decrease because soil moisture becomes increasingly more limited. Conversely, in water-limited environments, as soil moisture increases (decreasing aridity), AET will increase and pan evaporation will decrease. This decrease in aridity is associated with an increase in specific humidity and a decrease in vapor pressure deficit that, in turn, would suppress evaporation from the free-water surface of a pan. The complementary relation in water-limited environments was recently verified experimentally at two sites in the United States by Kahler and Brutsaert (2006).

In another recent study Roderick *et al.* (2007) reported that the decrease in evaporation in Australia during 1975–2004 was mostly due to decreasing wind speed. The issue of whether trends in pan evaporation indicate an intensification of the global hydrologic cycle and the role of global dimming and brightening may not be fully resolved (Ohmura and Wild, 2002; Roderick *et al.*, 2009; Wild, 2009; Wild *et al.*, 2004), but the analyses of Brutsaert and Parlange (1998), Golubev *et al.* (2001), Brutsaert (2006), and Szilagyi *et al.* (2002) support increasing ET during this period.

3.1.2. Indirect measurements

3.1.2.1. Water-balance studies Arguably the most compelling evidence for change in the rate of ET from large land areas with multidecadal record length comes from river basin water-balance studies. In these studies, the objective is to estimate ET as the difference between precipitation and runoff, usually on an annual basis. This approach assumes that there are no significant net changes in water storage within the basin (or that the changes could be quantified) such as depletion or accumulation of groundwater, surface water, soil moisture, or snow and ice. In many moist-to wet-temperate systems, the assumption of no significant change in storage relative to the magnitude of rainfall and runoff appears to be appropriate. In addition, having many years in the dataset would tend to "average out" small net changes in storage during wet versus dry years. This approach also assumes that there is no significant interbasin exchange or loss of water through groundwater. As basin size decreases, these assumptions become more tenuous.

Both precipitation and runoff have increased during the twentieth century in the Mississippi River Basin (Milly and Dunne, 2001; Walter *et al.*, 2004). However, increases in precipitation were substantially higher than increases in runoff, indicating that ET had also increased. Milly and Dunne (2001) reported that the rate of increase in ET from 1949 through 1997 was 0.95 mm a^{-2}. Qian *et al.* (2007) studied trends in surface-water and energy-budget components of the Mississippi River Basin from 1948 to 2004 using a combination of observations and model simulations and also concluded that ET had increased. Walter *et al.* (2004) also estimated ET using the water-balance method for several large basins in the United States (Mississippi, Colombia, Colorado, Susquehanna, Sacramento, and south-eastern U.S. basins) and found that, on average, ET was increasing at a rate of 1.04 mm a^{-2} from 1950 to 2000 (Fig. 4). Similar analyses for the La Plata River Basin in southeastern South America, the second largest basin in South America, are consistent with increasing ET (Berbery and Barros, 2002). Berbery and Barros (2002) reported that precipitation had increased by 16%, runoff had increased by 35%, and ET by 9% between the periods 1951–1970 and 1980–1999. This increase in ET corresponds to a rate of 1.29 mm a^{-2} during the 49 years of record.

Streamflow has been stable or decreasing in recent decades in most of Canada (Déry and Wood, 2005; Déry *et al.*, 2005; Rood *et al.*, 2005; Schindler and Donahue, 2006) but precipitation has been increasing

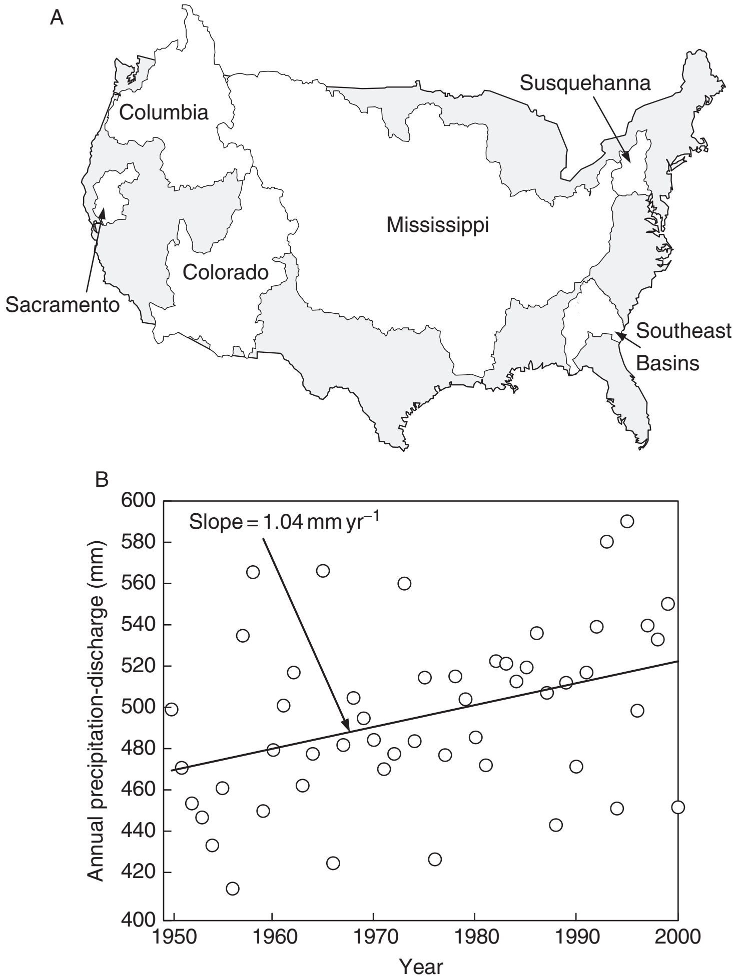

Figure 4 River basins studied (A), and trend in the area-weighted difference between annual precipitation and annual stream discharge from 1950 to 2000 (B). Modified from Walter *et al.* (2004), and used with permission.

(Zhang *et al.*, 2000). Together, these observations suggest that ET has been increasing. The most recent analysis of streamflow in northern Canada shows a reversal of trends toward increasing rates of discharge to polar seas from 1989 to 2007 (Déry *et al.*, 2009).

3.1.2.2. Satellite data and modeling using meteorological and landscape data Wentz *et al.* (2007) used satellite observations from the Special Sensor Microwave Imager (SSM/I) from 1987 to 2006 to measure precipitation, total water vapor, and surface-wind stress over the oceans and a blend of satellite and land-based precipitation gages. ET over the oceans was computed using National Center for Atmospheric Research Community Atmospheric Model 3.0 and ET over land was assigned a constant value of 527 mm a^{-1} for all of the continents, excluding Antarctica where a value of 28 mm a^{-1} was used (Wentz *et al.*, 2007). Their analysis suggested that ET, precipitation, and total water vapor had all increased at rates of approximately 7% K^{-1} over this period.

Fernandes *et al.* (2007) studied trends in ET across Canada (but predominantly in southern Canada) using 1960–2000 meteorological data from 101 sites and a land-surface model. They found that 81 sites had increasing trends (35 were statistically significant) and that the increases were related to temperature, total downwelling surface radiation, and precipitation. Using another land-surface model, Park *et al.* (2008b) reported that ET was increasing in the Lena River in eastern Siberia. Serreze *et al.* (2003) concluded that ET was increasing in the Yenisey River in eastern Siberia where ET was computed from P and P − ET, which was computed from the vertically integrated vapor-flux convergence adjusted by the time change in precipitable water. Wang *et al.* (in press, 2010) used a semiempirical model and observations of surface solar radiation, surface air temperature, humidity, and vegetation at 265 sites over the period 1982–2002 and estimated that 77% of the sites had increasing ET. Zhang *et al.* (2009) used satellite-remote-sensing inputs, including AVHRR GIMMS NDVI, MODIS land cover and NASA/GEWEX solar radiation and albedo, and regionally corrected NCEP/NCAR Reanalysis daily surface meteorology to develop an algorithm for ET. They determined that temporal trends in ET showed generally positive trends over the pan-Arctic basin and Alaska during the period 1983 to 2005. Zhang *et al.* (2009) concluded that their data on all components of the water cycle indicated that the hydrologic cycle was intensifying.

3.1.2.3. Ocean salinity Possible trends in evaporation over the oceans and their relation to precipitation and runoff have been addressed indirectly using ocean salinity time-series data. Salinity in the upper water column (surface to approximately 1000-m depth) increased significantly between the periods 1955–1969 and 1985–1999 along a transect in the western basin of the Atlantic Ocean at latitudes between 40°N and 20°S (Fig. 5). (Curry *et al.*, 2003). Curry *et al.* (2003) also reported systematic freshening poleward of these latitudes. The salinity increase was spatially coherent with measured warming of the sea surface (Curry *et al.*, 2003). Increases in salinity were attributed to changes in evaporation and precipitation because no additional sources of salt exist (from mixing) for these maximum salinity

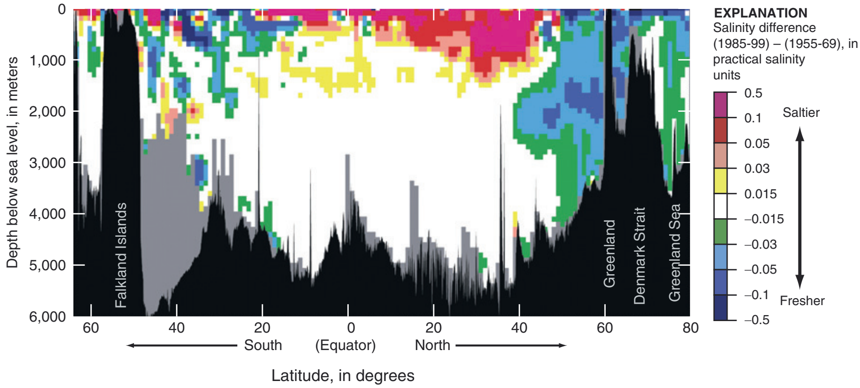

Figure 5 **Salinity difference (1985–1999) minus (1955–1969) by depth along a western Atlantic Ocean meridonal transect from 64°S latitude (Antarctica) to 80°N latitude (Fram Strait). Black indicates ocean bottom and gray indicates missing data. Modified from Curry *et al.* (2003), updated and used with permission.**

waters (Curry *et al.*, 2003). For 24°N latitude (the salinity maximum), the inferred evaporation − precipitation (E − P) anomaly averaged 5 cm a^{-1} during the 40-year period (Curry *et al.*, 2003). The increase in E − P could be a result of increases in E or decreases in P. There is no evidence for a decrease in P, and satellite-derived increases in E, SST, and P for this region during 1987 through 2006 (Wentz *et al.*, 2007) support an increase in E as the explanation for the long-term salinity anomaly. Sea-surface warming over the same region and time period as the salinity anomaly suggests an increase in net evaporation that is consistent with predictions derived from the Clausius–Clapeyron equation and possible changes in the hydrologic cycle (Curry *et al.*, 2003). In another recent study covering 1950–2008 Durack and Wijffels (2010) reported similar results in a study of the Atlantic, Pacific, and Indian Ocean from 1950 to 2008. They reported salinity increases in evaporation-dominated regions and freshening in precipitation-dominated regions with the spatial pattern of change similar to the mean salinity field.

Increases in salinity also have been reported in some subtropical regions of the Pacific Ocean (Boyer *et al.*, 2005; Wong *et al.*, 1999) and in the Mediterranean Sea (Béthoux *et al.*, 1998; Roether *et al.*, 1996). Wong *et al.* (1999) concluded that the salinity changes observed in the Pacific Ocean were consistent with a "strengthening" of the water cycle during an average 22-year period from the mid- to late-1960s to the mid- to late-1980s. Boyer *et al.* (2005) largely confirmed the trends reported by Curry *et al.* (2003) for the Atlantic and reported increasing salinity for the Indian Ocean.

However, the Boyer *et al.* (2005) findings contrasted with Wong *et al.* (1999) for the Pacific Ocean. For the Pacific Ocean, Boyer *et al.* (2005) found no trends in the Tropics or Northern Hemisphere subtropics, but evidence for increasing salinity in the Southern Hemisphere subtropics and generally freshening at higher latitudes. Béthoux *et al.* (1998) attributed increases in salinity in the Mediterranean to anthropogenic factors (reduced freshwater inputs, and more saline inputs via the Red Sea), reductions in precipitation, and warming-induced increases in evaporation.

3.1.3. Length of the growing season

An increase in the duration of the growing season is a logical response to warmer spring and fall air temperatures in temperate regions where the growing season is confined to the period when air temperatures remain above freezing. Transpiration is greatly reduced during the dormant season. Modeled ET increases as the length of the growing season increases in humid regions of the eastern United States (Eagleman, 1976). Mean annual ET, estimated from measured precipitation minus runoff, increases at a rate of about 3 cm $°C^{-1}$ in eastern North America (Huntington, 2003a). Thus, any extension of the growing season will increase total annual ET, provided moisture is not limited, thereby intensifying the hydrologic cycle. There is now extensive evidence that the growing season has been getting longer in temperate climates over the historical observational record. Because of this global trend towards lengthening of the growing season, it is reasonable to assume that the seasonal period of active plant transpiration has lengthened in synchrony (White *et al.*, 1999). In the following section, the evidence for a lengthening of the growing season will be reviewed.

An increase in the length of the growing season in temperate and boreal ecosystems is inferred from studies that have monitored temporal trends in plant phenology, such as the date of first leaf out, bud break, and flowering during the twentieth century (e.g., see reviews by Menzel *et al.*, 2006; Root *et al.*, 2003; Schwartz *et al.*, 2006). These reviews focus on the Northern Hemisphere, hence responses in the Southern Hemisphere are less certain. Many of the most compelling studies were carefully controlled to minimize variation in phenotype, for example, by planting genetically identical varieties. Advances in the timing of many animal phenological events in the Northern Hemisphere also have been reported (Parmesan and Yohe, 2003; Walther *et al.*, 2002). Together these extensive reviews of phenological studies strongly point to increases in growing-season duration.

Substantial increases in growing-season length have also been inferred in regional studies from temperature records (Cooter and LeDuc, 1995) and reports of killing frosts (Baron and Smith, 1996). Fitzjarrald *et al.* (2001) reported an advance in the timing of the spring decrease in the Bowen ratio in the eastern United States, indicating earlier leaf emergence and rapid increase in the rate of transpiration. Trends in high northern latitude soil-freeze-and-thaw cycles have been studied using satellite data from the Scanning Multichannel Microwave Radiometer and Special Sensor Microwave/Imager (Smith *et al.*, 2004). In North America, Smith *et al.* (2004) reported a trend toward longer growing seasons in evergreen conifer forests and boreal tundra during the period 1988–2002. Smith *et al.* (2004) found earlier thaw dates in tundra and larch biomes over Eurasia. However, trends toward earlier thaw dates in Eurasian larch forests did not lead to an increase in growing season length because of parallel changes in timing of the fall season (Smith *et al.*, 2004).

Increases in growing-season duration also are inferred from a variety of hydrologic and climatologic variables that are correlated with earlier spring warming. For example, earlier spring snowmelt runoff (Cayan *et al.*, 2001; Cunderlik and Burn, 2004; Hodgkins *et al.*, 2003; Leith and Whitfield, 1998, Yang *et al.*, 2002; Zhang *et al.*, 2001a), earlier river ice-out (Hodgkins *et al.*, 2005; Jeffries *et al.*, in press); earlier lake ice-out (Hodgkins *et al.*, 2005; Jeffries, *et al.*, in press; Magnuson *et al.*, 2000), lengthening of the frost-free season (Easterling, 2002; Frich *et al.*, 2002; Kunkel *et al.*, 2004), and decreases in spring snow-cover extent across the former Soviet Union and Peoples Republic of China (Brown, 2000), in the Swiss Alps (Scherrer *et al.*, 2004), and in the Northern Hemisphere (Hall and Robinson, in press). An increase in the length of the growing season was inferred from an advance in the timing of the spring seasonal drawdown in atmospheric CO_2 concentrations (Fang *et al.*, 2003; Hicke *et al.*, 2002; Myneni *et al.*, 1997). That drawdown was coincident with an advance in the timing of the "onset of greenness" (inferred from NOAA advanced very high-resolution radiometer (AVHRR) satellite data showing the normalized difference vegetation index) in northern temperate regions (Myneni *et al.*, 1997).

3.2. Atmospheric water vapor

Another dimension of an intensification of the hydrologic cycle is an increase in atmospheric water-vapor content as predicted by the Clausius–Clapeyron equation. In spite of substantial regional variation and uncertainty in the data, there is evidence for an increase in water vapor at the surface over most northern latitudes (>30°N), with the exception of Greenland and extreme northeastern Canada, during the period 1975–1995 (New *et al.*, 2000; Rinke *et al.*, 2009). Dai (2006) reported trends of increasing annual mean specific humidity over the surface of the globe between latitude 60°S and latitude 75°N for 1975–2005 (Fig. 6). Willett *et al.* (2008) reported increased specific humidity at the Earth's surface from latitude 70°N to latitude 70°S of between 0.07 and 0.11 g kg^{-1} per decade from 1973 to 2003. Studies using radiosonde measurements have also reported increases in lower troposphere water vapor beginning in 1973 in the Northern Hemisphere (Ross and Elliott,

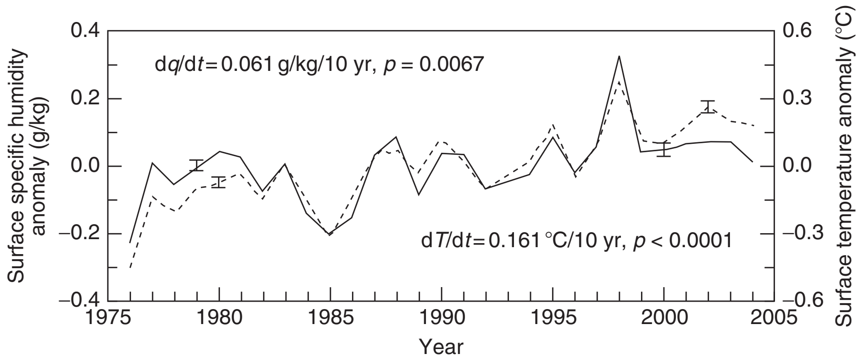

Figure 6 Time series of annual-mean surface specific humidity (g kg^{-1}, solid curve) and surface (air over land and sea surface over oceans) temperature (°C, short-dashed curve) anomalies averaged over 60°S–75°N. The linear trends (dq/dt and dT/dt) and their statistical significance levels (p) are also shown. The error bars are estimated ± standard error ranges based on spatial variations. Modified from Dai (2006), and used with permission.

2001; Zhai and Eskridge, 1997) and, more recently, using SSM/I measurements (Trenberth *et al.*, 2005; Wentz *et al.*, 2007). Deficiencies in the data, large interannual and regional variations, the relatively short-term nature of the data, and the association of these trends with ENSO and sea-surface temperature suggest caution in making inferences about long-term trends (Trenberth *et al.*, 2005).

Minschwaner and Dessler (2004) report that recent satellite measurements also indicate trends toward increasing water vapor in the tropical (20°S to 20°N) upper troposphere (UT) (above 215 mb) during 1993–1999 that were consistent with model predictions. However, they concluded that models that assume constant relative humidity overestimate the warming-induced water-vapor feedback. Their data indicate that the relationship between UT humidity and sea-surface temperature within the convective regions of the tropical oceans lies between the cases of constant mixing ratio (specific humidity) and constant relative humidity (Minschwaner and Dessler, 2004).

3.3. Changes in cloudiness

Trends in cloudiness may also be related to an intensification of the hydrologic cycle. Climate warming-induced changes in cloudiness would be a feedback on the hydrologic cycle because of the influence of clouds on the radiation budget of the earth. Studying the Mississippi River Basin from 1948 to 2004, Qian *et al.* (2007) noted an increase in cloudiness that was associated with a decrease in net shortwave radiation, but this decrease was compensated for by decreases in net longwave radiation and sensible-heat flux, while the latent-heat flux increased in association with wetter soil conditions.

Cloudiness increased from the 1940s to 1990 over may continental regions of the United States, over mid-latitude Canada, Europe, Australia, and over the former USSR (Dai *et al.*, 1999). Recent assessments, consistent with Dai *et al.* (1999), show continuing increases in cloudiness in many continental region of the United Sates, over mid-latitude Canada, western Europe, Australia, and over the former USSR, but they indicate decreases in cloudiness over China, Italy, central Europe, and possibly over certain ocean regions (Dai *et al.*, 2006; Trenberth *et al.*, 2007b). Large interdecadal variability in cloud cover has been reported, including a decrease in cloud cover over global land areas (latitude 60°S to 75°N, but excluding the United States and Canada where cloud-cover trends were increasing) from the late 1970s to the mid-1980s were followed by a gradual increase (Trenberth *et al.*, 2007b). The long-term trend remains uncertain (Folland *et al.*, 2001; Trenberth *et al.*, 2007b). The DTR is strongly and inversely related to cloudiness (Dai *et al.*, 1999), and DTR decreased over most global land areas during the latter half of the twentieth century (Easterling *et al.*, 1997). Given the strong relation between cloudiness and DTR, the long-term downward trend in DTR is an indication that cloudiness has increased during the same time period. Increases in cloudiness that result in significant decreases in solar radiation could decrease ET and act to dampen the hydrologic cycle, thus constituting a negative feedback.

3.4. Precipitation

On a globally averaged basis, annual precipitation over land (excluding Antarctica) is estimated to have increased by 9–24 mm (1–3%) during the twentieth century (Dai *et al.*, 1997; Hulme *et al.*, 1998; New *et al.*, 2000). Changes in rainfall amounts over time differ among regions and between different time periods within regions (Trenberth *et al.*, 2007b). Many terrestrial regions experienced significant increases in rainfall; however, other regions experienced decreases during the twentieth century, but the oceans have been poorly studied, so the average global trends remain uncertain. Another recent study averaging all global land surfaces during 1901–2003 found increases in maximum amounts of 1- and 5-day precipitation and in the number of very wet days (Alexander *et al.*, 2006).

Regional variations in precipitation amounts are highly significant. For example, zonally averaged precipitation increased by 7–12% between latitude 30°N and 85°N, compared with a 2% increase between latitude 0°S and 50°S, and precipitation decreased substantially in some regions (Folland *et al.*, 2001; Trenberth *et al.*, 2007b). Groisman *et al.* (2004) reported increases in precipitation over the conterminous United States during the twentieth century, with most of the increase confined to spring, summer, and fall. Increases in precipitation have been reported for most of China (Liu *et al.*, 2005; Ye *et al.*, 2004), with the exception of the North China Plain (Fu *et al.*, 2009).

Seasonal snow-water equivalent (SWE) can be considered a proxy for winter precipitation in many high-latitude regions. Brown (2000) found systematic increases in winter (December through February) SWE over North America averaging 3.9% per decade during 1915–1992. Increases in winter snow accumulation were also reported in Russia from latitude 60°N to 70°N and from longitude 30°E to 40°E, during 1936–1983 (Ye *et al.*, 1998); Canada, north of approximately latitude 55°N (Karl *et al.*, 1993; Zhang *et al.*, 2000); interior (higher elevations) of Greenland (Johannessen *et al.*, 2005; Thomas *et al.*, 2006); and during 1992–2002, in East Antarctica (Zwally *et al.*, 2005). Ye *et al.* (1998) estimated SWE from measured snow depth using a ratio of 10:1 for snow volume to water volume. The large increases in snow depth (4.7% per decade) and the relatively small sensitivity to temperature of the ratio suggest that any error in using a fixed ratio would not alter the results appreciably (Ye *et al.*, 1998). Furthermore, the fact that the observed temperature of the surface air generally increased over this region during most of this period suggests that snow density likely increased, making the fixed ratio over time a conservative estimate. These reports are consistent with the Clausius–Clapeyron relationship, in that increasing winter temperatures result in increased precipitation, depending on the slope of the relationship between snowfall and temperature (Davis *et al.*, 1999).

Human activities that increase the atmospheric burden of sulfate, mineral dust, and black carbon aerosols have the potential to affect the hydrologic cycle by suppressing rainfall in polluted areas and reducing the solar irradiance reaching the Earth's surface (Liepert *et al.*, 2004; Ramanathan *et al.*, 2001; Wild *et al.*, 2004). The primary mechanism for suppressing rainfall is that aerosols increase concentrations of cloud condensation nuclei and reduce the mean size of cloud droplets, resulting in less-efficient coalescence into rain drops (Ramanathan *et al.*, 2001). These effects are thought to be responsible for drier conditions in the north and wetter conditions in the south of China (Menon *et al.*, 2002). Aerosol-induced reduction in solar irradiance reaching the Earth's surface could reduce surface evaporation and, consequently, precipitation and thus dampen the hydrologic cycle (Ramanathan *et al.*, 2001; Wild *et al.*, 2004). Under conditions of reduced evaporation over land, precipitation can increase over land only if there is a corresponding advection of moist air from the oceans to the land (Wild *et al.*, 2004). Whether the overall effects of aerosols will be primarily a spatial redistribution of precipitation that affects only polluted areas, or a more general weakening of the water cycle is uncertain. On the one hand, there is evidence that solar irradiance reaching the land surface has been reduced during the last 50 years (Stanhill and Cohen, 2001), which is consistent with the potential for a dampening of the hydrologic cycle. On the other hand, the evidence for increasing precipitation, evaporation, and runoff over many regions over the same time period suggests that aerosols have not resulted in a widespread, detectable dampening of the hydrologic cycle, at least to date. More recent analyses indicate that trends in aerosol effects on solar irradiance have reversed in recent years and the Earth is now brightening (Wild *et al.*, 2005), thereby reversing the dampening effect on the hydrologic cycle (Andreae *et al.*, 2005; Wild *et al.*, 2008).

Dyurgerov (2003) and Dyurgerov and Meier (in press) showed that seasonal changes in mass balance of about 300 mountain and subpolar glaciers increased in amplitude during the period 1961 through 1998 (Fig. 7). These findings indicated that wintertime increases in glacier mass were related to increases in snowfall amounts and that summertime decreases in mass were related to a warming-induced increased rate of melting. Summertime glacier melting outweighed wintertime ice accretion, resulting in an underlying trend toward declining glacier mass throughout the world (Dyurgerov, 2003, Dyurgerov and Meier, in press; Oerlemans, 2005; Williams and Ferrigno, in press). The increase in snowfall at these sites throughout the world where there are very few robust precipitation measurements is another indication of increasing precipitation over land and is consistent with a recent intensification of the global hydrologic cycle.

3.5. Runoff

An analysis of trends in continental runoff from major rivers worldwide from 1910 through 1975 found that runoff increased about 3% (Probst and Tardy, 1987). A reanalysis of these trends from 1920 to 1995, in which data were reconstructed to fill in missing records, confirmed an increase in world continental runoff during the twentieth century (Labat *et al.*, 2004). Labat *et al.* (2004, p. 631) conclude, " . . . this contribution provides the first experimental data-based evidence demonstrating the link between global warming and the intensification of the global hydrologic cycle." In a recent global land-surface modeling study, Gerten *et al.* (2008) reported that during 1901–2002, global river discharge increased by 30.8 $km^3\ a^{-2}$, equivalent to 7.7%, due primarily to increasing precipitation. In contrast to these findings, Dai *et al.* (2009) reported no increase in global river discharge, and recent reviews have been inconclusive (Bates *et al.*, 2008; Trenberth *et al.*, 2007b).

In regional studies, increases in precipitation have been associated with corresponding increases in runoff in river basins in the conterminous United States (Groisman *et al.*, 2001; Lins and Slack, 1999; McCabe and Wolock, 2002) (Fig. 8). In Canada, by contrast, increasing temperature, combined with almost no change in precipitation, resulted in no change in annual

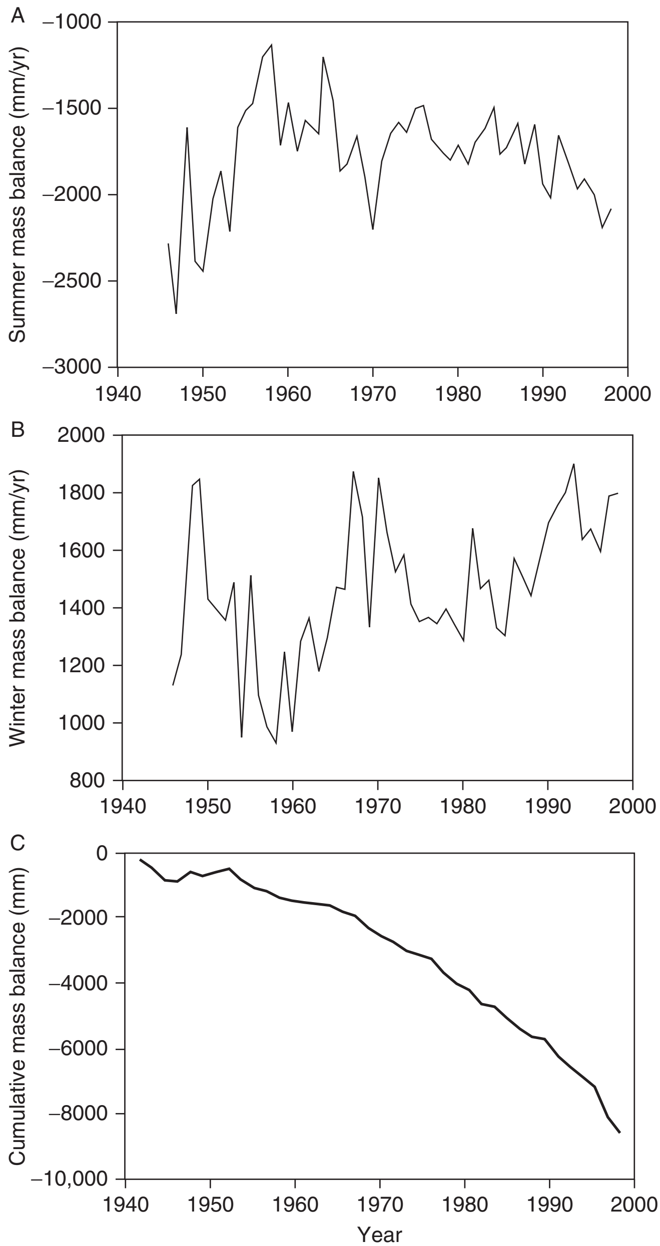

Figure 7 Summer (A), winter (B), and cumulative annual (C) trends in glacier mass balance for about 300 mountain and subpolar glaciers outside Greenland and Antarctica. Figure modified from Dyurgerov (2003), and used with permission.

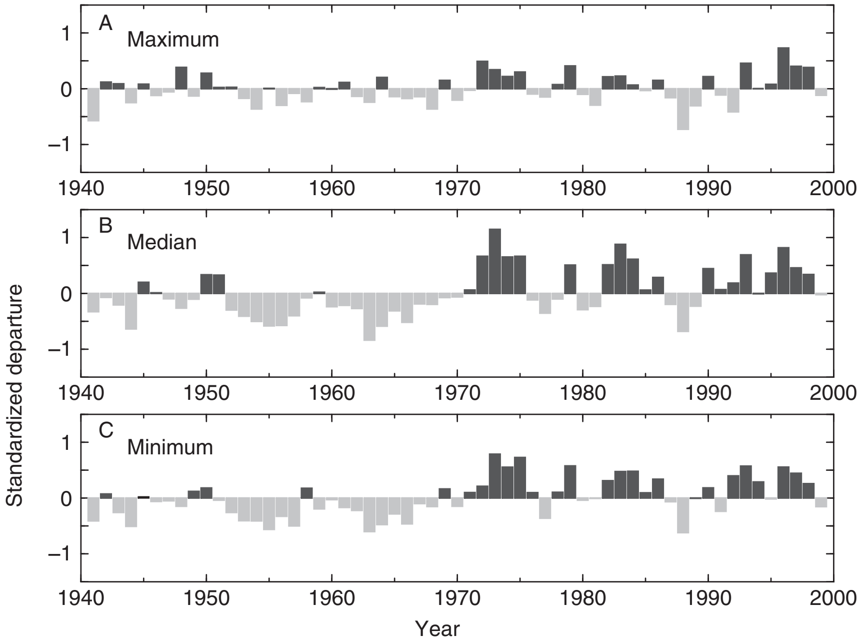

Figure 8 Mean standardized departures of annual maximum (A), median (B), and minimum (C) daily streamflow for 400 sites in the conterminous United States (1941–1999). Modified from McCabe and Wolock (2002), and used with permission.

streamflow from 1947 to 1996 for most regions (Zhang *et al*., 2001a). One striking exception in Canada is the Winnipeg River Basin, where precipitation and runoff have increased markedly (St. George, 2006). The basins studied in North America were selected because of minimal human perturbations to the hydrologic cycle. Typical criteria for basin selection exclude basins where consumptive use, land-use changes, intrabasin diversions, and/or significant regulation through the management of reservoir levels could influence flow (Harvey *et al*., 1999; Slack and Landwehr, 1992). There have been no globally extensive studies on trends in streamflow from minimally impacted basins. Uncertainty remains about whether increasing ET could offset increasing precipitation and the melting of ice and permafrost, ultimately resulting in decreased freshwater inputs to the Arctic (Anisimov *et al*., 2001).

Increases in precipitation and runoff have been shown to be quite variable among different regions (Karl and Riebsame, 1989; Keim *et al*., 1995). Recent reports indicate increasing annual streamflow in Arctic rivers (Fig. 9) (Lammers *et al*., 2001; McClelland *et al*., 2004; Peterson *et al*., 2002) and in western Russia (Georgievsky *et al*., 1996). Precipitation increased, snowfall decreased, and runoff decreased or did not change during the latter

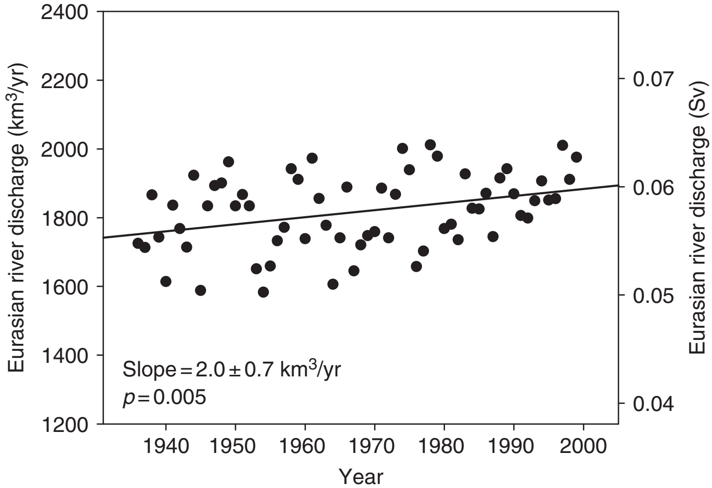

Figure 9 Trend in combined annual discharge from the six largest Eurasian arctic rivers from 1936 to 1999. Units are in $km^3\ a^{-1}$ and in Sverdrup units ($1\ Sv = 10^6\ m^3\ s^{-1}$). Modified from Peterson *et al.* (2002), and used with permission.

half of the twentieth century in the Tien Shan mountains in northern Eurasia (Aizen *et al.*, 1997). In other parts of China, trends in streamflow are mixed (Tao *et al.*, 2003). Streamflow has increased in the upper Yangtze River (Zhang *et al.*, 2006) but decreased in the Yellow River (Chen *et al.*, 2003; Jiongxin, 2005). The decrease in runoff may be associated with decreasing meltwater from receding glaciers (Aizen *et al.*, 1997; Khromova *et al.*, 2003). Increases in runoff have been observed in major river basins in South America (Berbery and Barros, 2002; Garcia and Mechoso, 2005). There have also been reported increases in streamflow in Switzerland (Birsan *et al.*, 2005), Finland (Hyvärinen, 2003), and other Nordic countries (Hisdal *et al.*, 2004).

It is evident that temporal trends in river discharge are variable among regions and that the long-term global trend is not clearly identified (Bates *et al.*, 2008). Human alterations, including irrigation, dam building (including multiple dams on several major river systems), changes in land cover, and extraction of groundwater affect river discharge (Vörösmarty and Sahagian, 2000), but these are of minor importance on a global scale compared with precipitation and ET (Gerten *et al.*, 2008). In some regions, climate warming may cause increasing precipitation and compensating increases in ET that, combined, result in no increase in river discharge.

These results for major rivers, in conjunction with independent reports of increasing runoff from many smaller rivers in the Northern Hemisphere, provide possible evidence for the validity of the conceptual framework for an intensification of the hydrologic cycle. These increases in runoff are consistent with the results of modeling studies that suggest that runoff is likely to increase in high latitudes and in many equatorial regions, but decrease in the middle latitudes and some subtropical regions as a result of differential responses to climate warming in different regions (Alcamo *et al.*, 1997; Kundzewicz *et al.*, 2007; Manabe *et al.*, 2004). A modeling and observational analysis of the Arctic Ocean freshwater budget from 1950 through 2050 is consistent with an acceleration of the Arctic hydrologic cycle: freshwater inputs to the ocean from net precipitation to the ocean surface increased as did river runoff and net ice melt (Holland *et al.*, 2007; Rawlins *et al.*, in press). It is worth noting that if rates of ET increase more than rates of precipitation, then runoff would decrease, even if precipitation increased.

Human modifications of the landscape can have large effects on trends in runoff from some river basins. Conversion from forest to agricultural land may increase runoff from rivers (Vörösmarty and Sahagian, 2000); in other cases, abandonment of agricultural land and subsequent reforestation could result in decreases in runoff. Consumptive use, such as crop irrigation, has greatly decreased flow from some rivers, such as the Syr Darya River and Amu Darya River, which drain into the Aral Sea in central Asia (Vörösmarty and Sahagian, 2000), and the Yellow River in China (Chen *et al.*, 2003). Reservoir construction can have short-term effects on stream flow as reservoirs fill and longer term effects if evaporation losses are high. The net annual effect of reservoirs on the global hydrologic cycle is diminishing, however, because the rate of large reservoir construction has declined markedly in recent decades (Avakyan and Iakovleva, 1998).

Major river basins integrate the effects of climate variation, of human engineering projects, and changes in land cover, making it difficult to accurately determine the cause of changes in the basin. In addition, some part of the increase in runoff from river basins containing "permanent" ice and snow is likely attributable to the melting of glaciers and permafrost rather than to increased precipitation (see, e.g., Kulkarni *et al.*, 2003; McClelland *et al.*, 2004; Yang *et al.*, 2002). McClelland *et al.* (2004) concluded that increasing precipitation was the most viable explanation for increasing Arctic river discharge.

The Mississippi River Basin has had well-documented increases in precipitation and runoff during the latter half of the twentieth century. The mean annual discharge from the Mississippi River from 1949 through 1997 was 187 mm a^{-1} and during this period it increased by 0.85 mm a^{-2}, or 25% (Milly and Dunne, 2001). During the same time period, mean annual precipitation was 835 mm a^{-1} and during this period it increased by 1.78 mm a^{-2}, or 11% (Milly and Dunne, 2001). During the same time period mean annual ET was 649 mm a^{-1} and during this period, it increased by 0.95 mm a^{-2}, or 7% (Milly and Dunne, 2001). Anthropogenic changes in the hydrologic cycle in the Mississippi River Basin during the twentieth century have been comparatively small and dominated by increases in consumptive use that cause a decrease in runoff (Milly and Dunne, 2001). Two of the more significant changes in the Mississippi River Basin in the twentieth century are the abandonment of cultivated farmlands and their conversion to forest or pasture, particularly in the southeastern part of the basin (Clawson, 1979; Wear and Greis, 2002) and the construction of numerous large dams. Both of these changes would have decreased runoff. Increasing precipitation and runoff in the Mississippi River Basin from 1949 through 1997 is consistent with an intensification of the global hydrologic cycle.

3.6. Soil Moisture

Soil-moisture content increased during the last several decades in parts of Eurasia (Robock *et al.*, 2000) and in much of the continental United States during the twentieth century (Andreadis and Lettenmaier, 2006). Recently, Sheffield and Wood (2008) reported a weak trend toward an increase in global soil moisture from 1950 through 2000. This upward trend has occurred simultaneously with an increasing temperature trend that would otherwise (in the absence of increased rainfall) be expected to decrease soil moisture. In this case, increases in precipitation are thought to have been more than compensated for by increased losses due to increases in ET (Robock *et al.*, 2000; Sheffield and Wood, 2008). In addition to directly indicating an intensification of the global hydrologic cycle directly, in soil moisture suggest the potential for increasing ET and thereby indirectly intensifying the global hydrologic cycle. The response of soil moisture to climate warming may not be monotonic; rather, it is possible that in some regions soil moisture might first increase in response to increasing precipitation but then decrease because ET may increase faster than precipitation as temperature rises. Yamaguchi *et al.* (2005) have shown that soil moisture could initially increase in summer in northern high latitudes as thaw depth increased, but simulations show that in the late twenty-first century, a reduction in soil moisture eventually occurs (Kitabata *et al.*, 2006).

3.7. Precipitation recycling

Precipitation recycling is the process whereby precipitation falls within a specific area, returns to the atmosphere over that area by evaporation and transpiration, and condenses and falls as precipitation again over the same area (Brubaker *et al.*, 1993; Eltahir and Bras, 1996). Intensification of the hydrologic cycle can include an increase in the average global rate of precipitation recycling where the precipitation is derived from local evaporation and transpiration rather than an increase in moisture advected from outside of the area of interest. Recent investigations have defined the precipitation-recycling ratio as the ratio of precipitation derived from moisture originating within the region of interest to moisture advected from outside the region. These studies have attempted to determine if the P-recycling ratio has changed over time. The P-recycling ratio is proportional to the size of the area of interest; the larger the area, the higher the P-recycling ratio (Dirmeyer and Brubaker, 2007; Dominguez *et al.*, 2006; Trenberth, 1999). A regional decrease in the P-recycling ratio has been associated with the persistence of drought (Brubaker *et al.*, 1993).

In global studies using observations and a water-vapor-tracing algorithm, Dirmeyer and Brubaker (2006, 2007) found trends in the P recycling ratio from 1979 through 2003 over large areas at high latitudes that are consistent with an expansion into spring of the warm-season regime of water-vapor recycling. They noted that the trends were consistent with observed vegetation-related changes often attributed to global climate change, and were most evident over northern Europe and North America where the density of meteorological data influencing the atmospheric analyses is high. Dirmeyer and Brubaker (2006, 2007) found that the increase in recycling ratio was much stronger in spring and fall as would be expected if the increased moisture were derived from higher ET resulting from a longer growing season.

By contrast, Serreze *et al.* (2003) reported that there was no trend in the P-recycling ratio for the Arctic basins of the Lena, Yenisey, Ob, and Mackenzie Rivers from 1960 through 1999. For the Amazon River Basin, it has been shown that an increase in precipitation derived from moisture advected from outside the basin, associated with a 50-year trend toward increasing sea-surface temperatures over the South Atlantic, is associated with a decrease in P-recycling (Bosilovich and Chern, 2006).

4. Mount Pinatubo: The Natural Experiment in Aerosol Optical Depth

The explosive eruption of Mount Pinatubo in 1991 provided a natural experimental test of the hypothesis that global cooling would dampen (weaken or decelerate) the hydrologic cycle. Whereas this review chapter examines the evidence for a warming-induced intensification of the hydrologic cycle over the long-term historical observations, the response to the Mount Pinatubo explosive eruption constitutes a complementary test of the reverse hypothesis, albeit over a much shorter time period. Evidence for dampening of the hydrologic cycle following cooling would provide evidence of the same mechanism whereby warming causes intensification of the hydrologic cycle.

The eruption of Mount Pinatubo in 1991 resulted in an injection of sulfur dioxide into the lower stratosphere (Hansen *et al.*, 1992; Harries and Futyan, 2006; Robock and Oppenheimer, 2003). The sulfur dioxide was oxidized to sulfate particles (aerosols) that remained in the atmosphere for more than 1 year. The increase in the atmospheric burden of sulfate aerosols increased atmospheric albedo (reflectance) by up to 0.007 resulting in the reflection of up to an additional 2.5 W m^{-2} of solar radiation during the following 2 years (Harries and Futyan, 2006; Wielicki *et al.*, 2005). The result of the increase in albedo was a decrease in the absorbed short wave-length solar radiation at the Earth's surface of 3–4.5 W m^{-2} from late 1991 through 1992 (Soden *et al.*, 2002). The reduction in absorbed solar radiation, in turn, resulted in a decrease in global average surface air temperature of up to about 0.5 °C in 1992 relative to the long-term average prior to the eruption (Soden *et al.*, 2002).

Effects on global hydrologic variables were detected in the years following the eruption of Mount Pinatubo that are consistent with the effects of increasing atmospheric sulfate aerosols on the Earth's radiation budget. Atmospheric water-vapor content (total water column in the atmosphere) decreased by up to about 0.75 mm (~3%) in 1992 (Randel *et al.*, 1996; Soden *et al.*, 2002). During the period October 1991 through September 1992, global precipitation was 3.12 standard deviations below normal from 1950 through 2004 (Fig. 10) (Trenberth and Dai, 2007). Moderate or severe

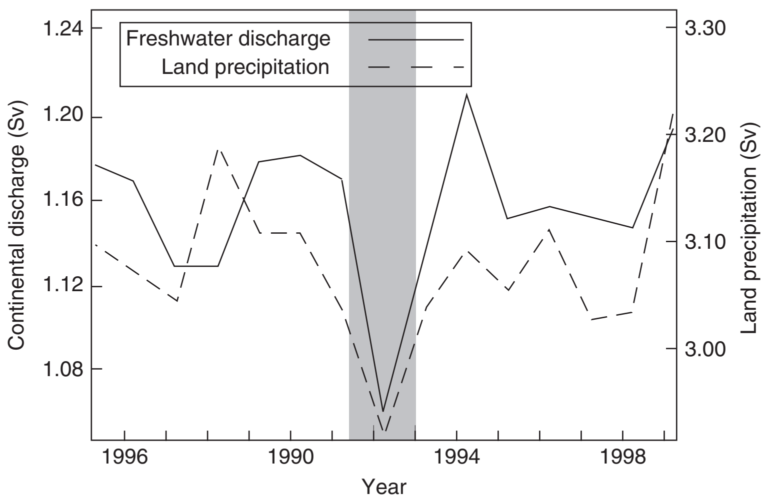

Figure 10 Time series of the annual water year (October to September) continental freshwater discharge and land precipitation in Sverdrup units (1 Sv = 10^6 m^3 s^{-1}). The period clearly influenced by the Mount Pinatubo eruption is indicated by grey shading. Modified from Trenberth and Dai (2007), and used with permission.

drought (as inferred from the Palmer Drought Severity Index (PDSI)) was widespread in 1992 (Dai *et al.*, 2004). Trenberth and Dai (2007) reported that during October 1991 through September 1992, global continental runoff was by far (3.67 standard deviations below normal) the lowest recorded during the period 1950–2004 (Fig. 10). The observed changes in global surface air temperature, atmospheric water-vapor content (Fig. 10), precipitation, and continental runoff are strong evidence for a global cooling-induced dampening of the hydrologic cycle. This, in turn, supports the hypothesis that warming is intensifying the hydrologic cycle.

5. Hydrologic Responses to Intensification—Extreme Events (Including Droughts)

One of the more important potential consequences of an intensification of the hydrologic cycle is that the frequency, intensity, or duration of severe weather may change (Kundzewicz *et al.*, 2007). It is noteworthy that whereas recent evidence points toward increases in atmospheric water vapor and precipitation in the range of 7% °C as discussed earlier, the intensity of precipitation extremes may increase at substantially lower rates (O'Gorman and Schneider, 2009). Considerable emphasis has been placed on testing whether the frequency or intensity of hurricanes, typhoons, floods, and droughts has changed during the period of observational record. Economic losses from damages associated with natural disasters increased during the latter part of the twentieth and early twenty-first century but adjusting for time-variant economic factors and the value of properties in the path of major storms and floods has not shown a large upward trend over time (Rosenzweig *et al.*, 2007). Insurance companies and the international reinsurers that underwrite them have expressed serious concern about their potential for increased liability for claims involving weather-related natural disasters, if climate warming results in increasing frequency, intensity, or both, of severe weather (Berz, 1999; Lindenschmidt *et al.*, 2005). Increases in precipitation in the higher precipitation quantiles have been observed in regional studies (Dai *et al.*, 1997; Folland *et al.*, 2001; Groisman *et al.*, 2004; Hayhoe *et al.*, 2007; Hulme *et al.*, 1998; Klein Tank *et al.*, 2002; Kunkel *et al.*, 2008; Tebaldi *et al.*, 2006; Trenberth *et al.*, 2007b). Increases in property losses (adjusted for increases in property values) due to hailstorms during 1950–2006 increased substantially (Changnon, 2009).

Observed twentieth-century increases in precipitation, particularly in higher precipitation quantiles (e.g., Groisman *et al.*, 2004), may have increased the frequency of flooding. However, a review of the empirical evidence to date does not consistently support an increase in the highest flow quantiles globally (Kundzewicz *et al.*, 2005) nor regionally in the

United States (Collins, 2009; Douglas *et al.*, 2000; Lins and Slack, 1999; McCabe and Wolock, 2002; Vogel *et al.*, 2001), Canada (Zhang *et al.*, 2001b); Scandinavia (Hyvärinen, 2003; Lindstrom and Bergstrom, 2004); or central Europe (Brázdil *et al.*, 2006; Mudelsee *et al.*, 2003). In contrast with these studies, Milly *et al.* (2002) reported that the frequency of floods with discharges exceeding 100-year levels from 29 basins larger than 200,000 km^2 increased substantially during the twentieth century. Milly *et al.* (2002) also stated that their conclusions were tentative and that the frequency of floods having return intervals shorter than 100 years has not changed.

Several time-series analyses of tropical storms have found no evidence for an increase in frequency (Chan and Liu, 2004; Easterling *et al.*, 2000; Elsner *et al.*, 2004; Folland *et al.*, 2001; Landsea *et al.*, 2009; Solow and Moore, 2002; Vecchi and Knutson, 2008), intensity (Free *et al.*, 2004), or duration of the storm season (Balling and Cerveny, 2003) during the twentieth century. However, other recent analyses have reported increases in storm frequency and intensity. For example, Emanuel (2005) reported increasing destructiveness of tropical cyclones in recent decades. Webster *et al.* (2005) evaluated data on the intensity of tropical cyclones and on the number of tropical cyclones and cyclone days during the past 35 years; they found a large increase in the number and proportion of hurricanes reaching categories 4 and 5 on the Saffir–Simpson scale, the categories of which range from 1 (least intense) to 5 (most intense). Hoyos *et al.* (2006) showed that the trend of increasing numbers of category 4 and 5 hurricanes for 1970–2004 is directly linked to the global trend in rising sea-surface temperature. Klotzbach (2006) and Klotzbach and Gray (2008) analyzed trends in global tropical-cyclone activity during recent decades and reported a positive upward trend in tropical-cyclone intensity and longevity for the North Atlantic basin, and a considerable negative downward trend for the Northeast Pacific, but no net trend in global activity. Curry *et al.* (2006) reviewed the evidence for a linkage between climate warming, increasing sea-surface temperature, and an increase in hurricane intensity; they report substantial evidence to support the hypothesis that warming has resulted in increasing sea-surface temperature and that the number of more intense hurricanes has increased since 1970. Given that storm intensity is related to wind speed, the question of whether wind speed is increasing is of considerable importance. Recent studies suggest a decrease in wind speed measured over land areas in recent decades, although there are inconsistencies depending upon the data or methods used (e.g., Brazdil *et al.*, 2009; McVicar *et al.*, 2008; Pryor *et al.*, 2009; and references therein). The state of science on this issue might be best summarized by the World Meteorological Organization's "Summary Statement on Tropical Cyclones and Climate Change" released in December 2006: "Although there is evidence both for and against the existence of a detectable anthropogenic signal in the tropical cyclone record to date, no firm conclusion can be made on this point." (http://www.wmo.ch/pages/prog/avep/tmrp/documents/iwtc_summary.pdf).

Drought frequency, intensity, and duration is another aspect of extreme weather that could be affected by intensification, if there are associated changes in the spatial and temporal pattern of precipitation and regional changes in the relative rates of precipitation and ET. From 1900 to 1995, large, multiyear-to-decadal variations in the percentage of land area undergoing severe drought or receiving surplus moisture were observed; however, secular trends were small (Dai *et al.*, 1998). After the late 1970s, the combined percentage of areas with severe drought or moisture surplus expanded, resulting from increased extent of either the drought area (e.g., in the Sahel, eastern Asia, and southern Africa) or of both the drought and wet areas (e.g., in the United States and Europe) (Dai *et al.*, 1998, 2004). For a given value of ENSO intensity, the response in areas affected by drought or by excessive wetness was more extreme after 1970 (Dai *et al.*, 1998). There is great uncertainty in the potential relation between climate warming and the frequency and strength of ENSO events (e.g., Collins and The CMIP Modelling Groups, 2005; Latif and Keenlyside, 2009) although an increase in the frequency or intensity of El Nino events is possible (Herbert and Dixon, 2002; Timmermann *et al.*, 1999) and a regime shift was noted after 1970 (Latif and Keenlyside, 2009). In a global analysis, Dai *et al.* (2004) concluded that the proportion of the land surface characterized as "very dry" (PDSI < -3.0) more than doubled since the 1970s, and that global "very wet" areas (PDSI $> +3$) declined slightly since the 1970s. An increase in the proportion of land area in drought since the 1970s is also reported by Burke *et al.* (2006). These changes are highly variable among regions and are attributed to both ENSO-induced decreases in precipitation and to warming-induced increases in evaporation and ET; however, the changes are consistent with increasing risk of more frequent and more intense drought over some regions (Dai *et al.*, 2004). In a global analysis using a soil-moisture-based index derived from the variable infiltration capacity (VIC) model, Sheffield and Wood (2008) reported a longer term (1950–2000) trend toward a decrease in drought but a weak trend reversal towards increasing drought after 1970.

6. Potential Impacts on Agriculture

6.1. General findings and projections

Recent assessments have evaluated a wide range of potential effects of climate change on agriculture (food and fiber) (Easterling *et al.*, 2007; European Environmental Agency, 2007; CCSP, 2008). A comprehensive review of these effects, even one confined to the potential effects of an intensification of the hydrologic cycle, is beyond the scope of this chapter. Interested readers are encouraged to explore the cited international and national assessments. The following section will briefly summarize many of the potential impacts on agriculture that could occur as a result of an intensification of the hydrologic cycle. It should be noted that the assessments cited above include both positive and negative impacts on agriculture from projected increases in temperature, precipitation, atmospheric-CO_2 concentration, and increases in the frequency, intensity, and duration of extreme-weather events. Climate changes will also likely result in poleward migration of climates suitable for specific crops or forest tree species (Schröter *et al.*, 2005). The largest uncertainty in assessing impacts on agriculture is whether precipitation regimes will become more or less favorable compared with historical observations. Increasing precipitation during the growing season in regions prone to drier than optimal conditions would likely constitute a positive impact of a warming-induced intensification of the hydrologic cycle, provided extremes in precipitation do not increase to the point where agriculture is adversely affected.

The primary impact of an intensification of the hydrologic cycle on agriculture will likely be highly regionally specific and related most closely to changes in precipitation regime, where "regime" includes precipitation frequency, intensity, and duration. Substantial changes that result in wetter or drier conditions could have adverse or favorable effects on crop, pasture, rangeland, forest, and livestock systems. There would also be interactions between changes in precipitation regime, increasing temperature, and lengthening of the growing season, all affecting transpiration, that could affect agriculture in complex ways. Of particular interest is the possibility that intensification could include an increase in frequency of heavy rainfall, flooding, droughts, hurricanes, wind storms, and ice storms. All of these extreme-weather events would be potentially damaging to agricultural production through direct crop losses or indirectly by weakening plant resistance to insects and diseases. Many regions have experienced increases in heavy rainfall or drought conditions and modeling studies have suggested that these regions are likely to experience similar increases in the future (Christensen *et al.*, 2007; Good *et al.*, 2006; Klien Tank, 2004; Kunkel *et al.*, 2008; Palmer and Räisänen, 2002; Palutikof and Holt, 2004).

6.2. Primary effects on forests

Increases in precipitation are likely to result in increases in forest productivity in water-limited regions (Knapp *et al.*, 2002) provided there are no other limitations to growth such as nutrients (Boisvenue and Running, 2006). In some regions, increases in precipitation could exacerbate existing nutrient limitations because the increases could accelerate leaching losses; for example, leaching of calcium and magnesium may be accelerated in acidic forest soils (Huntington, 2005). Decreases in precipitation and increases in drought are likely to reduce forest productivity, especially in regions where water is already limiting. Changes in precipitation can interact with increasing temperature to result in indirect adverse effects on forests. For example, increasing rainfall and temperature could increase over-winter survival, abundance, or virulence of forest insect pests or diseases. One example is the effect of drought that weakens the resistance of Pinyon Pine to Ips beetle (*Ips confusus*) that has greatly increased tree mortality in the western United States in recent years (Ryan *et al.*, 2008). Many recent insect-related, forest-mortality events in North America may be related to both increases in temperature and drought (Ryan *et al.*, 2008). Projected climate change in the northeastern United States is expected to increase the negative impacts of insect pests and diseases in the forests (Dukes *et al.*, 2009). An increase in the frequency and severity of forest fires in the western United States (Westerling *et al.*, 2006) and in boreal forests (Kasischke and Turetsky, 2006) has been related to increasing temperature and drier soil conditions. Droughts also weaken trees, making them less likely to survive forest fire (Westerling *et al.*, 2006). It is also likely that forest-species composition will change if precipitation changes substantially (Breshears *et al.*, 2005).

6.3. Potential primary effects on cropland, pasture, and livestock

Elevated atmospheric-CO_2 concentrations are expected to result in positive effects on crop growth for many agriculturally important plant species, but potential increases in productivity may not be as high as once thought, and increases in temperature and changes in precipitation regime, including increasing frequency of extreme-weather events, could outweigh potential benefits (Easterling *et al.*, 2007). Elevated atmospheric-CO_2 concentrations also have the potential to improve water-use efficiency, thereby enhancing adaptive capacity toward drought in some situations, but the global-scale potential benefits are uncertain because of the interactions among the many variables that control plant-water relations (Allen *et al.*, 2003; Centritto, 2005; Huntington, 2008; Schäfer *et al.*, 2002; Wullschleger *et al.*, 2002).

The primary impacts of an intensification of the hydrologic cycle on crop plants are likely to be a result of changes in precipitation regime that cause increasing frequency of extreme-weather events, including flooding, heavy downpours, droughts, and increases in variability (Easterling *et al.*, 2007; European Environmental Assessment, 2007; Hatfield *et al.*, 2008; Porter and Semenov, 2005). More frequent flooding of fields could lead to crop losses directly or indirectly due to lowering soil O_2, increasing susceptibility to root diseases, or increasing soil compaction and subsequent loss of soil aeration due to use of heavy equipment on wet soils (Hatfield *et al.*, 2008; Rosenzweig *et al.*, 2002). Heavy downpours and flooding could cause severe erosion and sedimentation that degrade soils and decrease productivity. Excessively wet conditions during harvesting could reduce the quality of many crops, including hay and silage. Increasing frequency of drought would reduce crop yields in non-irrigated areas that are already prone to water limitations and increase water demands in irrigated areas (Easterling *et al.*, 2007). Droughts would be exacerbated by higher temperatures because of increases in crop water requirements under warmer temperatures (Hatfield *et al.*, 2008; Lobell and Field, 2007). Drought adds to the multiple interacting stresses including excessively high temperatures, ozone, pests and pathogens, and soil degradation acting on agricultural systems, reducing resilience and adaptive capacity. More frequent heavy rainfall and flooding would most likely increase losses of agricultural chemicals, which would increase the potential for contamination and eutrophication of water bodies and may result in a need for more frequent chemical applications.

Increases in temperature, precipitation, and humidity would also affect plant pathogens (Coakley *et al.*, 1999; Evans *et al.*, 2008). Leaf and root pathogens are highly responsive to increases in humidity and rainfall; therefore, climate changes that lead to these increases would likely lead to an increase in plant diseases (Coakley *et al.*, 1999). Increases in climate extremes may also promote more frequent plant diseases and pest outbreaks, and the range and severity of outbreaks is likely to increase (Easterling *et al.*, 2007; Evans *et al.*, 2008; Gan, 2004).

Heat stress can result from excessively high temperatures and high-specific humidity. As humidity increases, the heat stress associated with a given temperature increases. The evidence is mounting that specific humidity is increasing with increasing surface-air temperature while relative humidity remains constant, as noted earlier (Section 3.2). Heat stress can have many negative impacts on livestock, including decreases in weight gain and lower reproductive success (Easterling *et al.*, 2007; Hatfield *et al.*, 2008). One of the effects of heat stress in agricultural systems is that it can cause decreases in milk production (Hatfield *et al.*, 2008; Klinedinst *et al.*, 1993; Wolfe *et al.*, 2008). Heat stress also reduces the ability of livestock to cope with parasites and disease pathogens (Easterling *et al.*, 2007; Hatfield *et al.*, 2008). Parasites or pathogens that thrive under conditions of higher temperatures and higher humidity may become more virulent and migrate poleward as the climate warms (Easterling *et al.*, 2007). Livestock are especially at risk under conditions of increasing drought (Easterling *et al.*, 2007). Human populations are also likely to suffer more from heat stress as the climate warms because of more frequent excessively high temperatures and accompanying increases in specific humidity (Gaffen and Ross, 1998; Jendritzky and Tinz, 2009).

Intensification of the hydrologic cycle could have substantial effects on the rate of soil erosion, particularly in cultivated agricultural soils. Nearing *et al.* (2004) reviewed a number of studies that related changes in rainfall regime to changes in erosion rate to assess potential impacts of climate change. The most robust response was that if the intensity (mm h^{-1}) and duration of major rainfall events (erosivity) increases, then the rate of erosion will increase. Increases in rainfall intensity and duration have been observed during the twentieth century and are expected to increase further during the twenty-first century as noted earlier (Section 5). In most studies, increases in rainfall amounts lead to increases in soil erosion (see Nearing *et al.*, 2004 and studies cited therein). Nearing *et al.* (2004) noted that if more winter precipitation falls as rain rather than snow, as has been observed in parts of the United States (Huntington *et al.*, 2004; Knowles *et al.*, 2006), then soil-erosion rates are likely to increase in these regions. Nearing (2001) used GCM projections together with the Water Erosion Prediction Project (WEPP) model to assess the impacts of climate change on erosion and concluded that increases in erosion between 17% and 58% by 2100 compared with current rates were likely. They noted that there would very likely be large regional variations depending on soil, vegetation, management practices, and biological responses to other aspects of climate change. If warming-soil temperatures result in net losses of soil organic matter, soil structure could be degraded and potential erodibility could be increased (Huntington, 2003b).

7. Conclusions

Temporal trends in the components of the hydrologic cycle including evaporation, ET, water vapor, precipitation, and runoff were reviewed to assess whether the evidence suggested an intensification of the hydrologic cycle during the twentieth century. This assessment is complicated by a lack of spatially, temporally, and methodologically consistent data and overall variability in trends among regions and within regions over time. Water-balance studies based on long-term observations in some large river basins, notably the Mississippi and La Plata Rivers, strongly support an ongoing intensification. Analyses of other river basins, such as those in the pan-Arctic regions that have shorter and less-complete records, are generally consistent with intensification, but with more spatial variability and less certainty for some components of the hydrologic cycle.

There is relatively strong support for intensification from trends in variables such as evaporation, ET, and atmospheric water-vapor concentrations. Trends in precipitation, runoff, and soil moisture are more uncertain. One of the more consistent findings is that trends in some regions are consistent with increasing precipitation, while other regions have experienced drying. Regional and hemispheric spatial-scale studies exhibit consistent and strongly positive trends toward increases in the duration of the growing season that are consistent with observations of increasing temperature and ET. Taken together, these observations support an ongoing intensification of the hydrologic cycle.

Preliminary studies on trends in precipitation recycling in the Northern Hemisphere are also generally consistent with an intensification of the hydrologic cycle. Hydrologic responses to the eruption of Mount Pinatubo provided a natural experimental test that indicated that global cooling weakened the hydrologic cycle, lending further support to the process of warming-induced intensification. The evidence for an increase in the frequency, intensity, or duration of extreme-weather events like hurricanes is mixed and remains uncertain. There are weak trends toward increases in the frequency and intensity of heavy rainfall events; however, some studies have reported weak trends toward increasing frequency of drought.

On balance, the preponderance of evidence supports an ongoing intensification of the hydrologic cycle with significant regional variations, including drying trends in some areas. Overall, the trends indicate increases in evaporation, ET, and atmospheric water-vapor content with implications for the strength of the water-vapor feedback and with potential impacts to agricultural systems. Recent projected temperature increases in the twenty-first century are within the ranges associated with "tipping points" or critical thresholds beyond which the state of specific climate systems could change, resulting in major adverse environmental consequences (Lenton *et al.*, 2008; Ramanathan and Feng, 2008; Schellnhuber *et al.*, 2006; Smith *et al.*, 2009). These analyses have argued that anthropogenic increases in greenhouse gases have already committed the Earth to significant environmental changes. Many effects are likely to involve changes in regional hydrologic regimes and result in impacts on human, other animal, and plant populations. Ironically, one of the most dangerous potential impacts of intensification of the hydrologic cycle is the likelihood that drought will become more prevalent and more severe in some regions.

The largest potential impacts to agricultural systems depend greatly on the responses of hydrologic variables that are the most uncertain; for example, intensity and duration of heavy-rainfall events; frequency, intensity and duration of major storms (e.g., hurricanes, typhoons) and droughts; and rates of erosion. Impacts on agriculture will depend greatly on how insects, diseases, weeds, nutrient cycling, effectiveness of agrichemicals, and heat stress are affected by an intensification of the hydrologic cycle.

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