



Evidence for intensification of the global water cycle: Review and synthesis

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Abstract

One of the more important questions in hydrology is: if the climate warms in the future, will there be an intensification of the water cycle and, if so, the nature of that intensification? There is considerable interest in this question because an intensification of the water cycle may lead to changes in water-resource availability, an increase in the frequency and intensity of tropical storms, floods, and droughts, and an amplification of warming through the water vapor feedback. Empirical evidence for ongoing intensification of the water cycle would provide additional support for the theoretical framework that links intensification with warming. This paper briefly reviews the current state of science regarding historical trends in hydrologic variables, including precipitation, runoff, tropospheric water vapor, soil moisture, glacier mass balance, evaporation, evapotranspiration, and growing season length. Data are often incomplete in spatial and temporal domains and regional analyses are variable and sometimes contradictory; however, the weight of evidence indicates an ongoing intensification of the water cycle. In contrast to these trends, the empirical evidence to date does not consistently support an increase in the frequency or intensity of tropical storms and floods.

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1. Introduction

There is a general consensus that global average surface air temperature increased during the 20th century, and, although there is great uncertainty about the magnitude of future increases, most assessments indicate that future warming is ‘very likely’ (Houghton et al., 2001; NAST, 2001; ACIA, 2004). There is also a theoretical expectation that climate

warming will result in increases in evaporation and precipitation leading to the hypothesis that one of the major consequences will be an intensification (or acceleration) of the water cycle (DelGenio et al., 1991; Loaciga et al., 1996; Trenberth, 1999; Held and Soden, 2000; Arnell et al., 2001). The theoretical basis for this intensification is summarized in the Clausius–Clapyeron relation that implies that specific humidity would increase approximately exponentially with temperature. Recent modeling studies suggest that as a consequence of this relation precipitation would increase by about 3.4% per degree Kelvin (Allen

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and Ingram, 2002). The slope of this relation is substantially less than the 6.5% per degree Kelvin indicated by the Clausius–Clapyeron relation because evaporation would be energy limited (Allen and Ingram, 2002).

It is now well established that surface air temperatures and precipitation over land have increased during the 20th century (Folland et al., 2001). Results from recent simulations using one of about 20 coupled ocean–atmosphere–land models based on the IS92A mid-range emission scenario indicate that global mean surface air temperature, precipitation, evaporation, and runoff will increase 2.3 °C, 5.2, 5.2, and 7.3%, respectively, by 2050 (Wetherald and Manabe, 2002). As global temperature increased considerably over the 20th century, especially since the 1970s, (Jones and Moberg, 2003), it is reasonable to ask whether trends in hydrologic variables and related indicators are consistent with an intensified water cycle during that period. Consistency among indicator variables would greatly strengthen our confidence in projections of the potential vulnerability of water resources that could be caused by future temperature increases. Some aspects of an intensified water cycle, such as more frequent occurrence of extreme events, are a potential threat to at-risk populations. Tropical storms, floods, and droughts can affect human welfare directly through catastrophic damage or indirectly through adverse effects on crop productivity. Such threats are likely to occur disproportionately in developing countries with the fewest resources for mitigation and adaptation (Arnell et al., 2001; Manabe et al., 2004).

Several lines of evidence can be used to assess the hypothesis of a warming-induced intensification of the water cycle. The trend analyses reviewed in this paper were conducted at various spatial and temporal scales that are not directly comparable among studies or variables. In spite of these limitations, synthesizing the results from a number of studies can provide an insight into the response of the water cycle to past and future climatic changes. This article briefly reviews the evidence from time-series analysis of several hydroclimatic variables to assess whether there have been systematic changes in the 20th century. Some of this information was summarized in the Intergovernmental Panel on Climate Change (IPCC) Third

Assessment Report (TAR) (Folland et al., 2001), but many new reports are now available that provide a more comprehensive picture. The IPCC TAR includes analysis of changes in precipitation, stream runoff, frequency and intensity of extreme events, atmospheric water vapor, cloudiness, pan evaporation, and soil moisture. New insights are now available relating to world continental runoff, tropospheric water vapor, El Nino Southern Oscillation (ENSO), glacier mass balance, evaporation, and evapotranspiration (ET). In addition, a growing body of research on hydrologic and phenological indicators shows that the length of the growing season has increased substantially suggesting that, at least in humid regions, ET has been affected.

2. Trends in hydrologic variables

On a globally averaged basis, precipitation over land increased by about 2% over the period (1900–1998) (Dai et al., 1997; Hulme et al., 1998). Regional variations are highly significant. For example, zonally averaged precipitation increased by 7–12%, between 30°N and 85°N, compared with a 2% increases for 0°S–55°S, and has decreased substantially in some regions (Folland et al., 2001). Groisman et al. (2004) reported increases in precipitation over the conterminous USA during the 20th century, with most of the increase confined to the spring, summer, and fall. Brown (2000) found systematic increases in winter (December through February) snow–water equivalent over North America averaging 3.9% per decade over the period 1915 through 1992. Increases in winter snow accumulation have also been reported in Russia from 60°N to 70°N and 30°E to 40°E during 1936–1983 (Ye et al., 1998; Zhang et al., 2001a) and in Canada, north of approximately 55°N (Karl et al., 1993). Ye et al. (1998) estimated snow–water equivalent 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 temperature sensitivity of the ratio suggest that the error in using a fixed ratio would not alter the results significantly (Ye et al., 1998). Furthermore, the fact that the observed surface air temperature, generally, warmed 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 increasing winter temperatures resulting in increasing precipitation following the Clausius–Clapeyron relationship, depending on the slope of the snowfall-temperature relationship (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 water cycle through the suppression of rainfall in polluted areas and through reducing the solar irradiance reaching the earth's surface (Ramanathan et al., 2001; Liepert et al., 2004; Wild et al., 2004). The primary mechanism for the former effect 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). In the latter effect, aerosol-induced reduction in surface solar irradiance could reduce surface evaporation and consequently precipitation and thus dampen the water cycle (Ramanathan et al., 2001; Wild et al., 2004). The potential for both decreased evaporation and increasing precipitation over land is only possible 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 affecting polluted areas, or a more general weakening of the water cycle is uncertain. On the one hand, there is evidence for reductions in solar irradiance reaching the land surface during the last 50 years (Stanhill and Cohen, 2001) that is consistent with the potential for a dampening of the water 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 water 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); reversing the dampening effect on the hydrologic cycle (Andreae et al., 2005).

Increases in precipitation over land have been associated with corresponding increases in runoff in

river basins in the conterminous USA (Lins and Slack, 1999; Groisman et al., 2001; McCabe and Wolock, 2002). In contrast, in Canada, increasing temperature combined with almost no change in precipitation, resulted in no change in annual streamflow from 1947 to 1996 for most regions (Zhang et al., 2001b). The basins studied in North America were selected because of minimal human perturbations to the water cycle. Typical criteria for basin selection exclude basins where consumptive use, land-use changes, intra-basin diversions, and/or significant regulation through the management of reservoir levels could influence flow (Slack and Landwehr, 1992; Harvey et al., 1999). 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 (Peterson et al., 2002) and in Western Russia (Georgievskii et al., 1996). Precipitation increased, snowfall decreased, and runoff decreased or did not change during the latter half of the 20th century in Tien Shan mountains in Northern Eurasia (Aizen et al., 1997). The decrease in runoff may be associated with decreasing meltwater from receding glaciers (Aizen et al., 1997; Khromova et al., 2003). There have been no extensive studies globally on trends in streamflow from minimally impacted basins.

An analysis of trends in world continental runoff from major rivers from 1910 to 1975 found an increase in runoff of about 3% (Probst and Tardy, 1987). A recent re-analysis of these trends for the period 1920–1995 using data reconstruction for filling in missing records confirmed an increase in world continental runoff during the 20th century (Labat et al., 2004). Labat et al. (2004) conclude, 'this contribution provides the first experimental data-based evidence demonstrating the link between the global warming and the intensification of the global hydrological cycle'.

These results for major rivers, in conjunction with independent reports of increasing runoff from many smaller rivers in the northern hemisphere, provides possible evidence for the validity of the conceptual framework for a warming-associated intensification of the water cycle. These increases in runoff are consistent with the results of modeling studies that suggest runoff is likely to increase in high latitudes

and in many equatorial regions, but decrease in mid-latitudes and some subtropical regions as a result of differential responses to climate warming in different regions (Alcamo et al., 1997; Arnell, 1999; Manabe et al., 2004). Decreases in runoff could occur as a result of increases in evapotranspiration that outweigh increases in precipitation.

Some proportion of increases in runoff from major rivers may be attributable to human alterations such as conversion from forest to agricultural land uses (Vörösmarty and Sahagian, 2000). In other cases, abandonment of agricultural land and subsequent reforestation could result in decreases in runoff. Human alterations to the water cycle can be extreme. For example, flood-prevention measures can reduce peak flows, consumptive use and evaporation from impoundments can reduce flows, and land-use conversion from native vegetation to agricultural or developed land results in decreases in ET and increases in runoff. Major river basins integrate the effect of climatic variation and human alterations, making it difficult to differentiate the cause of changes in the basin. In addition, part of the increase in runoff from river basins containing 'permanent' ice and snow is likely attributable to melting of glaciers and permafrost rather than increased precipitation (Kulkarni et al., 2003; McClelland et al., 2004; Yang et al., 2004).

One example of a river basin where increases in precipitation and runoff during the latter half of the 20th century have been well documented is the Mississippi river basin in the USA. Runoff from the Mississippi river increased by 22% from 1949 to 1997, during which time precipitation increased by 10% (Milly and Dunne, 2001). Human alterations to the water cycle in the Mississippi river basin during the 20th century have been dominated by increases in consumptive use that decrease runoff (Milly and Dunne, 2001). Two of the more significant changes in the Mississippi river basin in the 20th century are the abandonment of cultivated farmlands and conversion to forest or pasture, particularly in the southeastern part of the basin (e.g. Clawson, 1979; Wear and Greis, 2002) and the construction of numerous large impoundments. Both of these changes would have decreased runoff. Increasing precipitation and runoff in the Mississippi river basin from 1949 to 1997 is consistent with an intensification of the water cycle.

Increases in ET have also been inferred from another recent hydrologic budget analysis of long-term data in four major river basins in the conterminous USA. Area-weighted average precipitation and runoff both increased during the period 1950–2000 in three large and five smaller river basins in the conterminous USA. (Walter et al., 2004). Changes in storage were not measured but considered to be minor over this time period. Walter et al. (2004) concluded that since precipitation increased substantially more than runoff ET had likely increased at a rate of about 1.04 mm/year during the period 1950–2000.

Human alterations have had large effects on trends in runoff from some river basins. Consumptive use has greatly decreased flow from some rivers, such as the Syr-Darya River draining to 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 and if flow regulation is managed to avert dangerous flooding. The net annual effect of reservoirs on global water cycle changes is diminishing, however, because the rate of large reservoir construction has declined markedly in recent decades (Avakyan and Iakovleva, 1998).

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 ($>30^{\circ}\text{N}$), with the exception of Greenland and extreme Northeastern Canada, during the period 1975–1995 (New et al., 2000). Data were insufficient for trend detection south of 30°N latitude (New et al., 2000). Studies have also reported increases in lower troposphere water vapor using radiosonde measurements beginning in 1973 in the Northern Hemisphere (Ross and Elliott, 2001; Zhai and Eskridge, 1997) and, more recently, extending this record using special sensor microwave imager (SSM/I) measurements (Trenberth et al., *in press*). Deficiencies in the data, large inter-annual and regional variations, the relatively short-term nature of the data, and the association of these trends with ENSO and sea surface temperature suggest great caution in making inferences about long-term trends (Trenberth et al., *in press*).

Recent satellite measurements also indicate trends towards increasing water vapor in the tropical

(20°S–20°N) upper troposphere (above 215 mb) (UT) during 1993–1999 that were consistent with model predictions (Minschwaner and Dessler, 2004). However, they concluded that models that assume constant relative humidity overestimate the warming-induced water vapor feedback. Their data suggest 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).

Cloudiness increased before the 1980s (Dai et al., 1999), but this trend reversed during the late 1980s to the early 1990s so the long-term trend remains uncertain (Folland et al., 2001). The diurnal temperature range (DTR) is strongly and inversely related to cloudiness (Dai et al., 1999) and has decreased over most global land areas over the latter half of the 20th century (Easterling et al., 1997). Given the strong relation between cloudiness and DTR, the long-term downward trend in DTR suggests that cloudiness has increased over the same time period.

Considerable emphasis has been placed on testing whether the frequency or intensity of extreme weather events (e.g. hurricanes, typhoons, floods, and droughts) has changed in recent decades. The probability of occurrence of substantially more extreme precipitation events could increase dramatically if there are increases in both the mean and the variance of precipitation amounts (Katz, 1999). Increases in precipitation in higher precipitation quantiles have been observed in regional studies (Dai et al., 1997; Hulme et al., 1998; Folland et al., 2001; Groisman et al., 2004). Increases in precipitation intensity with increasing mean annual surface air temperature for a fixed precipitation amount also have been reported (Karl and Trenberth, 2003).

Observed 20th century increases in precipitation, particularly in higher precipitation quantiles (Groisman et al., 2004), could 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 in the USA (Lins and Slack, 1999; Douglas et al., 2000; McCabe and Wolock, 2002; Vogel et al., 2002), Canada (Zhang et al., 2001b), Scandinavia (Lindstrom and Bergstrom, 2004; Hyvarinen, 2003), or central Europe (Mudelsee et al., 2003). In contrast to

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 km² increased substantially over the 20th century. Milly et al. (2002) also stated that their conclusions were tentative and that the frequency of floods having return intervals shorter than 100 year did not change. Time series analyses have found no evidence for an increase in tropical storm frequency (Easterling et al., 2000; Folland et al., 2001; Solow and Moore, 2002; Elsner et al., 2004), intensity (Free et al., 2004), or duration of storm season (Balling and Cerveny, 2003) during the 20th century.

From 1900–1995, large, multi-year to decadal variations in the percentage of land area experiencing severe drought or moisture surplus were observed; however, secular trends were small (Dai et al., 1998). Since the late 1970s, there were some increases in the combined percentage of areas with severe drought or moisture surplus, resulting from increases in the drought area (e.g. in the Sahel, Eastern Asia and Southern Africa) or both the drought and wet areas (e.g. in the USA and Europe) (Dai et al., 1998; Dai et al., 2004). For a given value of ENSO intensity, the response in areas affected by drought or excessive wetness was more extreme after 1970 (Dai et al., 1998). The frequency of average strength ENSO events appears to be positively related to surface air temperature and to have increased during the last 122 years (Hunt, 1999; Herbert and Dixon, 2002). In a global analysis, Dai et al. (2004) concluded that the proportion of the land surface characterized as very dry (Palmer Drought Severity Index (PDSI) < -3.0) more than doubled since the 1970s and global very wet areas (PDSI > +3) declined slightly since the 1970s. These changes are highly variable among regions and are attributed to both ENSO-induced decreases in precipitation and warming-induced increases in evaporation; however, they are consistent with increasing risk of more frequent and intense drought conditions over some regions (Dai et al., 2004).

Evidence indicates that summer soil moisture content has increased during the last several decades at almost all sites having long-term records in the Global Soil Moisture Data Bank (Robock et al., 2000). These sites include grasslands, and forest sites at Valdai, Russia, steppe sites in Kamennaya, Russia,

winter and spring cereal sites in Russia, pasture and cereal sites in Mongolia, and agricultural sites in Illinois. Only one site, in Iowa, showed a decreasing trend, and Robock et al. (2000) noted that both the Iowa and Illinois trends were relatively short-term compared with most of the trends in Russia. This upward trend in soil moisture 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 and cloud cover are thought to have more than compensated for increased losses due to ET (Robock et al., 2000). In addition to indicating an intensification of the water cycle directly, increases in soil moisture suggest the potential for increasing ET and thereby indirectly intensifying the water cycle.

Subpolar and mountain glaciers are declining in mass throughout the world in response to warming (Dyurgerov, 2003; Oerlemans, 2005). Dyurgerov (2003) has shown increasing amplitude in seasonal (winter and summer) changes in mass balance of about 300 mountain and subpolar glaciers providing further evidence for a recent intensification of the water cycle. Summertime decreases in glacier mass are related to increasing air temperatures and wintertime increases in glacier mass are related to increases in snowfall (Dyurgerov, 2003). The combination of these seasonal changes in glacier mass balances is an indication that under the current climatic regime the rates of glacier melting and snow accumulation on glaciers have increased.

3. Trends in evaporation and evapotranspiration

Evaporation and evapotranspiration are central to the water cycle and long-term measurements of their annual rates would be excellent indicators of the intensity of the water cycle. Unfortunately, both are difficult to measure: to date, only a few dozen ET monitoring sites operate in the world, and the period of record is quite short. Other indirect approaches to estimate evaporation and ET, or variables directly related to ET, can provide insight into the likely trends in these variables.

Decreases in pan evaporation have been observed over most of the USA and the former USSR between

1950 and 1990 (Peterson et al., 1995). Such decreases are generally thought to be inconsistent with observed trends towards 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 water cycle (Brutsaert and Parlange, 1998; Roderick and Farquhar, 2002; Golubev et al., 2001; Roderick and Farquhar, 2004). Various mechanisms have been suggested to explain the apparent paradox. For example, it has been suggested that decreases in solar irradiance, resulting from increasing cloud coverage and aerosol concentrations, and decreases in diurnal temperature range would cause the observed decrease in pan evaporation (Peterson et al., 1995; Roderick and Farquhar, 2002). Roderick and Farquhar (2004) have reported consistency between decreases in pan evaporation on the one hand and decreases in aridity in Australia on the other hand that are comparable to similar findings in the Northern Hemisphere. Brutsaert and Parlange (1998) concluded that increasing water vapor concentration, resulting from a warming-induced increasing ET, would inhibit pan evaporation. Golubev et al. (2001) reported increasing ET (measured empirically using massive weighing lysimeter data) and decreasing pan-evaporation trends during the post-WWII to 1990 period at most sites in the former USSR where long-term data were available. Golubev et al. (2001) concluded that the observed opposing trends supported the mechanism proposed by Brutsaert and Parlange (1998). The issue of whether trends in pan evaporation indicate an intensification of the water cycle is not fully resolved (Ohmura and Wild, 2002; Wild et al., 2004), but the analyses of Golubev et al. (2001); Brutsaert and Parlange (1998) do support an increase in ET. A trend towards increasing ET is also inferred from continental-scale water balance studies that documented increases in precipitation that were substantially greater than increases in runoff during the period 1950–2000 in the conterminous United States (Milly and Dunne, 2001; Walter et al., 2004).

Possible trends in evaporation over the oceans and their relation to precipitation and runoff have been addressed indirectly using salinity time-series data. Salinity in the surface 500–1000 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 (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). For 24°N latitude (the salinity maximum), the evaporation-minus-precipitation (E–P) anomaly averaged 5 cm/year during the 40-year period (Curry et al., 2003). The increase in E–P could be a result of either an increase in E with a decrease, or no change, in P or an increase in P with a decrease, or no change, in E. Sea-surface warming over the same region and time period 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).

Increases in salinity also have been reported in some subtropical regions of the Pacific Ocean (Wong et al., 1999; Boyer et al. 2005) and in the Mediterranean Sea (Roether et al., 1996; Béthoux et al., 1998). 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, Boyer et al.’s 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.

There is substantial evidence for lengthening of the growing season throughout the Northern Hemisphere that is consistent with the concurrent warming trend. For northern temperate humid climates, this lengthening of the growing season is consistent with an overall increase in ET, because the period for active transpiration is longer and warmer (White et al., 1999). A recent increase in the length of the growing

season is inferred from an advance in the timing of the ‘onset of greenness’ and the spring seasonal draw-down in atmospheric CO₂ concentrations (Myneni et al., 1997; Hicke et al., 2002; Fang et al., 2003; Zhou et al., 2003). The drawdown was coincident with an advance in the timing of the ‘onset of greenness’ (inferred from advanced very high-resolution radiometer satellite data showing the normalized difference vegetation index) in northern temperate regions (Myneni et al., 1997). Advances in the timing of many plant and animal phenological events in the Northern Hemisphere (Menzel and Fabian, 1999; Schwartz and Reiter, 2000; Walther et al., 2002; Parmesan and Yohe, 2003) strongly point to increases in growing-season length.

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). 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 they reported a trend towards longer growing seasons in evergreen conifer forests and boreal tundra over the period 1988–2002. Smith et al. (2004) found earlier thaw dates in tundra and larch biomes over Eurasia. 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 freeze (Smith et al., 2004).

Increases in growing-season length also are inferred from a variety of hydrologic and climatologic variables that are correlated with earlier spring warming. For example: earlier spring snowmelt runoff (Leith and Whitfield, 1998; Cayan et al., 2001; Zhang et al., 2001b; Yang et al., 2002; Hodgkins et al., 2003; Cunderlik and Burn, 2004); earlier river ice-out (Dudley and Hodgkins, 2002; Huntington et al., 2003); earlier lake ice-out (Magnuson et al., 2000; Hodgkins et al., 2002); lengthening of the frost-free season (Easterling, 2002; Frich et al., 2002); and decreases in spring snow-cover extent across the Former Soviet Union and People’s Republic of China (Brown, 2000) and in the Swiss Alps (Scherrer et al., 2004).

Historical trends in North American snow cover extent (SCE) are more uncertain. Long-term trends

(1915–1997) for North America for March and April showed increases in SCE, though not significantly, but March and April SCE decreased rapidly after 1980 (Brown, 2000). Brown (2000) also reported widespread and significant trends towards earlier disappearance of snow cover throughout Canada over the period 1955 through 1977 significant declines in April snow water extent over North America over the period 1915 through 1997. There is also evidence that the ratio of snow to total precipitation has decreased in March in New England, USA during the period 1949–2000 (Huntington et al., 2004). Karl et al. (1993) reported a decrease in the ratio of snow to total precipitation for Canada south of 55°N latitude but no trend for Canada north of that.

Increasing growing-season length 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, and modeled ET increases as the length of the growing season increases in humid regions of the Eastern USA (Eagleman, 1976). Mean annual ET, estimated from measured precipitation minus runoff, increases at a rate of about 3 cm/°C in eastern North America (Huntington, 2003). Thus, any extension of the growing season will increase total annual ET, provided moisture is not limited, thereby intensifying the water cycle.

Although there are no long-term ET measurements with which to evaluate trends, measured ET is positively correlated with growing-season temperature (GST) for humid regions. The Fluxnet program involves the measurement of carbon dioxide and water vapor exchange using the eddy covariance approach (Law et al., 2002). In the Fluxnet program, water vapor exchange has been measured continuously for up to about 5 years over forest, grassland, and agricultural ecosystems. Plotting annual ET against growing-season temperature reported by Law et al. (2002) results in a significant (p -value < 0.0001) positive relation (Pearson's $r=0.58$) (Fig. 1). Ordinary least-squares simple linear regression gives a best-fit line of $ET_{mm} = 115 + 19.7 \times GST_{\text{°C}}$, 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 USA. This relation between ET and temperature

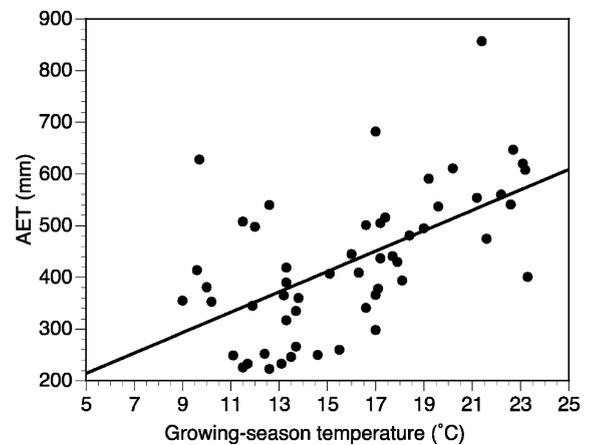


Fig. 1. Annual actual evapotranspiration (AET) versus growing-season temperature for all Fluxnet data reported in Law et al. (2002), except for Aberfeldy, Scotland in 1997 that was excluded because of a negative value for AET. Line shown is the ordinary least-squares simple linear regression.

suggests that observed temperature increases during the 20th century may have resulted in increasing ET where moisture is not limiting.

4. Summary

Substantial uncertainty regarding trends in hydroclimatic variables remains because of differences in responses among variables and among regions as well as major spatial and temporal limitations in data. There are large gaps in spatial coverage for some hydrologic indicators; therefore, trends in these areas are unknown. The risk in assuming that trends in these areas are comparable to those measured in other related areas is that the observed trends may simply represent regional redistribution rather than true global intensification. In spite of these uncertainties, the observed trends in most of the variables are consistent with an intensification of the water cycle during part or all of the 20th century at regional to continental scales (Table 1).

Consistency in response among multiple variables lends observational support for theoretical arguments and GCM predictions that warming will likely result in further increases in evaporation and precipitation. The theoretical hydrologic response to a warming-induced intensification as manifested in an increasing frequency

Table 1

Summary of trends in hydroclimatic variables indicating the primary period (or periods) of record considered and trends exhibited by the majority of studies evaluated in this study and within the studies cited in this paper, and whether the trends were regional or global (land area) in scale

Variable	20th century	Latter half 20th century	Majority trend regional (R) or global (G)
Precipitation	✓		Increasing (R,G)
Runoff	✓	✓	Increasing (R,G)
Tropospheric water vapor		✓	Increasing (R)
Cloudiness		✓	No change
Tropical Storm frequency and intensity		✓	No change
Floods	✓	✓	No change/increasing (R)
Droughts		✓	Increasing (R)
Soil moisture		✓	Increasing (R)
Seasonal glacier mass balance		✓	Increasing (G)
Pan evaporation		✓	Decreasing (R)
Actual evapotranspiration		✓	Increasing (R)
Growing-season length ^a	✓	✓	Increasing (R)
Growing-season length ^b		✓	Increasing (R)

^a Based on records of temperature or agricultural killing frost.

^b Based on satellite-derived 'onset of greenness' normalized difference vegetation index.

and intensity of tropical storms and floods (Knutson and Tuleya, 1999; Tuleya and Knutson, 2002; Karl and Trenberth, 2003) is not supported by the preponderance of evidence to date. Because of the long-term return intervals and stochastic nature of the occurrence of extreme events, however, it may require substantially more time before a change in frequency can be detected (Free et al., 2004). The lack of detectable trends in the frequency and intensity of tropical storms during the 20th century should not be taken as evidence that further warming will not lead to such changes in the future, particularly as the rate of warming in the 21st century is expected to be several times greater than in the 20th century (Cubasch and Meehl, 2001).

On balance, the weight of evidence is consistent with an ongoing and future intensification of the hydrologic cycle and emphasizes the need for improving our capabilities to monitor and predict the consequences of changing hydrologic regimes. Future improvements in spatial resolution and longer periods of data collection, combined with enhanced process-level understanding of complex feedbacks involving water, will reduce our current levels of uncertainty. Primary hydrologic feedbacks include increases in atmospheric water vapor that result in more heat trapping, changes in cloudiness and the properties of clouds that can increase or decrease surface warming, changes in snow cover and snow or

ice surface melt that influence albedo and therefore the radiative balance (Abdalati and Steffen, 1997; Karl and Trenberth, 2003).

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