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Review article

Climate change and changes in global precipitation patterns: What do we know?

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Abstract

The objective of this paper is to synthesize the large literature recording changing patterns of precipitation in the observed data, thus indicating that climate change is already a reality. Such a synthesis is required not only for environmental researchers but also for policy makers. The key question is the broad picture at major regional and continental levels. Some interesting conclusions for this survey are emerging. For example, the review shows increased variance of precipitation *everywhere*. Consistent with this finding, we observe that wet areas become wetter, and dry and arid areas become more so. In addition, the following general changing pattern is emerging: (a) increased precipitation in high latitudes (Northern Hemisphere); (b) reductions in precipitation in China, Australia and the Small Island States in the Pacific; and (c) increased variance in equatorial regions. The changes in the major ocean currents also appear to be affecting precipitation patterns. For example, increased intensity and frequency of El Niño and ENSO seem associated with evidence of an observed "dipole" pattern affecting Africa and Asia, although this time series is too short so far. But the changing pattern calls for renewed efforts at adaptation to climate change, as the changing precipitation pattern will also affect the regional availability of food supply.

Keywords: Precipitation pattern; Northern Hemisphere; El Niño

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1. Introduction

With the recent ratification by Russia, the Kyoto Protocol came into force as a global treaty, binding its signatories to the reduction of greenhouse gases as set out in the Protocol, though the United States and Australia remain outside this fold. Nevertheless, the ratification shows that a global commitment to take some action to mitigate global climate change under the general framework the United Nations Framework Convention on Climate Change is finally underway, with further amendments and tightening of harmful emissions now a real possibility. Most climate change scientists are hoping that further international action may mirror the actions taken after the initial signing of the Montreal Protocol, which was followed by a number of additional amending agreements. Thus, there is much hope that Kyoto may be the start of a similar process. However, a series of scientific studies and number of press reports show that climate change is well underway. While the subject of climate change is vast, there is at least one topic within climate change that deserves urgent and systematic attention, and that is the changing pattern of precipitation around the world. If climate change is already underway, how is it affecting observed precipitation? The objective of this paper is to synthesize the vast literature on the changing pattern of observed precipitation and to discern some general patterns at major regional and continental levels. Some interesting conclusions for this survey are emerging. For example, one systematic result is increased variance of precipitation *everywhere*. Consistent with this finding, we observe that wet areas become wetter, and dry and arid areas become more so. In addition, the following general changing pattern is emerging: (a) increased precipitation in high latitudes (Northern Hemisphere); (b) reductions in precipitation in China, Australia and the Small Island States in the Pacific; and (c) equatorial regions become more variable, i.e., increased variance. The changes in the major ocean currents also appear to be affecting precipitation patterns. For example, increased intensity and frequency of El Niño and ENSO seem associated with evidence of an observed "dipole" pattern affecting Africa and Asia, although this time series is too short so far. But the changing pattern calls for renewed efforts for adaptation to climate change, as the changing precipitation pattern will also affect the regional availability of food supply.

Increasing global surface temperatures are very likely to lead to changes in precipitation and atmospheric moisture because of changes in atmospheric circulation, a more active hydrological cycle, and increases in the water-holding capacity throughout the atmosphere. The El Niño-Southern Oscillation (ENSO) is the primary global mode of climate variability in the 2- to 7-year time frame. El Niño is defined by sea surface temperature (SST) anomalies in the eastern tropical Pacific, while the Southern Oscillation Index (SOI) is a measure of the atmospheric circulation response in the Pacific–Indian Ocean region. Both the activity and periodicity of ENSO have varied considerably since 1871 with considerable irregularity in time. There was an apparent "shift" in the temperature of the tropical Pacific around 1976 to warmer conditions, which appeared to continue until at least 1998. During this period, ENSO events were more frequent, intense or persistent. ENSO has been related to variations of precipitation and temperature over much of the tropics and sub-tropics, as well as some mid-latitude areas. All this evidence needs to be systematically synthesized and integrated to see what global picture emerges. This paper is a first attempt to do that.

This paper is organized as follows. Section 1 considers the changing pattern at a synoptic level: land areas with mid- and high latitudes and the tropics, followed by the oceans. Section 2 covers the growing evidence of climate variability and extremes. Section 3 is a more detailed breakdown by regions and main continents. This is followed by some concluding remarks.

2. Changing patterns in observed precipitation data

2.1. Land

Overall, global land precipitation has increased by about 2% since the beginning of the 20th century (Jones and Hulme, 1996; Hulme et al., 1998). The increase is statistically significant, though neither spatially nor temporally uniform (Karl and Knight, 1998; Doherty et al., 1999). Dai et al. (1997) found a global long-term increase in precipitation separate from ENSO and other modes (patterns) of climate variability.

2.1.1. Mid- and high latitudes

Over the 20th century, annual zonally averaged precipitation increased by between 7% and 12% for the zones 30°N to 85°N and by about 2% between 0°S and 55°S. The increase in the Northern Hemisphere is likely to be slightly biased because adjustments have not been made for the increasing fraction of precipitation falling in liquid as opposed to frozen form. The exact rate of precipitation increase depends on the method of calculating the changes, but the bias is expected to be small, because the amount of annual precipitation affected by this trend is generally only a few percent. Nevertheless, this unsteady, but highly statistically significant trend towards more precipitation in many of these regions is continuing. For example, in 1998, the Northern Hemisphere high latitudes (55°N and higher) had their wettest year on record, and the mid-latitudes have had precipitation totals exceeding the 1961 to 1990 mean every year since 1995.

Why is the change in the distribution between the Northern and Southern Hemispheres asymmetrical? The answer may lie in the physical distribution of more landmass in the North than in the South, and hence a greater thermal effect in the North than in the South. But in any case, there is no a priori reason to expect a symmetrical distribution. After all, the ocean–atmospheric interactions that determine precipitation are fundamentally nonlinear.

In the Northern Hemisphere mid- and high latitudes, precipitation has mostly been increasing, especially during the autumn and winter, but these increases vary both spatially and temporally. For example, precipitation over the United States has increased by between 5% and 10% since 1900, but this increase has been interrupted by multi-year anomalies such as the drought years of the 1930s and early 1950s (Karl and Knight, 1998; Groisman et al., 1999). The increase is most pronounced during the warm seasons. Using data selected to be relatively free of anthropogenic influences such as ground water pumpage or land use changes, several recent analyses (Lettenmaier et al., 1999; Lins and Slack, 1999; Groisman et al., 2001) have detected increases in streamflow across much of the contiguous United States, confirming the general tendency to increasing precipitation. However, Lins and Michaels (1994) found in some regions that increased streamflow did not relate well to an increase in rainfall. This has been further evaluated by Groisman et al. (2001), who show that changes in snow-cover extent also influence the timing and volume of streamflow.

Regionally, Mekis and Hogg (1999) showed that precipitation in Canada has increased by an average of more than 10% over the 20th century. Zhang et al. (2000) report an increase in Canadian heavy snowfall amounts north of 55°N and Akinremi et al. (1999) found rainfall significantly increasing in the Canadian prairies from 1956 to 1995. Regarding precipitation in the Canadian prairies, there are conflicting reports. For example, Akinremi et al. (1999) reported significant increase from 1956 to 1995, but Gan (1998) reported marginal increase in precipitation between 1949 and about 1990s. Multidecadal streamflow data in Canada are not extensive, but there are no apparent inconsistencies between observed changes in streamflow or precipitation (Zhang et al., 2000).

Over the last 50 years, there has been a slight decrease in annual precipitation over China (Zhai et al., 1999a), which is supported by a significant (5% confidence level) decrease in the number of rainy days (3.9% per decade). In contrast, the area affected by the upper 10% of heaviest precipitation has significantly increased. Zhai et al. (1999b) show a significant increase in precipitation over the middle and lower reaches of the Yangtze River and west China during the latter part of the 20th century, while also detecting a declining trend in precipitation over northern China.

There have been marked increases in precipitation in the latter part of the 20th century over northern Europe, with a general decrease southward to the Mediterranean (Schönwiese and Rapp, 1997). Dry wintertime conditions over southern Europe and the Mediterranean (Piervitali et al., 1998; Romero et al., 1998) and wetter than normal conditions over many parts of northern Europe and Scandinavia (Hanssen-Bauer and Førland, 2000) are linked to strong positive values of the North Atlantic Oscillation (NAO), with more anticyclonic conditions over southern Europe and stronger westerlies over northern Europe.

Recent research has found that, over the former USSR, precipitation has increased since 1891 by about 5% west of 90°E for both warm and cold seasons (Bogdanova and Mestcherskaya, 1998; Groisman and Rankova, 2001). Georgievsky et al. (1996) also noted increases in precipitation over the last several decades over western Russia, accompanied by increases in streamflow and a rise in the level of the Caspian Sea. In eastern Russia, a negative precipitation trend since 1945 is embedded in the century-long positive precipitation trend (Gruza et al., 1999). Soil moisture data for large regions of Eurasia (Robock et al., 2000) show large upward trends. The rate of increase is more than 1 cm per decade in the available soil moisture in the top 1 m of soil, and these large positive trends occur simultaneously with positive trends in temperature that would normally reduce soil moisture.

An analysis of rainfall data since 1910 by Haylock and Nicholls (2000) reveals a large decrease in total precipitation and related rain days in southwestern Australia. Annual total rainfall has increased over much of Australia with significant increases of 15% to 20% in large areas. The increase in total rainfall has been accompanied by a significant 10% rise in the average number of rain days over Australia (Hennessy et al., 1999). Elsewhere in the Southern Hemisphere, a long-term increase in precipitation in Argentina has been observed for the period 1900 to 1998 (Dai et al., 1997).

2.1.2. Tropics and sub-tropics

The increase in precipitation in the mid- and high latitudes contrasts with decreases in the northern sub-tropics (with marginal statistical significance) that were largely responsible for the decade-long reduction in global land precipitation from the mid-1980s through the mid-1990s. Since 1995, record low precipitation has been observed in equatorial regions, while the sub-tropics have recovered from their anomalously low values of the 1980s.

Regionally positive but non-significant trends have occurred in the rainy season rainfall in northeast Brazil and northern Amazonia (Marengo et al., 1998). River data from northern Amazonia indicate wetter periods in the mid-1970s and in 1990, as well as drier periods between 1980 and 1990, consistent with rainfall anomalies. Northern Amazonian rainfall appears to be modulated by multi-decadal climate variations.

There is little evidence for a long-term trend in Indian monsoonal rainfall, but there are multidecadal variations (Kumar et al., 1999a,b). From 1906 to about 1960, monsoonal rainfall increased, then decreased through 1974 and has increased since. In Central America, for much of the period from the early 1940s to present, western Mexico has experienced an increasingly erratic monsoonal rainfall (Douglas and Englehart, 1999).

Since 1976, increases in precipitation in the South Pacific have occurred to the northeast of the South Pacific Convergence Zone (SPCZ), while decreases have occurred to its southwest (Salinger et al., 1996). There have also been significant decreases in rain days since 1961 throughout Southeast Asia and the western and central South Pacific, but increases in the north of French Polynesia and Fiji (Manton et al., 2001).

Streamflow data for major rivers in southeastern South America for the period 1901 to 1995 show that streamflow has increased since the mid-1960s (Garcia and Vargas, 1998; Genta et al., 1998). There have been increases in precipitation since 1900 along the South American eastern coastal areas, with less extensive increases since 1976.

There has been a pattern of continued aridity since the late 1960s throughout North Africa south of the Sahara. This pattern is most persistent in the western region. The driest period was in the 1980s with some recovery occurring during the 1990s, particularly in the easternmost sectors where rainfall in some years was near or just above the long-term mean (Nicholson et al., 2000). Southern Africa was relatively moist in the 1950s and 1970s (Nicholson et al., 2000), but Hulme (1996) found significant decreases in precipitation being observed since the late 1970s. Early 2000, however, has seen flood-producing rains in the eastern part of southern Africa.

The distributional consequences are obviously very important for the poorest countries in the world and they are mostly in Africa. In contrast to the general increase in the mean precipitation of other continents, some parts of Africa, e.g., East Africa (Ethiopia, Uganda, Tanzania) have suffered increasingly severe droughts in recent decades (e.g., Ntale and Gan, 2003). Ntale and Gan (2004) found that ENSO responses in East African rainfall are both region- and season-dependent, and the influence of El Niño is stronger and opposite to that of La Niña. East African rainfall exhibits large spatial and temporal variability partly because of its complex topography, the presence of large lakes such as Lake Victoria and the seasonal migration of the Inter-Tropical Convergence Zone (ITCZ). Using wavelet-based principal component analysis, Mwale et al. (2004) found that East Africa suffered a consistent decrease in the September–October–November rainfall from 1962 to 1997, resulting in 12 droughts between 1965 and 1997. Other than the Indian Ocean SST, East African rainfall has been found to be also significantly linked to the South Atlantic Ocean SST (Mwale et al., 2004). The non-stationary SST fields of the South Atlantic and Indian Oceans are also found to be associated with coherent regions of rainfall variability in central southern Africa (Mwale et al., 2004). Finally, Dore and Lamarche (2005) find evidence of a dramatic decline in precipitation in the Sahel, enough to characterize it as a "structural break".

2.2. Oceans

The strong spatial variability inherent in precipitation requires the use of estimates based on satellite observations for many regions. Thus, satellite data are essential to infer global changes in precipitation, as the oceans account for 70% of the global surface area. Since adequate observations were not made until the early 1970s, no satellite-based record is sufficiently long to permit estimates of century-long changes. The first satellite instrument specifically designed to make estimates of precipitation did not begin operation until 1987. At the present time, three data sets are available: (a) the Global Precipitation Climatology Project (GPCP) product, which spans the period from 1987 to the present (Huffman et al., 1997); (b) the Climate Precipitation Center Merged Analysis of Precipitation (CMAP) product, covering the period from 1979 to 1998 (Xie and Arkin, 1997); and (c) microwave sounding unit (MSU)-derived precipitation estimates since 1979 (Spencer, 1993). While the period from 1987 appears to be well observed, it is too short to draw conclusions regarding decadal-scale variations. The longer CMAP data set assumes that the various satellite-derived estimates have no trend over the period, and hence no longer time-scale conclusions are possible. Nonetheless, analyses of the CMAP product and associated data from the National Centers for Environmental Prediction (NCEP) reanalysis project indicate that there have been substantial average increases in precipitation over the tropical oceans during the last 20 years, related to increased frequency and intensity of ENSO (Trenberth et al., 2001). However, ENSO conditions are not related to positive precipitation anomalies everywhere over the tropical oceans (e.g., the southwestern Tropical Pacific).

3. Climate variability and extremes

Groisman et al. (1999) developed a simple statistical model of the frequency of daily precipitation based on the gamma distribution. They applied this model to a variety of regions around the world (40% of the global land area) during the season of greatest precipitation. Although Wilks (1999) shows that the gamma distribution under some circumstances can underestimate the probability of the highest rainfall amounts, Groisman et al. (1999) applied the distribution to the upper 5 and 10 percentiles of the distribution, which are less subject to underestimation. Their analysis period varied from region to region, but within each region it generally spanned at least the last several decades and for some regions much of the 20th century (Australia, United States, Norway and South Africa). Katz (1999) obtained results consistent with those of Groisman et al. (1999). For many regions of the world, it was found that an increase in the mean total precipitation is disproportionately reflected in increased heavy precipitation rates. So given the patterns of mean total precipitation changes during the 20th century, it could be anticipated that, in general, for those areas with increased mean total precipitation, the percentage increase in heavy precipitation rates should be significantly larger and vice versa for total precipitation decreases. Regional analyses of annual precipitation in the United States (Karl and Knight, 1998; Trenberth, 1998; Kunkel et al., 1999), Canada (Stone et al., 1999), Switzerland (Frei and Schär, 2001), Japan (Iwashima and Yamamoto, 1993; Yamamoto and Sakurai, 1999), wintertime precipitation in the UK (Osborn et al., 2000), and rainy season precipitation in Norway, South Africa, the northeast of Brazil and the former USSR (Groisman et al., 1999; Gruza et al., 1999; Easterling et al., 2000) confirm this characteristic of an amplified response for the heavy and extreme events.

Increases in heavy precipitation have also been documented even when mean total precipitation decreases. This can occur when the probability of precipitation (the number of events) decreases, or if the shape of the precipitation distribution changes, but this latter situation is less likely (Buffoni et al., 1999; Groisman et al., 1999; Brunetti et al., 2000a,b). For example, in Siberia for the summer season during the years 1936 to 1994, there was a statistically significant decrease in total precipitation of 1.3% per decade, but the number of days with precipitation also decreased. This resulted in an increase (1.9% per decade) in the frequency of heavy rainfall above 25 mm. The opposite can also occur when the number of rainfall events increases; thus, no trends were found in 1-day annual maximum precipitation in the Nordic countries, even when mean total precipitation increased (Førland et al., 1998).

There has also been a 10% to 45% increase in heavy rainfall, as defined by the 99th percentile of daily totals, over many regions of Australia from 1910 to 1995, but few individual trends were statistically significant (Hennessy et al., 1999). In southwest Australia, however, a 15% decrease has been observed in winter rainfall on very wet days (Hennessy et al., 1999; Haylock and Nicholls, 2000).

In Niger, a recent analysis of hourly rainfall data (Shinoda et al., 1999) reveals that the droughts in the 1970s and 1980s were characterized primarily by a reduced frequency of heavy rainfall events (those exceeding 30 mm/day) rather than by a reduction in rainfall amount within heavy events. Such a result is still consistent with the model of Groisman et al. (1999), as a decrease in the frequency of rainfall events has been responsible for the decrease in total rainfall. In the Sahel region of Nigeria; however, there has been a decrease in the heaviest daily precipitation amounts, coincident with an overall decrease in annual rainfall. This pattern is apparent throughout the Sudano-Sahel Zone, including the Ethiopian plateau (Nicholson, 1993; Tarhule and Woo, 1998; Easterling et al., 2000). Again, it is apparent that there has been an amplified response of the heaviest precipitation rates relative to the percentage change in total precipitation.

Since large portions of the mid- and high-latitude land areas have had increasing precipitation during the last half the 20th century, the question arises as to how much of this area is affected by increases in heavy and extreme precipitation rates. Frich et al. (2001) suggest an overall increase in the area affected by more intense daily rainfall. They found that widely distributed parts of the mid- and high latitudes have locally statistically significant increases in both the proportion of mean annual total precipitation falling into the upper five percentiles and in the annual maximum consecutive 5-day precipitation total. However, for the regions of the globe sampled taken as a whole, only the latter statistic shows a significant increase. Regional analyses in Russia (Gruza et al., 1999), the United States (Karl and Knight, 1998) and elsewhere (Groisman et al., 1999; Easterling et al., 2000) confirm this trend. Although the trends are by no means uniform, as would be anticipated with the relatively high spatial and interannual variability of precipitation, about 10% of the stations analyzed show statistically significant increases at the 5% level. This equates to about a 4% increase in the annual maximum 5-day precipitation total. The number of stations reflecting a locally significant increase in the proportion of total annual precipitation occurring in the upper five percentiles of daily precipitation totals outweighs the number of stations with significantly decreasing trends by more than 3 to 1. Although not statistically significant when averaging over all stations, there is about a 1% increase in the proportion of daily precipitation events occurring in the upper five percentiles. Overall, it is likely that there has been a 2% to 4% increase in the number of heavy precipitation events when averaged across the mid- and high latitudes.

3.1. Snow cover

Satellite records indicate that the Northern Hemisphere annual snow-cover extent (SCE) has decreased by about

10% since 1966 largely due to decreases in spring and summer since the mid-1980s over both the Eurasian and American continents (Robinson, 1997, 1999). Winter and autumn SCE show no statistically significant change. Reduction in snow cover during the mid- to late 1980s was strongly related to temperature increases in snow-covered areas. There is a highly significant interannual (+0.6) and multidecadal correlation between increases in the Northern Hemisphere spring land temperature and a reduction in the Northern Hemisphere spring snow cover since data have been available (1966). Snow-cover extent has decreased about 10% since 1966. The improvements in the quantity and quality of the visible satellite imagery used to produce the operational snow-cover product cannot account for the observed changes in snow cover.

Longer regional time series based on station records and reconstructions suggest that Northern Hemisphere spring and summer SCEs in the past decade have been at their lowest values in the past 100 years. In the other seasons, it is likely that extents in the latter portion of the 20th century exceeded those of earlier years (Brown, 2000).

Reconstructions for North America suggest that, while there has been a general decrease in spring SCE since 1915, it is likely that winter SCE has increased (Brown and Goodison, 1996; Frei et al., 1999; Hughes and Robinson, 1996; Hughes et al., 1996). Similar to the results in North America, in Eurasia, April SCE has significantly decreased, but lack of data has prevented an analysis of winter trends (Brown, 2000). Over Canada, there has been a general decrease in snow depth since 1946, especially during spring, in agreement with decreases in SCE (Brown and Braaten, 1998). Winter depths have declined over European Russia since 1900 (Meshcherskaya et al., 1995), but have increased elsewhere over Russia in the past few decades (Fallot et al., 1997). The common thread between studies that have examined seasonality is an overall reduction in spring snow cover in the latter half of the 20th century.

There have been relatively few studies of snowfall trends across the globe. Statistically significant increases in seasonal snowfall have been observed over the central USA in the 20th century (Hughes and Robinson, 1996). In recent decades, snowfall has also been heavier to the lee of the North American Great Lakes than earlier in the century (Leathers and Ellis, 1996). These findings are in line with observations from Canada and the former Soviet Union, reflecting a trend towards increased precipitation over the mid-latitude lands in the Northern Hemisphere (Groisman and Easterling, 1994; Brown and Goodison, 1996; Ye et al., 1998). Specifically on Canada, while there is an overall increasing trend in precipitation, a regional analysis makes it clear that the changes depend on regions. For example, Gan (1998, 1995) showed no significant changes to precipitation and streamflow in the Canadian prairies in the second half of the 20th century, but Dore (2001) shows significant increases in precipitation in eastern Canada.

3.2. Droughts and wet spells

An intensification of the hydrological cycle is projected to occur as the globe warms. One measure of such intensification is to examine whether the frequency of droughts and wet spells is increasing. Karl et al. (1995) examined the proportion of land areas having a severe drought and a severe moisture surplus over the United States. Dai et al. (1998) extended this analysis to global land areas using the water balance approach of the Palmer Drought Severity Index (PDSI). There have been severe droughts in recent decades in places such as California, and the mid-west states of Minnesota, Iowa, Nebraska and Kansas (Frederick, 1993), as well as droughts in the Canadian prairies (Akinremi et al., 1999).

Long-term global trends for 1900 to 1995 are relatively small for both severe drought and wet area statistics. However, during the last two to three decades, there have been some increases in the globally combined severe dry and wet areas, resulting from increases in either the dry area, e.g., over the Sahel, eastern Asia and southern Africa or the wet areas, e.g., over the United States and Europe. Most of the increases occurred after 1970. Except for the Sahel, however, the magnitude of dry and wet areas of recent decades is not unprecedented during this century, but it should be noted that rainfall in the Sahel since the height of the drought has substantially increased. In related work, Frich et al. (2001) found that, in much of the mid- and high latitudes, there has been a statistically significant increase in both the number of days with precipitation exceeding 10 mm/day and in the number of consecutive days with precipitation during the second half of the 20th century.

Recent changes in the areas experiencing severe drought or wet spells are closely related to the shift in ENSO towards more warm events since the late 1970s and coincide with record high global mean temperatures. Dai et al. (1998) found that, for a given value of ENSO intensity, the response in areas affected by drought or excessive wetness since the 1970s is more extreme than prior to the 1970s, also suggesting an intensification of the hydrological cycle.

4. Changing precipitation patterns by region

4.1. Africa

4.1.1. The 1997–1998 ENSO event

ENSO appears to play a major role in East Africa, but it masks the perhaps more important role of the other oceans, particularly the Indian Ocean. The 1961–1962 rains were spectacularly manifested as rapid rises in the levels of east African lakes. Lake Victoria rose 2 m in little more than a year (Flohn and Nicholson, 1980). This was not an ENSO year, but exceedingly high SSTs occurred in the nearby Indian Ocean as well as the Atlantic. Such high SSTs are associated with most ENSO events, and it is probably SSTs in these regions, rather than the Pacific ENSO (Nicholson and Kim, 1997), that have the largest influence on east African rainfall. In another example, the dipole pattern anticipated to occur during ENSO events did not occur during the 1997–1998 event. There was a tremendous increase in rainfall in east Africa, but intense drought conditions did not occur throughout southern Africa. The reason appears to be an unusual pattern of SST in the Indian Ocean.

4.1.2. Drought conditions in the Sahel

One of the most significant climatic variations has been the persistent decline in rainfall in the Sahel since the late 1960s. The trend was abruptly interrupted by a return of adequate rainfall conditions in 1994. This was considered to be the wettest year of the past 30 and was thought to perhaps indicate the end of the drought. However, by the standard of the whole century, rainfall in 1994 barely exceeded the long-term mean. Also, the 1994 rainy season was unusual in that the anomalously wet conditions occurred toward the end of the rainy season and in the months following. Unfortunately, dry conditions returned after 1994. The persistent drying trend has caused concern among development planners regarding how to cope with losses of food production, episodes of food insecurity, displacements of populations, lack of water resources and constraints on hydroelectricity.

4.1.3. Interannual and interdecadal climate variability

Humans have adapted to patterns of climate variability through land-use systems that minimize risk, with agricultural calendars that are closely tuned to typical conditions and choices of crops and animal husbandry that best reflect prevailing conditions. Rapid changes in this variability may severely disrupt production systems and livelihoods. Interannual variability of the African climate is determined by several factors. The ENSO is the dominant perturbation responsible for interannual climate variability over eastern and southern Africa (Nicholson and Entekhabi, 1986). The typical rainfall anomaly associated with ENSO is a dipole rainfall pattern: eastern Africa is in phase with warm ENSO episodes, whereas southern Africa is negatively correlated with these events (Nicholson and Kim, 1997). The 1997–1998 ENSO event resulted in extreme wet conditions over eastern Africa and the 1999–2000 La Niña may have caused devastating floods in Mozambique. Modeling exercises indicate that climate change may increase the frequency of ENSO warm phases by increasing the warm pool in the tropical western Pacific or by reducing the efficiency of heat loss (Trenberth and Hoar, 1997; Timmermann et al., 1999).

In the Sahel and similar regions of West Africa, the problem is more complex. ENSO appears to influence year-to-year variations and reduces rainfall. Its influence appears to be greater within long dry intervals in the Sahel, but it is not the dominant factor controlling rainfall in this region (Ward, 1998).

Over northern Africa, the NAO is a key factor that is responsible for interannual variability of the climate (Lamb, 1978). Across western Africa, year-to-year changes in seasonal climatic conditions are determined primarily by the Atlantic Ocean, although the rest of the world's oceans also play important roles. Low-lying islands and coastal regions receive significant amounts of rainfall from tropical cyclone activity, which is sensitive to interannual variability of SST conditions over adjacent ocean basins.

The climate of Africa also exhibits high interdecadal variability. Rainfall variability in the Sahel derives from factors such as SST and atmospheric dynamics (Lamb, 1978; Folland et al., 1986; Hulme and Kelly, 1997; Nicholson and Kim, 1997) and is modulated by land surface effects related to soil moisture, vegetation cover, dust and so forth (Charney, 1975; Diedhiou and Mahfouf, 1996; Xue, 1997; Zeng et al., 1999). Modeling evidence also suggests that orographic control plays a significant role in promoting climate teleconnections between global SST anomalies and West African interannual climate variability (Semazzi and Sun, 1995).

Besides ENSO, the NAO and West African climate anomaly patterns, other continental-scale and subcontinental climate anomalies play significant roles in determining interannual and longer climate variability time scales (Nicholson et al., 2000). For instance, the decade 1950–1959 was characterized by above-normal precipitation over most of Africa, although rainfall deficiencies prevailed over the near-equatorial region. Later, during the period 1960–1969, this rainfall anomaly pattern dramatically reversed in sign, with rainfall deficits observed for most of Africa, while the equatorial region experienced widespread abundance of rainfall. These two time periods also coincide with a reversal in the sign of the Sahelian rainfall anomalies (Lamb and Peppler, 1992). More recently, the pattern has been one of increased aridity throughout most of the continent. Mean rainfall decreased by 20–49% in the Sahel between the periods 1931–1960 and 1968–1997 and generally 5–10% across the rest of the continent. In comparison with the period between 1950 and 1970, the average length of the rainy season has not changed significantly during the dry period 1970–1990. Instead, the decrease in rainfall in July and August explains most of the diminution of total annual rainfall over the Sahel since 1970. The average number of rainy events in August was reduced by about 30% (Le Barbé and Lebel, 1997).

4.2. Asia

Rainfall in boreal Asia is highly variable on seasonal and interannual as well as spatial scales. The time series of annual mean precipitation in Russia suggests a decreasing trend; these tendencies have amplified during 1951–1995, especially in warm years (Rankova, 1998). In long-term mean precipitation, a decreasing trend of about −4.1 mm/month/100 years has been reported in boreal Asia. During the past 10–15 years, however, precipitation has increased, mostly during the summer–autumn period (Izrael et al., 1997). As a result of this increase in precipitation, water storage in a 1-m soil layer has grown by 10–30 mm (Robock et al., 2000). The large upward trends in soil moisture (of more than 1 cm/10 years) have created favorable conditions for infiltration into groundwater. The levels of major aquifers have risen by 50–100 cm; the growth of groundwater storage has resulted in increasing ground river recharge and considerable low-water runoff.

Annual mean rainfall is considerably low in most parts of the arid and semi-arid region of Asia. Moreover, temporal variability is quite high: occasionally, as much as 90% of the annual total is recorded in just 2 months of the year at a few places in the region. Rainfall observations during the past 50 years in some countries in the northern parts of this region have shown an increasing trend on an annual mean basis. A decreasing trend in annual precipitation for the period 1894–1997 has been observed in Kazakhstan. The precipitation in spring, summer and autumn, however, has shown slight increasing trends. In Pakistan, 7 of 10 stations have shown a tendency toward increasing rainfall during monsoon season (Chaudhari, 1994).

In temperate Asia, the East Asian monsoon greatly influences temporal and spatial variations in rainfall. Annual mean rainfall in Mongolia is 100–400 mm and is confined mainly to summer. Summer rainfall seems to have declined over the period 1970–1990 in Gobi; the number of days with relatively heavy rainfall events has dropped significantly (Rankova, 1998). In China, annual precipitation has been decreasing continuously since 1965; this decrease has become serious since the 1980s (Chen et al., 1992). The summer monsoon is reported to be stronger in northern China during globally warmer years (Ren et al., 2000). On the other hand, drier conditions have prevailed over most of the monsoon-affected area during globally colder years (Yu and Neil, 1991).

In tropical Asia, hills and mountain ranges cause striking spatial variations in rainfall. Approximately 70% of the total annual rainfall over the Indian subcontinent is confined to the southwest monsoon season (June–September). The western Himalayas get more snowfall than the eastern Himalayas during winter. There is more rainfall in the eastern Himalayas and Nepal than in the western Himalayas during the monsoon season (Kripalani et al., 1996). The annual mean rainfall in Sri Lanka is practically trendless; positive trends in February and negative trends in June have been reported, however (Chandrapala and Fernando, 1995). In India, long-term time series of summer monsoon rainfall have no discernible trends, but decadal departures are found above and below the long time average alternatively for three consecutive decades (Kothyari and Singh, 1996). Recent decades have exhibited an increase in extreme rainfall events over northwest India during the summer monsoon (Singh and Sontakke, 2002). Moreover, the number of rainy days during the monsoon along east coastal stations has declined in the past decade. A long-term decreasing trend in rainfall in Thailand is reported (OEPP, 1996). In Bangladesh, decadal departures were below long-term averages until 1960; thereafter, they have been much above normal (Mirza and Dixit, 1997).

4.3. Australia and New Zealand

Australian annual mean rainfall has increased by a marginally significant amount over the past century (Collins and Della-Marta, 1999; Hennessy et al., 1999). However, increases in the frequency of heavy rainfalls and average rainfall are significant in many parts of Australia. Average rainfall has increased most in the northwest and southeast quadrants (Collins and Della-Marta, 1999). The largest and most statistically significant change has been a decline in rainfall in the winter–rainfall-dominated region of the far southwest of western Australia, where in the period 1910–1995, winter (June–July–August) rainfall declined by 25%, mainly during the 1960s and 1970s. Previous studies (Wright, 1974; Allan and Haylock, 1993; Yu and Neil, 1993), as well as a more recent one (Smith et al., 2000), have noted this decrease and attribute it to atmospheric circulation changes, predominantly resulting from natural variability.

There are marked interdecadal variations over northern and eastern Australia in summer half-year rainfall, which are dominated by ENSO-induced variations (Power et al., 1999a). There also are clear interannual and decadal variations in central and eastern Australian rainfall associated with Indian and Pacific Ocean SSTs (Power et al., 1999b). Some of the regional linear trends observed during the past century may merely reflect a particular pattern of decadal variation. Thus, the high degree of decadal variability may enhance or obscure a signal that is related to climatic change for several decades. A growing body of evidence is being obtained about past climate variability from coral cores (e.g., Lough and Barnes, 1997; Isdale et al., 1998; Quinn et al., 1998).

The strength of the relationship between eastern Australian climate and ENSO has been observed to vary over the past century. This seems to be linked to longer term climate oscillations such as the North Pacific Decadal Oscillation (NPDO) (e.g., Power et al., 1999a). Salinger and Mullan (1999) examined the 20-year periods before and after 1977 and showed increases after 1977 (some statistically significant) in mean rainfall for New Zealand's west coast, associated with strengthening westerly winds. These fluctuations in rainfall are partially explained by the increase in El Niño conditions over recent decades.

4.4. Europe

Annual precipitation trends in this century are characterized essentially by enhanced precipitation in the northern half of Europe (i.e., north of the Alps to northern

Fennoscandia), with increases ranging from 10% to close to 50%. The region stretching from the Mediterranean through central Europe into European Russia and Ukraine, by contrast, has experienced decreases in precipitation by as much as 20% in some areas. In time series analyses of precipitation averaged over the European region, it is difficult to determine a meaningful trend in precipitation, especially since the 1950s. The interannual variability seems to have decreased in the latter part of the record: the amplitude of departures in precipitation from long-term averages is far less than in the first half of the century. This pattern does not necessarily mean that the amplitude of interannual variability has decreased at the regional scale or at specific sites.

Trends in annual precipitation differ between northern Europe (wetting) and southern Europe (drying), reflecting a wider hemispheric pattern of contrasting zonal-mean precipitation trends between high and low latitudes (Dai et al., 1997; Hulme et al., 1998). Precipitation over northern Europe has increased by 10–40% in the 20th century, whereas some parts of southern Europe have dried by as much as 20%. Romero et al. (1998) show that, over the Spanish southern coast and the Pyrenees region, the numbers of days with precipitation have decreased by 50% and 30%, respectively, from 1964 to 1993. In Italy, total precipitation in the 20th century has decreased by about 5% in the north and by about 15% in the south (Buffoni et al., 1999; Brunetti et al., 2001). Analysis of moisture extremes over Europe using the PDSI (Briffa et al., 1994) showed strong decadal-scale variability in drought frequency; the 1940s and early 1950s experienced widespread and severe droughts—a pattern repeated in 1989 and 1990.

Analysis of 85 long-term maximum 1-day precipitation records in the Nordic countries indicates that there is a maximum in the 1930s and a tendency of increasing values during the 1980s and 1990s decades with relatively high regional summer temperatures. In western Norway, the past two decades have been exceptional, with substantial increases in orographic precipitation during autumn, winter and spring (Førland et al., 1998). Elsewhere, daily precipitation intensities over the UK have increased in winter over recent decades (Osborn et al., 2000), although not in other seasons. This increase in UK winter precipitation intensities has been paralleled by a marked decrease in the frequency of cold winter days in the UK (Jones et al., 1999).

4.5. Latin America

Glaciers in Latin America have receded dramatically in the past decades and many of them have disappeared completely (Williams and Ferrigno, 1998). In 18 glaciers in the Peruvian Andes, mass balances since 1968 and satellite images show a reduction of more than 20% of the glacial surface, corresponding to 11,300 million m^3 of ice (Morales-Arnao, 1969a,b). Significant reductions also have occurred in southern Chile and Argentina (e.g., glacier Sarmiento) (Basso, 1997). Deglaciation may have contributed to observed negative trends in streamflows in that region (Morales-Arnao, 1999). For rivers in arid lands in northwest Peru and northeast and southeastern Brazil, significant negative trends also have been detected, but these variations seem to be related to human water management for irrigation purposes and increases in agricultural areas, rather than climate-induced changes (Marengo, 1995, Marengo et al., 1998).

Between 20°S and 40°S, precipitation around the Andes occurs mainly during the winter. Snow accumulates in the high parts of the cordillera and melts during the summer, becoming the main source of water for rivers in the region. Agricultural activities in central Chile and the Argentinean central western plains are maintained through irrigation. Therefore, it may be said with high confidence that fluctuations in winter precipitation have a strong socioeconomic impact in the region.

The precipitation record for Santiago, Chile, is highly correlated with snow depth in the cordillera. Recorded precipitation exhibited a decreasing trend from the late 19th century through the mid-1970s but has reverted since then. A similar trend has been detected in streamflow in the region (Minetti and Sierra, 1989; Carril et al., 1997; Compagnucci and Vargas, 1998; Compagnucci et al., 2000; Waylen et al., 2000). In southern Chile and the Argentinean cordillera, a negative trend in precipitation and streamflow has been detected (Quintela et al., 1993; Nuñez et al., 1999).

In northwestern Mexico, there is a tendency for more winter precipitation, which has resulted in positive trends in river water levels. However, along with more intense winter precipitation, interannual climate variability has increased (Magaña and Conde, 2000). On the other hand, some parts of southern Mexico and Central America exhibit positive or negative rainfall trends, depending on the orientation of the catchment (Aparicio, 1993; IPCC, 1996; Jáuregui, 1997). For Nicaragua, rainfall analysis for 1961–1995 showed negative trends in the north and northwest parts of the country. A systematic increment was detected on the Caribbean coast, and almost no variation was found along the central and the Pacific coastal regions (MARENA, 2000).

In Colombia, weak rainfall trends have been observed for the period 1955–1995, with no preferred sign at a regional level. For central Colombia, rainy seasons have been occurring earlier in recent years than 25 years ago (Mesa et al., 1997). Trends in Colombian river streamflow are mixed, but the main river catchments such as the Cauca and Magdalena Rivers exhibit decreasing trends. Deforestation could account for such decreasing trends in river discharges (Poveda and Mesa, 1997).

For the Amazon region, Marengo et al. (2000) have identified multidecadal variations in rainfall in northern and southern portions of the basin, with opposite tendencies. Perhaps the most important finding is the presence of periods with relatively wetter or drier conditions that are more relevant than any unidirectional trends themselves. For instance, the period 1950–1976 was regionally wet in northern Amazonia, but since 1977 the region has been drier. This dryness does not seem to be related to regional deforestation (Marengo et al., 1998; Marengo and Nobre, 2001). Similarly, streamflow series in Amazonian rivers also exhibit multidecadal variations; they do not display significant unidirectional trends (Richey et al., 1989; Marengo, 1995).

In northeast Brazil, multidecadal variations in atmospheric circulation over the tropical Atlantic have been linked to similar time-scale variations in rainfall over the region (Hastenrath and Greischar, 1993; Nobre and Shukla, 1996; Wagner, 1996). On longer time scales, rainfall in northern northeast Brazil exhibits weak positive trends that are consistent with changes in decadal changes in circulation described in Wagner (1996).

Streamflow in the River Plate basin–particularly in the Negro, Paraguay, Paraná and Uruguay Rivers–exhibits a negative trend from 1901 to 1970, which reverses after this period. Multidecadal variability also is observed in discharges (Garcia and Vargas, 1998; Genta et al., 1998; Robertson and Mechoso, 1998). Moreover, there are written reports of alternating floods and drought periods during the 16th–18th centuries, indicating high natural variability (Prieto and Herrera, 1992).

In sub-tropical Argentina, Paraguay and Brazil, precipitation exhibits a long-term change, with a sharp increase in the period 1956–1990 after a dry period in 1921–1955 (Castañeda and Barros, 1996). In the Pampa region, there is a positive trend in precipitation during the period 1890–1984. This increase in annual rainfalls was accompanied by a relative increase in precipitation during the spring and summer (Penalba and Vargas, 1996; Hoffman et al., 1997; Krepper and Sequeira, 1998). At high elevations in northwest Argentina, paleoclimatic records suggest an increase in precipitation in the past 200 years (Villalba et al., 1997). In the same region, as well as in Bolivia and southeast Peru, records show that the 17th-century climate was wetter and less variable (fewer floods and droughts), whereas the 18th century was highly unstable, with a large amplitude in the annual cycle and recurrent wet and dry periods (Prieto and Herrera, 1992).

Variations in precipitation in Latin America have a strong effect on runoff and streamflow, which also are affected by melting of glaciers and snow. Based on available information, there is evidence that these variations and their sign depend on the geographical subregion under consideration.

4.6. North America

Seasonal and annual runoff may change over large regions as a result of changes in precipitation or evapotranspiration. Runoff is simply the area-normalized difference between precipitation and evapotranspiration; as such, it is a function of watershed characteristics, i.e., the physical structure of the watershed, vegetation and climate. Although most climate change models show increases in precipitation over much of North America, rates of evaporation and perhaps transpiration are also likely to increase with increasing temperatures. Therefore, regions in which changes in precipitation do not offset increasing rates of evaporation and transpiration may experience declines in runoff and consequently declines in river flows, lake levels and groundwater recharge levels (Schindler, 1997). Alternatively, regions that experience substantial increases in precipitation are likely to have substantial increases in runoff and river flows.

Seasonal changes in runoff also could be substantial. Most climate change scenarios suggest increased winter precipitation over much of North America, which could result in increased runoff and river flows in winter and spring. Several climate change scenarios show declines in summer precipitation in some regions (e.g., the southeastern United States; IPCC, 1996) or declines in summer soil-moisture levels (e.g., over much of North America; IPCC, 1996), which could result in significant declines in summer and autumn runoff in these regions. However, climate change scenarios showing summer declines in precipitation or soil-moisture levels in these regions generally are produced from simulations with doubled CO_2 forcing alone; when aerosol forcing is included, summer precipitation and soil-moisture levels increase only slightly. This pattern highlights the large uncertainty in climate change projections of runoff.

Seasonal patterns in the hydrology of mid- and high-latitude regions could be altered substantially, with runoff and streamflows generally increasing in winter and declining in summer.

Higher air temperatures could strongly influence the processes of evapotranspiration, precipitation as rain or snow, snow and ice accumulation, and melt—which, in turn, could affect soil moisture and groundwater conditions and the amount and timing of runoff in the mid- and high-latitude regions of North America. Higher winter temperatures in snow-covered regions of North America could shorten the duration of the snow-cover season. For example, one climate change scenario indicates up to a 40% decrease in the duration of snow cover in the Canadian prairies and a 70% decrease in the Great Plains (Boer et al., 1992; Brown et al., 1994). Warmer winters could lead to less winter precipitation as snowfall and more as rainfall, although increases in winter precipitation could also lead to greater snowfall and snow accumulation, particularly at the higher latitudes. Warmer winter and spring temperatures could lead to earlier and more rapid snowmelt and earlier ice break-up, as well as more rain-on-snow events that produce severe flooding, such as occurred in 1996–1997 (Yarnal et al., 1997).

4.7. Arctic

Snow-cover extent in the northern hemisphere has been reduced since 1972 by about 10%, largely as a result of spring and summer deficits since the mid-1980s (Brown, 2000; Serreze et al., 2000). Most Arctic regions have experienced increases in precipitation since at least the 1950s (Groisman et al., 1991; Groisman and Easterling, 1994; Georgiyevskii, 1998). Measurements from Spitsbergen show a statistically significant increase in precipitation during all seasons, except winter (Hanssen-Bauer and Førland, 1998).

Groisman et al. (1994) analyzed seasonal snow extent in the northern hemisphere and demonstrated an inverse relationship with near-surface air temperature. Recent findings have provided evidence of a significant decrease in spring snow extent since 1915 over Eurasia (Brown, 1997) and southern Canada (Brown and Goodison, 1996). Such trends may be related to low-frequency fluctuations in hemispheric atmospheric circulation patterns (Serreze et al., 2000).

4.8. Antarctic

Changes in precipitation in the Antarctic are more poorly understood. Model estimates from Smith et al. (1998) indicate that the accumulation rate for the East Antarctic ice sheet surface has increased by a rate of 1.9 mm/year (water equivalent) over the period 1950–1991. Their estimate of sensitivity is 12.5 mm/year per degree of warming. Examination of water-mass properties of oceans shows that significant changes have occurred over the past 30 years. Bindoff and McDougall (2000) and Wong et al. (1999) point out that sub-Antarctic mode water (SAMW) and Antarctic intermediate water (AAIW) have become less saline and cooler, and both water masses are now deeper. These changes indicate surface warming in the source region of SAMW and increased precipitation in the source region of AAIW.

4.9. Small island states

Recent work undertaken by the New Zealand Institute of Water and Atmospheric Research indicate that rainfall has increased in the northeast Pacific but has decreased in the southwest Pacific region. Interannual variations in temperature and rainfall are strongly associated with ENSO, resulting in water shortages and drought in Papua New Guinea, the Marshall Islands, the Federated States of Micronesia, American Samoa, Samoa and Fiji. Although a causal link has yet to be established, all of the foregoing changes have coincided with an eastward shift of the SPCZ since 1970. Research now suggests that some of the foregoing changes (including the shift in the SPCZ) may be closely correlated with interdecadal patterns of variability—for example, the Pacific Decadal Oscillation (PDO) (Salinger and Mullan, 1999). It should be noted, nevertheless, that the changes observed in the 20th century are considered to be consistent with patterns related to anthropogenic greenhouse gas (GHG)-induced climate change (Salinger et al., 1995; Hay, 2000).

5. Conclusions

Annual land precipitation has continued to increase in the middle and high latitudes of the Northern Hemisphere (very likely to be 0.5% to 1% per decade), except over Eastern Asia. Over the sub-tropics (10°N to 30°N), land-surface rainfall has decreased on average (likely to be about 0.3% per decade), although this has shown signs of recovery in recent years. Tropical land-surface precipitation measurements indicate that precipitation has probably increased by about 0.2% to 0.3% per decade over the 20th century, but increases are not evident over the past few decades and the amount of tropical land (versus ocean) area for the latitudes 10°N to 10°S is relatively small. Nonetheless, direct measurements of precipitation and model reanalyses of inferred precipitation indicate that rainfall has also increased over large parts of the tropical oceans. Where and when available, changes in annual streamflow often relate well to changes in total precipitation. The increases in precipitation over Northern Hemisphere mid- and high-latitude land areas have a strong correlation to long-term increases in total cloud amount. In contrast to the Northern Hemisphere, no comparable systematic changes in precipitation have been detected in broad latitudinal averages over the Southern Hemisphere.

Decreasing snow-cover and land-ice extent are positively correlated with increasing land-surface temperatures. Satellite data show that there are very likely to have been decreases of about 10% in the extent of snow cover since the late 1960s. There is a highly significant correlation between increases in Northern Hemisphere land temperatures and the decreases in snow cover. There is ample evidence to support a major retreat of alpine and continental glaciers in response to 20th century global warming. In a few maritime regions, increases in precipitation due to regional atmospheric circulation changes have overshadowed increases in temperature in the past two decades, and glaciers have re-advanced. Over the past 100 to 150 years, ground-based observations show that there is very likely to have been a reduction of about 2 weeks in the annual duration of lake and river ice in the mid- to high latitudes of the Northern Hemisphere.

New analyses show that in regions where total precipitation has increased, it is very likely that there have been even more pronounced increases in heavy and extreme precipitation events. The converse is also true. In some regions, however, heavy and extreme events (i.e., defined to be within the upper or lower 10 percentiles) have increased despite the fact that total precipitation has decreased or remained constant. Where this has occurred, it is attributed to a decrease in the frequency of precipitation events. Overall, it is likely that for many mid- and high-latitude areas, primarily in the Northern Hemisphere, statistically significant increases have occurred in the proportion of total annual precipitation derived from heavy and extreme precipitation events; it is likely that there has been a 2% to 4% increase in the frequency of heavy precipitation events over the latter half of the 20th century. Over the 20th century (1900 to 1995), there were relatively small increases in global land areas experiencing severe drought or severe wet conditions. In some regions, such as parts of Asia and Africa, the frequency and intensity of drought have been observed to increase in recent decades. In many regions, these changes are dominated by interdecadal and multidecadal climate variability, such as the shift in ENSO towards more warm events.

There is no doubt that in the observed precipitation, the changing pattern is the *signature* of global climate change. Precipitation is being globally reallocated by climate change. Perhaps it is the least developed that will experience the most adverse consequences of climate change. Richer countries have now lived with Third World poverty for decades and will view more disasters there, aggravated by extremes of climate, as nothing new. The consequences of global warming are more likely to be treated as calling for voluntary acts of *charity* rather than as a matter of *equity*, requiring compensation for the actions of the industrialized countries. That will be the greatest inequity of global climate change.

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