197: Observed Trends in Hydrologic Cycle Components

HARRY F LINS

United States Geological Survey, Office of Ground Water, Reston, VA, US

Documentation of change in the Earth's climate is accomplished by assessing the rates, magnitude, and distribution of changes in various elements of the climate system, such as the components of the hydrologic cycle. The present section reviews the general character of changes in precipitation, streamflow, and evaporation as determined using systematically collected data through the end of the twentieth century. Precipitation over global land areas increased about 2% during the century, and streamflow also exhibited widespread increases. There was good agreement regionally between the observed precipitation and streamflow increases. The precipitation increases appear to have occurred most commonly in higher intensity categories (>50 mm per day), while the streamflow increases were overwhelmingly observed in the low to moderate range of flows. No systematic increases were observed in peak streamflows. These findings indicate that a general intensification of the hydrologic cycle occurred during the twentieth century, but that this intensification did not result in increased hydrologic extremes.

INTRODUCTION

Climate change is documented by assessing the rates, magnitude, and distribution of changes in climate system components. Although simple in concept, such documentation has proven to be problematic in practice. Existing climate observing systems are capable of only partially answering critical questions associated with climate change, particularly for such hydrologic cycle variables as precipitation, runoff, and evaporation (NRC, 1999). Changes in station location, time of observation, and monitoring equipment, as well as difficulties in operating monitoring stations over multidecadal periods and at many locations worldwide, are all factors that contribute to this problem. Significantly, however, the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001) notes that the "certainty of conclusions that can be drawn about climate from observations depends critically on the availability of accurate, complete and consistent series of observations".

In addition, human alteration of the landscape and riverine systems can significantly affect hydrologic cycle changes, from small watershed to large river basin scales (Shiklomanov and Penkova, 2003). The data needed to account for such confounding effects, such as consumptive water use, reservoir storage, and land use change, are often less well measured or more difficult to obtain than those for precipitation, streamflow, and evaporation. Remotely sensed data are finding increasing use in hydrologic cycle investigations, most particularly in regions of the world where systematic *in situ* data collection networks are sparse or nonexistent. However, such systems are not without their own problems. In many instances, remotely sensed data are less than 20 years in length, limiting their utility for trend assessment, and they generally do not measure quantities that are directly comparable to ground-based observations.

Trend analysis results are also very sensitive to the conditions that existed at the endpoints of the time series. Differences of one or two years in the start or end points in a data time series, even when the time series are otherwise identical, can substantially alter results. Similarly, differences in analytical methods among published studies can compromise the significance of results and complicate summary assessments of change. Douglas *et al.* (2000) noted, for example, that spatial correlation among streamflow observing stations markedly affects the results of

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trend testing. They found that regional cross correlation of flow records dramatically reduced the effective number of samples available for trend assessment, and that by not taking this influence into account, erroneous conclusions would be drawn with respect to the absence or presence of regional trends.

Despite the many problems associated with the collection and analysis of the hydrologic cycle and related data, studies aimed at identifying trends in hydrologic cycle components at regional to continental scales are increasing. The most extensive work has addressed precipitation trends. Precipitation data have been collected longer and at more sites worldwide than have streamflow and evaporation data. It should be noted, however, that despite its breath of monitoring, measurement problems and bias continue to adversely affect the quality of precipitation data. Even so, the density of land precipitation monitoring networks is sufficient to facilitate global assessments of trend, such as those reported in recent climate change assessments by the IPCC (1996, 2001).

In contrast, investigations of runoff or streamflow trends have been more geographically restricted, with the most comprehensive analyses covering Canada, Europe, the United States, and to a lesser extent, Australia and South America. Comparatively, little streamflow data are available for Africa and Asia and record lengths in these regions tend to be relatively short. Another confounding issue in assessing streamflow trends relates to the influence of human activities on rivers and streams. Flows on most gauged watercourses are modified to some extent by human activities. Humans appropriate more than 50% of accessible renewable water resources globally (Postel *et al.*, 1996). By the late 1980s, there were more than 36 000 large dams worldwide, representing a 700% increase in the standing stock of natural river water (Vörösmarty *et al.*, 1997). In the contiguous United States alone, of the 5.2 million km of rivers, there are only 42 reaches with lengths greater than 200 km that are free flowing (Benke, 1990).

Avoiding potential problems in understanding how the streamflow component of the hydrologic cycle is changing through time is most easily achieved by using streamflow records that reflect natural or near-natural conditions. To this end, some hydrologists and hydrological services have identified climate-sensitive stations within their monitoring networks that reflect unimpaired basin conditions. Unimpaired generally means that there is no overt adjustment of natural streamflow by diversion or augmentation, regulation of the watercourse by a containment structure, or reduction of base flow by groundwater pumping. In practical terms, unimpaired records are generally considered to be those where the degree of human activity in the watershed is small enough so as not to affect significantly the value of monthly mean discharge as computed on the basis of daily mean discharge. The Reference Hydrometric Basin Network (RHBN), assembled by Environment Canada (Harvey *et al.*, 1999), and the Hydro-climatic Data Network (HCDN) of the US Geological Survey (Slack and Landwehr, 1992) are examples of streamgauging networks that have been identified as meeting specific climate sensitivity criteria.

Studies of trends in evaporation, as with streamflow, are limited geographically. Nearly all are based on pan evaporation measurements because pans have been systematically used longer and in more locations than other types of equipment. Historically, pan evaporation measurements have been viewed as an index of potential evaporation or the evaporation that occurs where there is an unlimited supply of water. Recently, however, Golubev *et al.* (2001) developed a method for estimating actual evaporation from the land surface using pan evaporation measurements, a more meaningful quantity when comparing with precipitation and streamflow. Despite this development, it should be noted that pan evaporation estimates are problematic at best. Pan evaporation must be adjusted by seasonally varying coefficients in order to provide estimates of lake evaporation, and these coefficient adjustments are only approximations (Mather, 1974).

A review of the primary recent literature documenting changes in hydrologic cycle components follows. This review does not purport to establish invariant and regionally detailed trends worldwide. Rather, its purpose is to provide a *snapshot* or generalized characterization of changes in precipitation, streamflow, and evaporation as determined using systematically collected data that end around the year 2000. The dynamic nature of hydrologic cycle variables, coupled with the analytical and interpretive limitations associated with monotonic trend tests, constrain the certainty and enduring relevance of specific results.

CHANGES IN PRECIPITATION

The IPCC third assessment (IPCC, 2001) reported that global land precipitation increased about 2% during the twentieth century, but that the increase was not uniform spatially or temporally. This is evident in the seasonal precipitation change maps in Figure 1. In the middle and high latitudes of the Northern Hemisphere, for example, there have been widespread precipitation increases, particularly during the autumn months. However, precipitation decreases have been observed in Europe, Western Russia, and around the Mediterranean. In Canada, precipitation increased by an average of more than 10% during the twentieth century (Mekis and Hogg, 1999), including increases in snowfall (Zhang *et al.*, 2000). Farther south, in the United States, precipitation increased between 5 and 10% over the century. Karl and Knight (1998) reported an increase in the United States of about 10% nationwide,

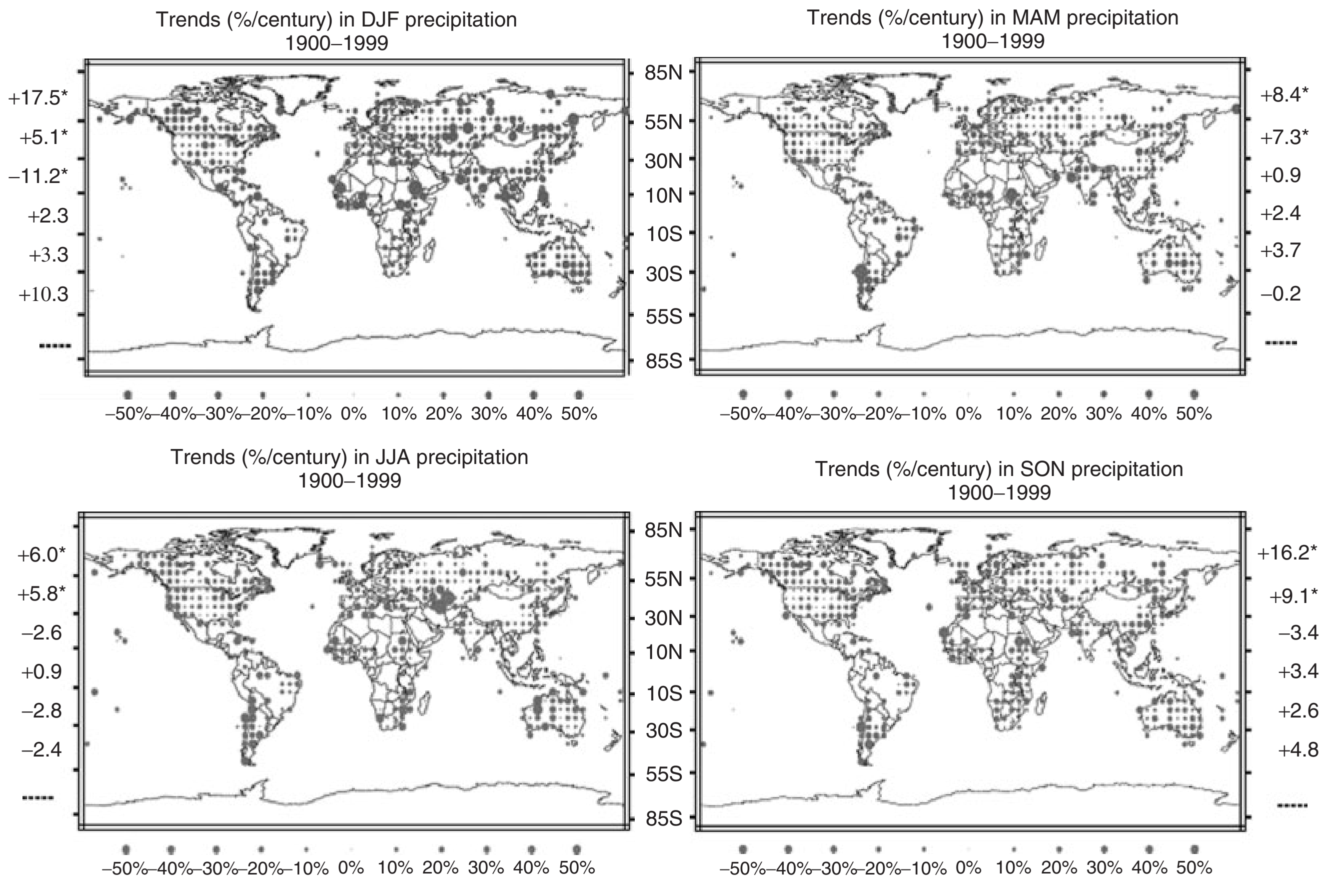

Figure 1 Trends in seasonal precipitation, 1900–1999. Trend magnitude is signified by the size of the circle (*Source:* Intergovernmental Panel on Climate Change (IPCC), 2001). Trend direction is represented by the color of the circle which can be seen in the color version of this image that is available at http://www.mrw.interscience.wiley.com/ehs

and that more than half of this increase was in heavier precipitation categories, that is, the upper 10 percentiles of the precipitation distribution. They also noted significant variability in the pattern of trends regionally and seasonally, with the increases being confined to the spring, summer, and autumn months. Groisman *et al.* (2004) confirmed this finding, adding that the largest trends were observed in the eastern two-thirds of the United States, and primarily in the warm season when intense rainfall events are most frequent. However, Kunkel *et al.* (2003) pointed out that during the late nineteenth century, intense precipitation events were nearly as high as during the late twentieth century. This suggests that the reporting of trends in precipitation since about 1900 may not encompass the full range of natural variability that has characterized the climate system in recent centuries.

During the second half of the twentieth century, annual precipitation decreased slightly in China, although increases were observed over the middle and lower Yangtze River basin (Zhai *et al.*, 1999a,b). Northern Europe and Scandinavia saw increased precipitation, while southern Europe, down to the Mediterranean, experienced a general decrease over these same decades. Coupling these results with those for North America and averaging zonally, annual precipitation increased between 7 and 12% for the zones from 30 °N to 85 °N (IPCC, 2001).

In the Northern Hemisphere subtropical and tropical zones, precipitation tended to decrease during all seasons in the twentieth century. This was particularly true in North Africa and the Asian subcontinent. Kumar *et al.* (1999a,b) found no evidence of a long-term trend in Indian monsoonal rainfall, although they did note significant multidecadal variations.

In the Southern Hemisphere, precipitation trends have also been mixed. Annual rainfall over most of Australia has increased, as have the number of rain days, but precipitation decreases during winter (June, July, and August) have been notable in the eastern and western thirds of the continent. Seasonal differences in trends have also characterized the changes in southern Africa, where warm season precipitation (December–May) has decreased and cool season precipitation (June–November) has increased. Precipitation increases have occurred in most of South America in all seasons with two notable exceptions, Chile and eastern

Brazil, where decreases were dominant during the twentieth century.

It is important to note that most of these reported changes in precipitation are within the measurement error that has been documented for precipitation. UNESCO (1978) and Legates (1987) estimate the bias in precipitation measurements, averaged globally, to be about 11%. Legates (1995) further argued that local increases in air temperature and decreases in wind speed, resulting from climatic variability or from local urbanization, can introduce spurious trends into the precipitation record. This is because the bias in measuring liquid precipitation is lower than for solid precipitation, as it is for lower wind speeds. Moreover, spurious trends can be introduced through monitoring station relocations and instrument changes (Groisman, 1991). It is likely that these factors have contributed to the variable and occasionally contradictory precipitation trend results that have been published.

CHANGES IN STREAMFLOW

Global assessments of trends in streamflow have proven to be more elusive, primarily because network limitations, data access, and data quality issues have hindered attempts at producing a unified global synthesis. However, several studies have provided noncomprehensive, low spatial density looks at worldwide trends in streamflow. Chiew and McMahon (1996) tested for trends in annual streamflow volumes and peak discharges at 142 stations on 6 continents. They found no consistent pattern of widespread trends in either variable, although most of their data ended before 1980. More recently, Kundzewicz *et al.* (2004) and Svensson *et al.* (2004) analyzed trends in annual maximum flow, and in peaks over threshold and annual low flows, respectively. The Kundzewicz *et al.* (2004) results utilized records from 195 stations on 6 continents, and are summarized in Table 1. The overwhelming majority of stations (92%) were located in North America, Europe, and Australia. Among all stations, 70% had no trend in the annual maximum flow, 14% had an increasing trend, and 16% a decreasing trend. Although the actual percentages varied from continent to continent, each exhibited a pattern of trends generally consistent with the aggregate totals. Using a much smaller sample of stations (21), Svensson *et al.* (2004) found a mixed pattern of trends in peaks over threshold, with approximately 30% of the stations exhibiting a trend, and with more downward trends than upward. A very different pattern was apparent in low flows, however (Figure 2).

Table 1 Trends ($p \leq 0.10$) in annual maximum streamflow, by continent, for 195 streamgauging stations worldwide

Region	Number of stations	Number with increasing trend	Number with no trend	Number with decreasing trend
Africa	4	1	1	2
Asia	8	0	5	3
South America	3	0	3	0
North America	70	14	44	12
Australia–Pacific	40	1	34	5
Europe	70	11	50	9
Totals	195	27(14%)	137(70%)	31(16%)

Source: Kundzewicz *et al.*, 2004.

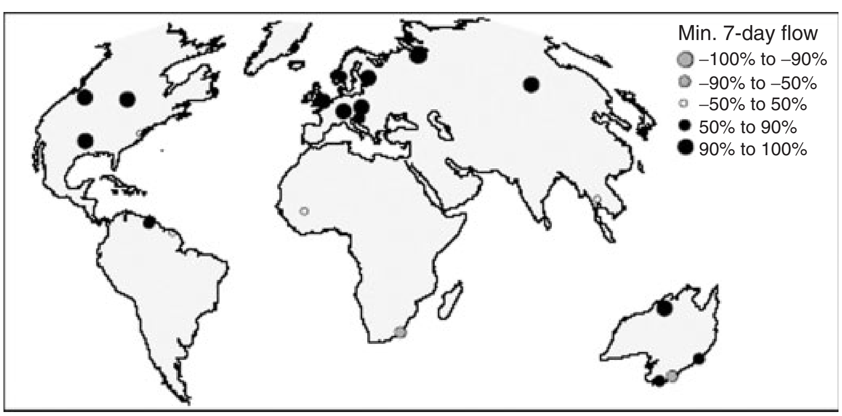

Figure 2 Trends in the annual minimum 7-day mean flow series at 21 stations worldwide. Negative trends are shown as gray circles and positive trends as black circles. The largest circles identify trends significant at $p \leq 0.10$ (*Source:* Svensson *et al.*, 2004)

Approximately 52% of the stations had statistically significant trends in seven-day low flows, and all of these were increasing trends. This implies a reduction in the incidence of hydrologic drought. Importantly, these broad-scale study results are very consistent with those from regionally specific investigations.

The most comprehensive documentation of streamflow change comes from regional studies and, of these, the most complete assessment exists for North America, where several national-scale studies have been published for Canada and the United States. Zhang *et al.* (2001) found that annual mean streamflow generally decreased in Canada between 1947 and 1996, with significant decreases occurring in the southern part of the country, particularly southern British Columbia and Alberta. They also found decreases in monthly mean streamflow for most months of the year except March and April when significant increases were observed. Changes in the frequency distribution of daily streamflow, from low to high, were also evaluated. In southern Canada, as with the annual mean, significant decreases were observed in all percentiles of daily flow. Over northern British Columbia and the Yukon Territory, however, significant increases were identified in the lower flow percentiles. Zhang and his collaborators also noted that the breakup of river ice and the ensuing spring freshet were occurring earlier, especially in British Columbia, and that river freeze-up appeared to be occurring earlier in the autumn in eastern Canada.

In the United States, numerous investigations have found a consistent pattern of streamflow increases across much of the country during the twentieth century. Lettenmaier *et al.* (1994) identified strong increases in monthly mean streamflow in the months from November to April for the years 1948–1988. The largest trend magnitudes were observed in the north-central states. This study also found streamflow decreases in the Pacific Northwest that were consistent with the streamflow decreases in the adjacent provinces of southwestern Canada noted by Zhang *et al.* (2001).

Lins and Michaels (1994) assessed trends in streamflow in the United States by region and by month. The regions were defined by principal components analysis of monthly mean streamflow. A separate analysis was performed for each calendar month. The resulting time series of component scores for each component and month were then tested for trend. Nearly all regions of the country experienced increasing streamflows between 1941 and 1988, but the significant trends were only observed during the autumn to early winter months. No regional trends were observed in the Pacific Northwest and, as Lettenmaier *et al.* found, the north-central region had the strongest trend.

During the 1990s, a series of major flooding events in the United States received significant attention and led to speculation that extreme hydrologic events (including both floods and droughts) were increasing, possibly in response to greenhouse warming. Lins and Slack (1999) evaluated this possibility by testing for trends in the percentiles of annual (on the basis of daily mean) streamflow for periods ranging from 30 to 80 years. They found that trends were most prevalent in the lower half of the frequency distribution, from the annual minimum to median flow, and that the trend was upward at 40–50% of the stations tested. In contrast, they reported a decline in the number of stations having trends in the upper half of the distribution, with the annual maximum flow reporting the least increasing trends (at 10% of the stations). The streamflow increases were observed across much of the United States, but particularly the northeastern quarter of the country, while decreases were detected in most percentiles in the Pacific Northwest and in the Southeast.

Douglas *et al.* (2000) also looked at trends in high and low flows using a regional trend test. They found no evidence for a coherent trend in high flows regionally, but did report upward trends in low flows in much of the northeastern quarter of the United States, supporting the Lins and Slack findings. A subsequent study by Groisman *et al.* (2001), however, appeared to arrive at a different conclusion with respect to trends in high flow. Working with a subset of the same data used in previous streamflow trend analyses, Groisman and his colleagues reported that the largest streamflow increase in the United States occurred in the highest streamflow percentiles, seemingly contradicting all previous work. Upon closer examination, however, what Groisman found was not that there were more stations having trends in the highest streamflow percentiles, or that the magnitude of the trend in percentage terms was greater. Their analysis actually yielded the following result: if one calculated the total volume of water that increased (or decreased) from 1939 to 1999, and then determined what proportion of that increase was produced by increases in the 0–5th percentile bin, 6–10th percentile bin, and so forth up to the 96–100th percentile bin, the bin that contributed most of the increase is the 96–100th percentile bin.

Importantly, this result is not inconsistent with, or contradictory to, the findings of previous studies that found relatively few stations with trends in the annual maximum streamflow. The reason for this is the quantity of water contained in each percentile bin of the annual streamflow distribution. Because streamflow is a lognormally distributed variable, where the annual maximum value is typically two or more orders of magnitude greater than the annual minimum value, the uppermost percentiles correspond to very large quantities of water relative to other parts of the distribution. So, even though the percentage increase in the annual maximum streamflow is relatively small (as noted by Lins and Slack and Douglas *et al.*), the corresponding volume increase can be very large. In other words, a small percentage change in a very large volume of water is a large value in comparison to a large percentage change in a relatively small volume. Thus, the differences between the Groisman *et al.* findings and those of the others are apparent and interpretive rather than substantive. This situation does, however, underscore the problems that can attend trend assessments on the basis of different analytical approaches.

Finally, McCabe and Wolock (2002) found a significant increase in annual minimum and median daily streamflow around 1970, and a less significant mixed pattern of increases and decreases in annual maximum daily streamflow. These changes were primarily observed in the eastern United States and are consistent with previous studies. Notably, though, McCabe and Wolock observed that the streamflow increases appeared as a step change rather than as a gradual trend, which has important implications (Figure 3). The inference drawn from a gradual trend is that

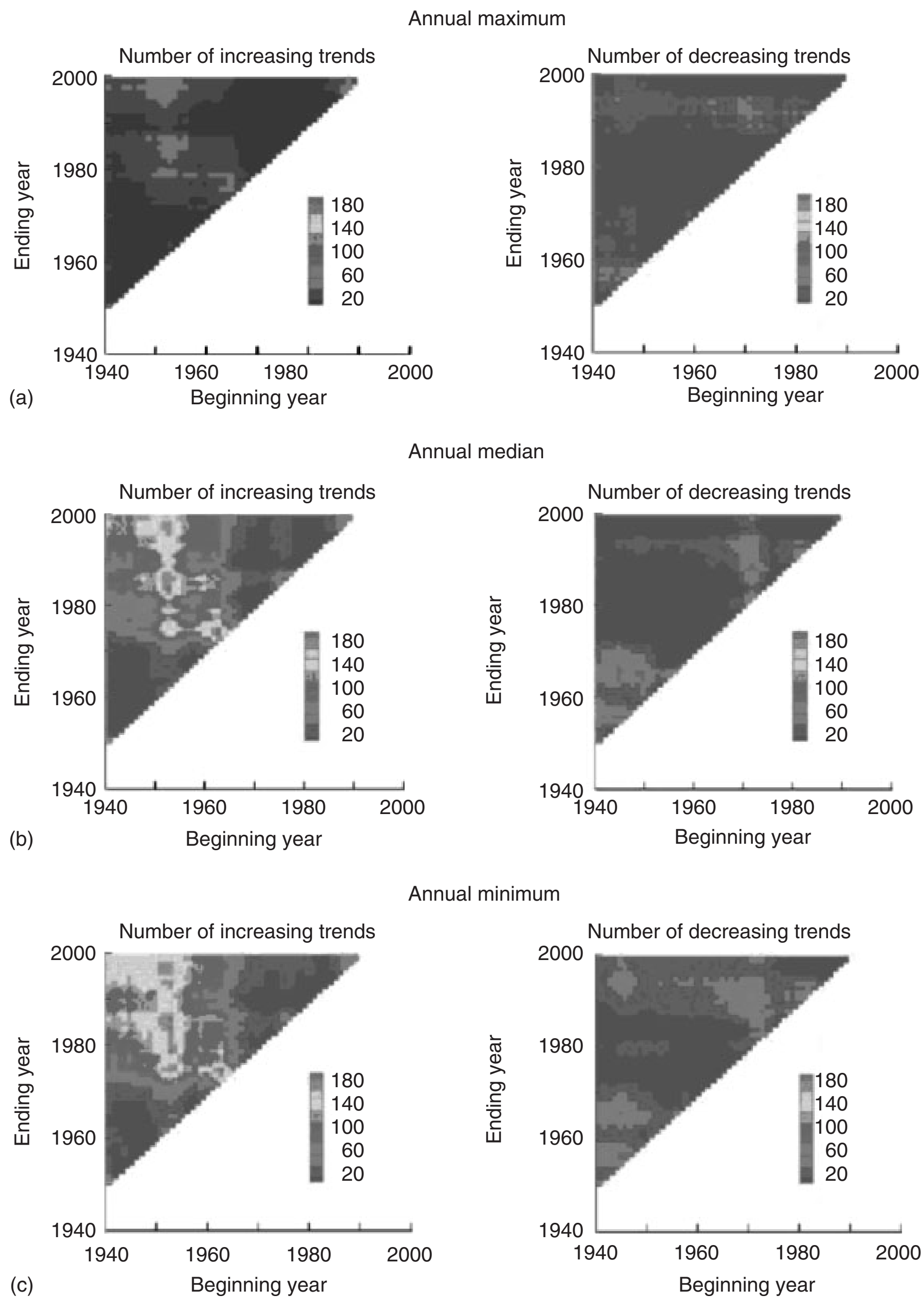

Figure 3 Number of sites with significant ($p \leq 0.05$) increasing and decreasing trends in (a) annual maximum, (b) median, and (c) minimum daily streamflow for various periods at least 10 years in length, and for 400 stations in the United States during 1941–1999 (Reproduced fromMcCabe and Wolock, (2002) by permission of American Geophysical Union (AGU)). A color version of this image is available at http://www.mrw.interscience.wiley.com/ehs

it is likely to continue into the future, while the implication of a step change is that the climate system has shifted to a new regime that will likely remain stable until a new shift occurs.

Fewer studies of streamflow trends have been published for other continental areas. In South America, discharge data for several major rivers in the southeastern part of the continent covering the period 1901–1995 indicate that streamflow increased after the mid-1960s (Garcia and Vargas, 1998; Genta *et al.*, 1998). This increase was also accompanied by a decrease in the amplitude of the seasonal cycle in most rivers.

In Europe, much of the published work on streamflow trends has focused specifically on flooding. Robson *et al.* (1998) and Robson (2002) evaluated local and national flood series in the United Kingdom, and the effect of climatic variability on trend detection. Their results indicated that more protracted episodes of high flow have occurred during the second half of the twentieth century. However, they found no statistical evidence of a long-term (80–120 years) trend in flooding. An analysis of systematic flood records for winter and summer seasons in central Europe since the middle of the nineteenth century, and longer-term historical records of major floods since the sixteenth century, was performed by Mudelsee *et al.* (2003). They found a decrease in the occurrence of winter floods on the Elbe and Oder rivers over an 80- to 150-year period with no trend in summer flooding. They attribute the winter season decrease in part to a decline in strong freezing events that reduce late winter ice jamming events and consequent higher flood peaks. This study also detected significant long-term changes in flood occurrence between the sixteenth and nineteenth centuries, but concluded that reductions in river length, construction of reservoirs, and deforestation had minor effects on flood frequency. One study, by Kahya and Kalayci (2004), focused on trends in average flow conditions. Using monthly mean streamflow records for 26 basins in Turkey from 1964 to 1994, they found that streamflow had generally decreased in western and southern Turkey, while not changing significantly in eastern Turkey. Finally, Hisdal *et al.* (2001) tested for trends in hydrologic drought using a pan-European data set of more than 600 daily streamflow records encompassing four time periods: 1962–1990, 1962–1995, 1930–1995, and 1911–1995. For most stations tested, no significant changes were detected, and the authors concluded that there was no evidence to indicate that drought conditions, in general, had become more severe or frequent.

CHANGES IN EVAPORATION

Most work on trends in evaporation has been done using pan measurements from the former Soviet Union and the United States. The IPCC Second Assessment Report (1996) described widespread decreases in pan evaporation during the twentieth century using these data. Subsequent to the Second Assessment, several authors noted an inconsistency between the reported decreases in pan evaporation, which was interpreted as a decrease in actual land surface evaporation, and observed increases in both temperature and precipitation in Russia and the United States. Brutsaert and Parlange (1998), for example, noted that the contradiction in the trends of evaporation, temperature, and precipitation was difficult to reconcile in the context of a general intensification of the hydrological cycle over northern extratropical land areas. Lawrimore and Peterson (2000) and Golubev *et al.* (2001) conducted additional studies and arrived at conclusions similar to Brutsaert and Parlange.

Golubev *et al.* (2001) developed a procedure for estimating actual land surface evaporation from pan evaporation measurements using coupled observations of both actual and pan evaporation at multiple field sites in Russia. In applying this procedure to pan data from Russia and the United States, they concluded that the actual evaporation increased over most arid regions of both countries, as well as over humid maritime regions of the eastern United States during the warm season. They also found that the actual evaporation decreased over heavily forested areas of Russia and the northern United States.

SUMMARY AND CONCLUSION

Analyses of trends in the hydrologic cycle indicate that precipitation over global land areas increased about 2% during the twentieth century, and that the streamflow also exhibited widespread increases. There was generally good agreement regionally between the observed trends in precipitation and streamflow. Moreover, some investigations that reported precipitation increases also found that these increases occurred more frequently in higher intensity categories (e.g. >50 mm per day). Notably, in regions where such precipitation increases were observed, there appeared to be increases in low to moderate streamflows. There is no evidence of widespread or systematic increases in peak streamflows, although there is widespread evidence of increases occurring in annual low flows. This pattern of trends indicates that a general intensification of the hydrologic cycle occurred during the twentieth century, but contrary to the hypothesis that such an intensification would result in increased hydrologic extremes (i.e. floods and droughts), it did so in a more benign and beneficial manner.

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