

THE CHANGING CHARACTER OF PRECIPITATION

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As climate changes, the main changes in precipitation will likely be in the intensity, frequency, and duration of events, but these characteristics are seldom analyzed in observations or models.

Why does it rain? If a parcel of air rises, it expands in the lower pressure, cools, and therefore condenses moisture in the parcel, producing cloud and, ultimately, rainfall—or perhaps snowfall. So a key ingredient is certainly the many and varied mechanisms for causing air to rise. These range from orographic uplifting as air flows over mountain ranges, to a host of instabilities in the atmosphere that arise from unequal heating of the atmosphere, to potential vorticity dynamics. The instabilities include those that result directly in vertical mixing, such as convective instabilities, to those associated with the meridional heating disparities that give rise to baroclinic instabilities and the ubiquitous fronts and low and high pressure weather systems. Thus cold air

pushing underneath warmer air (advancing cold front) or warm air gliding over colder air (advancing warm front), and so on, can all provide opportunities for air to rise. Henceforth we use the term “storm” as shorthand for all the potential disturbances that create upward motion in the atmosphere, since many will in fact be thunderstorms, or extratropical cyclones manifested as rain- or snowstorms. Although the distribution of these events around the globe vary with climate, the basic mechanisms for causing air to rise presumably do not in and of themselves change. They need to be better understood and modeled, but from a societal standpoint, the fact that their relative importance can change with time is a significant but often overlooked consequence.

Similarly, mechanisms involved in the actual condensation process are important. After a cloud forms, if the cloud droplets grow large enough ($> 4\text{-}\mu\text{m}$ diameter) or the air cools sufficiently for the cloud droplets to freeze, then rain and snow form, respectively.

The microphysics of cloud droplets matters. Human interference, such as putting various kinds of pollutants and aerosols into the atmosphere, can make important differences in the number and size of cloud droplets, precipitation formation, within-cloud heating, and the cloud’s lifetime (e.g., Rosenfeld 2000; Ramanathan et al. 2001; Kaufman et al. 2002). Light-absorbing aerosols can short-circuit the hydrological

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cycle by depositing heat directly into a layer that would otherwise be heated by the latent heating in precipitation originating from heat absorbed at the surface and lost through evaporation (see also Menon et al. 2002).

These aspects have been the focus of much meteorological and climate research but are not the focus of this article. The other main ingredient in the opening statement about why it rains is the assumption that there is moisture present. Where exactly does the moisture come from? It is argued that this aspect of precipitation is one that has been underappreciated and is worthy of more attention. After all, it will not rain at all unless there is a supply of moisture. Yet time after time in major droughts, such as the one experienced in the western United States in the summer of 2002, this aspect seems to be overlooked and fruitless calls are made for cloud seeding to produce rain and snow.¹ Cloud seeding cannot create moisture, nor can it make the large-scale environment more favorable for convection onset. It may harvest more moisture locally, but this is likely at the expense of precipitation downstream.

The character of precipitation depends not only on the nature of the storm, but also on the available moisture. We speak glibly about rainfall, or more generally, precipitation, and often place it on a par with other atmospheric variables such as temperature, pressure, wind, etc. Yet most of the time it does not rain. And when it does, the rain rate varies. At the very least we could always consider how frequent and how intense the rain is when it does fall, in addition to the total amounts.² Steady moderate rains soak into the soil and benefit plants, while the same rainfall amounts in a short period of time may cause local flooding and runoff, leaving soils much drier at the end of the day. This example highlights the fact that the characteristics of precipitation are just as vital as the amount. In models it may be possible to “tune” parameters to improve amounts, but unless the amounts are right for the right reasons—and these

include the correct combination of frequency and intensity of precipitation—it is unlikely that useful forecasts or simulations will result.

Moreover, we argue later that it is the characteristics of rain that are more apt to change as climate changes. This means that prospects are greater for changes in the extremes of floods and droughts than in total precipitation amount. These aspects are also very important for agriculture, hydrology, and water resources, yet have not been adequately appreciated or addressed in studies of impacts of climate change. Hence, a central purpose of this article is to highlight the need for more attention to this topic.

In this paper, we discuss issues with the changes to be expected in precipitation, problems in modeling it, and the need to look at the problems in new ways; ways that advance understanding and improve models. We focus on conceptual aspects to illustrate the main points, as definitive data often do not exist. These aspects are some of the drivers behind a new initiative at the National Center for Atmospheric Research (NCAR) on the water cycle, which will be briefly introduced later.

FACTORS INVOLVED IN THE CHARACTERISTICS OF PRECIPITATION.

Moisture sources. So where does rain come from? The precipitable water (column-integrated water vapor amount) in midlatitudes is typically 25 mm (an inch or so; e.g., Trenberth and Guillemot 1994, 1998) and this is also close to the global mean value. So how can we possibly get more than an inch of rainfall? The efficiency of rainfall mechanisms is not that great, perhaps 30% (Fankhauser 1988; Ferrier et al. 1996), as not all storm-ingested water vapor is converted to precipitation and it is not possible to dry out the air completely. Instead, the relative humidity of the air left behind is typically about 70% overall as there are dry downdrafts but also moist cloud debris that remain. So perhaps only about 7.5 mm of the precipitable water is really available for precipitation. However, it can and often does rain this amount in an hour and, as we argue below, the average rain rate globally is probably about 45 mm day⁻¹ when it is raining, and so about 6 times the locally available moisture can fall in 1 day.

The global average precipitation rate from global precipitation estimates (Huffman et al. 1997; Xie and Arkin 1997) is about 2.8 mm day⁻¹. Hence, this is also the global evaporation rate, as the imbalance is tiny. Moreover, evaporation is continuous, subject to availability of moisture from the surface (which is not a limitation over the oceans), and increases to

¹ Denver Water along with the Upper Arkansas Water Conservancy District and the Southeastern Colorado Water Conservancy District signed a \$700,000 contract for cloud seeding during the 2002/03 winter and spring snow season with a goal of enhancing precipitation. The method uses ground-based silver iodide generators when the time is judged right for seeding.

² Rain rate refers to the average amount of rain per unit time, regardless of whether or not it rains only part of the time. We use “intensity” to refer to the rain rate conditional on rain actually falling.

about 5 mm day^{-1} in summer (Trenberth and Guillemot 1998). So the moisture supply for moderate or heavy precipitation locally does not come directly from evaporation. Instead it has to come from transport, and thus from convergence of low-level moisture elsewhere in the atmosphere. These facts are reconciled when we recognize that it only rains about 5%–10% of the time on average. The frequency of rainfall locally varies wildly from 0% to over 50% (e.g., Trenberth 1998; Dai 2001a) but depends on the area and threshold used to detect precipitation; values in Trenberth (1998) are for 2° latitude by 2.5° longitude grid squares, not point measurements. Dai (2001a) used synoptic data of “present weather” to determine the frequency of different kinds of precipitation; values for nondrizzle precipitation for December–January–February (DJF) and June–July–August (JJA) are given in Fig. 1. This estimate combined categories of precipitation at the time of observation with those in the past hour, thereby perhaps somewhat overestimating the frequency. Zonal means range from about 30% poleward of 60° latitude to 5%–10% in the Tropics. However, these statistics are not able to account for a measurable threshold, and hence the global average frequency of occurrence is not well known. Somewhat equivalent is the areal extent of precipitation, which Burlutskiy (2000) cites as 5% from his data. Again, this depends on threshold and is too low compared with Dai (2001a). A reasonable working value is perhaps $\sim 7\%$ or $1/16$ of the globe (which is an average value from about 40°S to 40°N in Fig. 1 and discounts light snow at high latitudes). It means that there is a discrepancy of a factor of about 16 between the time-averaged rain rate and the actual rate conditional on when it is rain-

ing (and thus the 2.8 versus 45 mm day^{-1} for the global mean). This fact alone highlights the importance of not only how much moisture there is in the atmosphere but also its location. The former is tied to temperature, which determines the moisture-holding capacity of the atmosphere, along with the relative humidity.

Given this factor of 16 or so, we can take the square root to convert it from an areal measure to a linear measure of scales of systems. What this means is that on average, rainfall-producing weather systems reach out to distances about 3–5 times the radius of the precipitating region and gather in the moisture over that area. This is an interesting number and a question is the extent to which this does, in fact, vary from small-scale systems to large-scale systems *on average*; clearly it does vary widely for individual systems and different synoptic environments. However, what it implies for a small thunderstorm 4 km across (2-km radius) is that the moisture comes from a region extending about 8 km away and is drawn into the storm by the thunderstorm-scale circulation and low-level convergence. Of course because of prevailing winds and shear, the region may be irregular in shape. For an extratropical cyclone with rainfall over about a radius of 800 km, the moisture comes from up to about 3200 km away—or about 30° latitude—and so storms over the northern plains of the United States reach out and tap moisture from the Gulf of Mexico as part of the storm-scale circulation. It takes 1–2 days for that moisture to travel these distances, but that is compatible with the lifetime of the storms. An exception to this rule of thumb may well be hurricanes, which depend on warm waters to supply moisture for the storm. Hurricanes and some rapidly deepening oce-

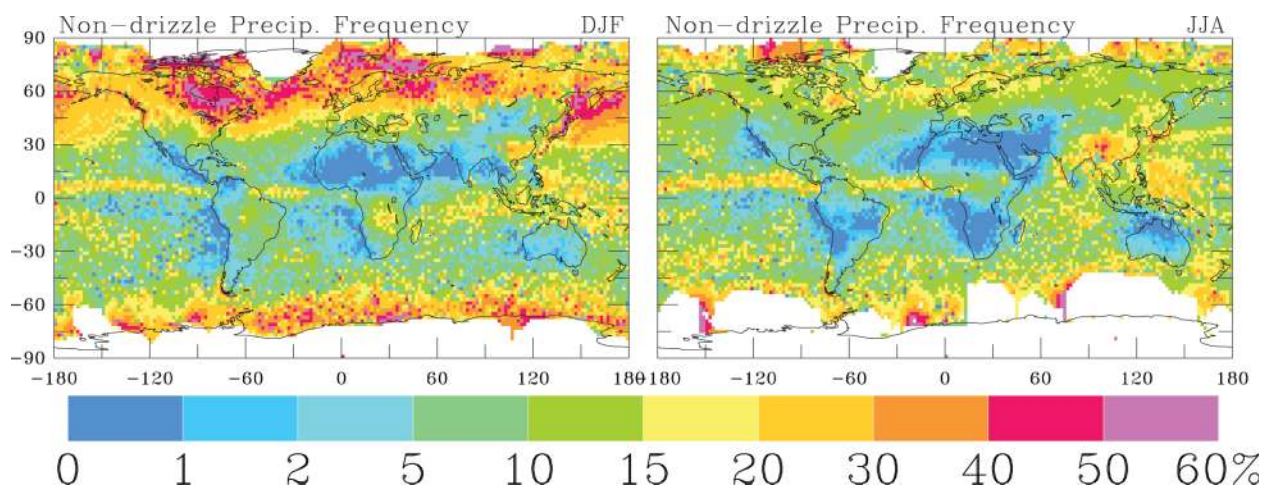


FIG. 1. Estimated frequency of occurrence (%) of nondrizzle precipitation either at time of observation or in the past hour from synoptic observations for (left) DJF and (right) JJA. From Dai (2001a).

anic cyclones can significantly increase the surface flux of moisture flowing into the storm, yet even in these cases, air spirals in from large distances and moisture is transported over scales much larger than the areas of heavy rain. In general, we have estimated that about 70% of the moisture in an extratropical cyclone comes from moisture already in the atmosphere at the start of the storm, while the rest comes from surface evaporation (Trenberth 1998). For a thunderstorm cell, the short lifetime mandates that nearly all of the moisture resides in the atmosphere at the start of the storm.

The ratio of how much precipitation comes from a local region through evaporation versus how much comes from advection into the region is known as the “recycling” ratio. It varies substantially from lower values in winter to higher values in summer, when the large-scale transports diminish in importance (Trenberth 1999b). Several attempts have been made to estimate recycling using observational data (e.g., Brubaker et al. 1993; Elathir and Bras 1996; Trenberth 1999b), as well as from models (e.g., Dirmeyer and Brubaker 1999; Numaguti 1999; Bosolovich and Schubert 2002) and isotopic measurements in precipitation and simulated in models based upon fractionation in rainfall and evaporation (e.g., Wright et al. 2001; Vuille et al. 2003). All methods have advantages and disadvantages related to assumptions, dependence on modeling parameterizations, and ad-

equacy of observations of isotopic ratios in precipitation. From Trenberth (1999b), for 500-km scales the global recycling averages about 10%, and a map of the estimated values for 1000-km scales is given in Fig. 2. Over the Mississippi basin on 500-km scales the annual mean of 6.6% ranges from 3.1% in DJF to 9.3% in JJA as the potential evapotranspiration peaks in summer while advection and atmospheric dynamics are more prominent in winter. Trenberth (1999b) estimated annual recycling for the basin as a whole at 21%. Although values differ using alternative methods, it is nonetheless clear that dry conditions in late spring are favorable for drought to develop or persist and become perpetuated throughout the summer because of the dependence on moisture from local evaporation. An example is the major drought throughout the intermountain region of the United States in the summer of 2002.

This discussion demonstrates the need to accurately measure and track moisture availability in the atmosphere. For the United States the source regions are the subtropical North Pacific, the Gulf of Mexico, and the tropical and subtropical Atlantic (Trenberth 1998). Tracking movement of moisture also serves to reveal the large-scale processes at work as the storm-scale circulation gathers up the moisture. Thus, it is possible to follow the large-scale low-level convergence and divergence patterns in the atmosphere (Dai et al. 1999, 2002; Dai and Deser 1999).

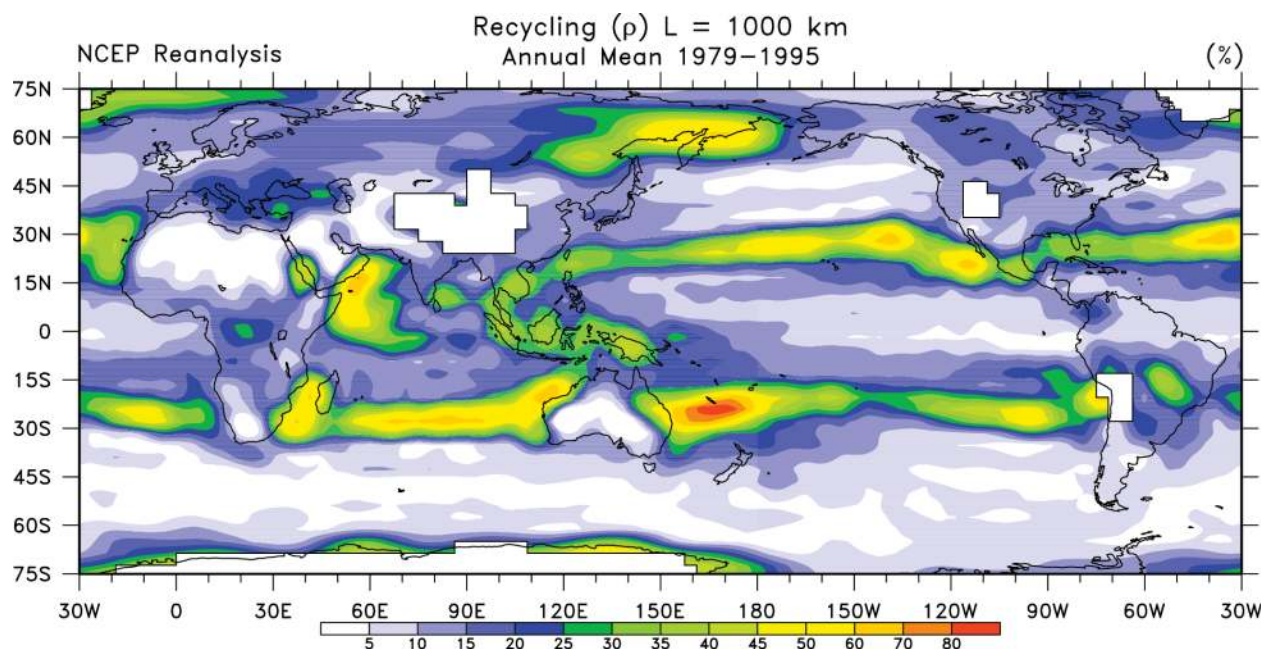


FIG. 2. Estimate of the annual mean recycling ratio of the percentage precipitation coming from evaporation within a length scale of 1000 km (adapted from Trenberth 1999b).

The diurnal cycle. A way to address the issues concerning frequency and intensity of precipitation is to systematically examine the timing and duration of precipitation events as a function of time of day. This allows the systematic errors in predicting onset time and duration of precipitation in models to be exposed. Hence, the diurnal cycle allows us to begin to come to grips with the characteristics of precipitation and how well they are modeled.

The diurnal cycle in precipitation is particularly pronounced over the United States in summer (Fig. 3) and is poorly simulated in most numerical models. The mean pattern of the diurnal cycle of summer U.S. precipitation is characterized by late afternoon maxima over the Southeast and the Rocky Mountains, and midnight maxima over the region east of the Rockies and the adjacent plains. Diurnal variations of precipitation are weaker in other seasons, with early to late morning maxima over most of the United States in winter. The diurnal cycle in precipitation frequency accounts for most of the diurnal variations, while the diurnal variations in precipitation intensity are small (see Dai et al. 1999). The solar-driven diurnal and semidiurnal cycles of surface pressure are associated with significant large-scale convergence over most of the western and eastern United States during the afternoon and evening, and over the region east of the Rockies at night (see Fig. 11 in Dai and Deser 1999).

As shown by Dai et al. (1999), the diurnal cycle of low-level large-scale convergence is consistent with suppression of daytime convection and favoring of nighttime moist convection over the region east of the Rockies and the adjacent plains. Over the central plains, diurnal variations in climatologically significant circulations, such as the low-level jet and north-south baroclinic gradients, interact to produce a nocturnal environment with little inhibition to convective onset, while maintaining high values of convective instability (Trier and Parsons 1993). The nocturnal maximum in the region east of the Rockies is also

enhanced by the eastward propagation of late afternoon thunderstorms generated over the Rockies and the development of the low-level jet out of the Gulf of Mexico (Higgins et al. 1997). Over the southeast

and the Rockies, both the static instability and surface convergence favor afternoon moist convection in summer, resulting in very strong late afternoon maxima of precipitation over these regions. The distinctive but complex diurnal cycle in atmospheric moisture over North America has been documented by Dai et al. (2002) using high-temporal-resolution Global Positioning System data, and a recent documentation of the progression of the diurnal precipitation cycle over the United States from a synoptic viewpoint is given by Carbone et al. (2002).

Models can typically simulate some but not all of the diurnal cycle pattern, but some models are wrong everywhere. For instance, the European Centre for Medium-Range Weather Forecasts (ECMWF) operational model tends to produce maximum precipitation at about local noon, corresponding to the time of maximum heating (P. Kållberg 2001, personal communication), and this is also true in some other models. This timing is about 3–4 h before that in nature. In the NCAR Community Climate System Model (CCSM) and the corresponding atmospheric module, the diurnal precipitation occurs about 2 h before it does in nature and the complex structure of nocturnal maxima in the U.S. Great Plains is absent (see Fig. 4). Figure 4 also illustrates the distinctive nature of the diurnal cycle in many other parts of the globe. Over many parts of the oceans, there is often a minimum in precipitation from late afternoon to about midnight, which is out of phase with most continental regions (e.g., Mohr and Zipser 1996; Dai 2001b; Sorooshian et al. 2002).

Model convection schemes explored by Dai et al. (1999) produced too much cloudiness over the Southeast, which reduced surface solar radiation and thus altered the daytime peak warming at the surface. Model criteria for the onset of moist convection are

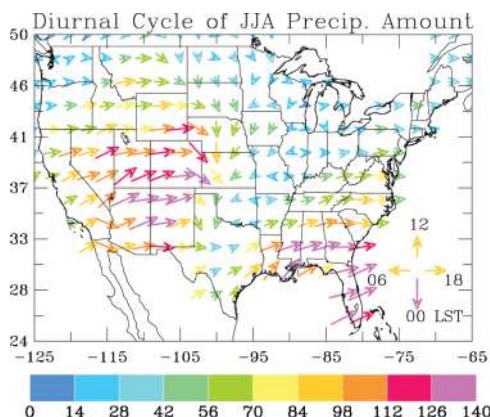


FIG. 3. Diurnal cycle of total precipitation amount from hourly data for JJA for the United States. Vector length and color indicates the amplitude as a percent of the diurnal mean, and the direction indicates the timing of maximum in local standard time, as given by the key at lower right. The diurnal cycle in amount comes almost entirely from changes in frequency (timing) rather than changes in intensity. From Dai et al. (1999).

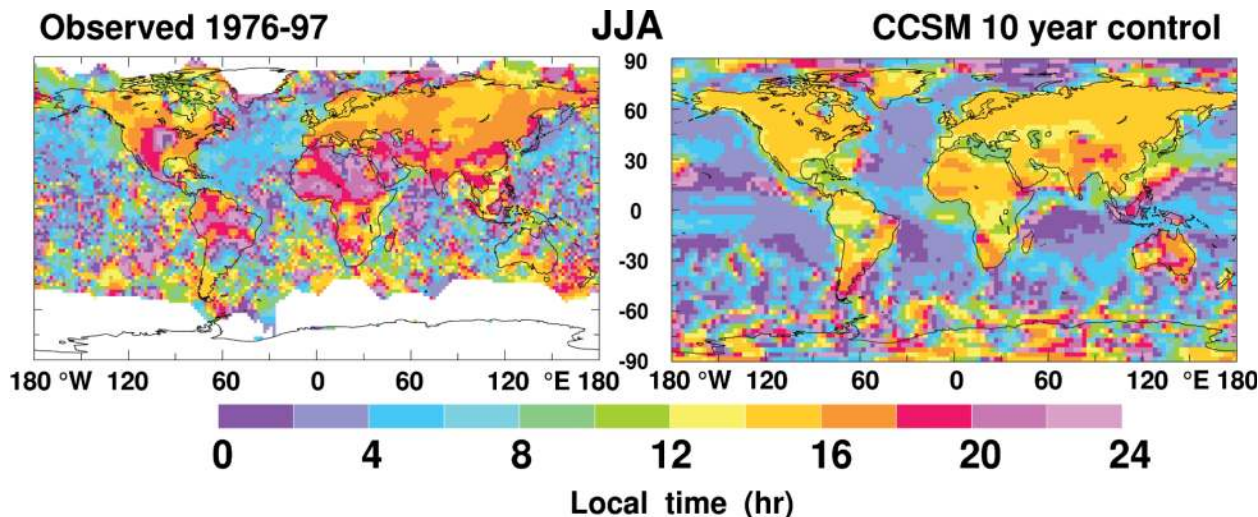


FIG. 4. The local solar timing (h) of the maximum of the diurnal cycle of precipitation for JJA is given for convective precipitation from (left) observations for 1976–97 (Dai 2001b) vs (right) a control run (10-yr avg) of the CCSM.

too weak, and so moist convection in the model starts too early and occurs too often. In the real world, premature triggering leads to weaker convection and precipitation, and weaker downdrafts and gust fronts. Subsequent convection is also expected to be weaker due to the prominent role gust fronts play in initiating convection (Wilson and Schreiber 1986). Premature triggering of convection and thus cloudiness disrupts the proper heating at the surface of the continent and thus prevents the continental-scale “sea breeze” and its associated convergence and divergence patterns from developing properly. Thus, the transport of moisture and its role in setting up convective instabilities is also disrupted. Figure 5 presents the typical processes, the associated errors in models, and their feedbacks. It is these kinds of interactions and processes that must be better simulated. Improvements are under way through improved model physics and dynamics (e.g., Liang et al. 2001; Liu et al. 2001) and implementation of “triggers” in parameterizing convection in models, but further progress is desirable.

Atmospheric circulation changes. For interannual and decadal variability of precipitation, another important aspect (briefly discussed for completeness) is the role of atmospheric circulation changes. Changes in natural modes of the atmospheric circulation have been documented and may be linked to anthropogenic climate change. In particular, the North Atlantic Oscillation (NAO), the Pacific–North American (PNA) teleconnection pattern, and El Niño–Southern Oscillation (ENSO) combine to influence the planetary

wave structure over the Northern Hemisphere such that most wintertime temperatures in recent years have been warming over North America and Eurasia, but cooling over the northern oceans (Wallace et al. 1996; Hurrell 1996).

The NAO index has been at exceptionally high levels for most of the 1980s and 1990s (Hurrell 1995), and such trends appear to be linked to warming of the tropical Pacific and Indian Oceans (Hoerling et al. 2001). Meanwhile ENSO has shown a statistically significant preference for the El Niño phase in the same period (Trenberth and Hoar 1996). One way in which rainfall patterns can change in midlatitudes is through

Key feedback mechanisms in diurnal cycle with typical model biases in red

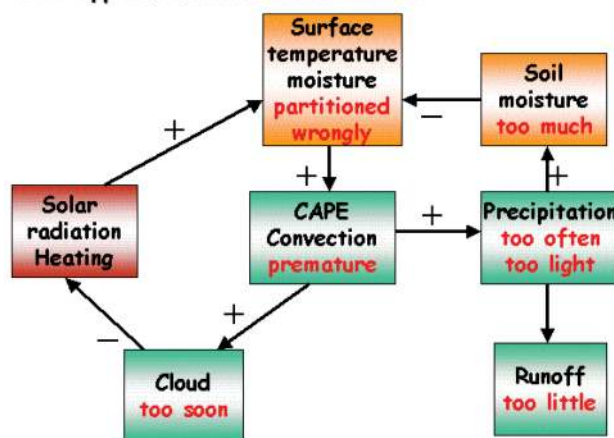


FIG. 5. Key feedback mechanisms involved in the diurnal cycle are given along with the model biases (in red).

a shift in storm tracks associated with teleconnections. A dipole pattern of change is found over Europe, with lower rainfalls over southern Europe and wetter conditions in Scandinavia as the NAO has been in a more positive phase (Hurrell 1995). In the Pacific, pronounced changes occur in storm tracks over the North Pacific in association with ENSO and the PNA (Trenberth and Hurrell 1994) leading to a dipole pattern of precipitation anomalies that extends to California at times and that has a component over the southeastern United States. Hence, there is enhanced storm track activity and rainfalls to the south and diminished rainfalls to the north. Moreover, floods and droughts in different locations around the globe are associated with ENSO through teleconnections (Dai et al. 1998). Trenberth and Guillemot (1996) show how storm tracks changed across North America to help bring about the spring–summer 1988 drought and 1993 floods. In the tropical Pacific, movement of the Inter-Tropical Convergence Zone and South Pacific Convergence Zone with ENSO creates dipole “boomerang” shaped structures (e.g., Trenberth and Caron 2000).

The prospects for changes in atmospheric circulation, whether linked to changes in sea surface temperatures or not, are real and obviously add considerable complexity to likely changes in precipitation amount locally. Nevertheless, changes in characteristics of precipitation may be more robust, as discussed below.

Trends in moisture and extreme precipitation events. Atmospheric moisture amounts are generally observed to be increasing in the atmosphere after about 1973 (prior to which reliable moisture soundings are mostly not available; Ross and Elliott 2001). In the Western Hemisphere north of the equator, annual mean precipitable water amounts below 500 mb increased over the United States, Caribbean, and Hawaii by about 5% decade⁻¹ as a statistically significant trend from 1973 to 1995 (Ross and Elliott 1996), and these correspond to significant increases of 2%–3% decade⁻¹ in relative humidities over the Southeast, Caribbean, and subtropical Pacific. Most of the increase is related to temperature and hence in atmospheric water-holding capacity. In China, analysis by Zhai and Eskridge (1997) also reveals upward trends in precipitable water in all seasons and for the annual mean from 1970 to 1990. Earlier, Hense et al. (1988) revealed increases in moisture over the western Pacific. Precipitable water and relative humidities have not increased over much of Canada, and decreases are evident where temperatures declined in northeast

Canada (Ross and Elliott 1996). In summary, while uncertainties exist due to errors in humidity measurements (e.g., Guichard et al. 2000; Wang et al. 2002), most studies indicate that water vapor increases are present in many regions.

Previously, we highlighted the importance of atmospheric moisture amounts over the adjacent oceans around North America for precipitation in the United States and there have been upward trends in precipitable water in all these regions since 1973 by over 10% (e.g., Ross and Elliott 1996). All things being equal, that should lead to 10% stronger rainfall rates when it rains, because low-level moisture convergence will be enhanced by that amount. It has been argued that increased moisture content of the atmosphere favors stronger rainfall and snowfall events, thus increasing the risk of flooding. There is clear evidence that rainfall rates have changed in the United States, for instance, in the area with total annual precipitation from 1-day extremes of more than 2-in. (50.8 mm) amounts after 1910 (Karl et al. 1996). The “much above normal” area, defined as the upper 10% overall, increased steadily throughout the twentieth century from less than 9% to over 11%, a 20% relative change in total. Karl and Knight (1998), in further analysis of U.S. precipitation increases, showed how it occurs mostly in the upper tenth percentile of the distribution and that the portion of total precipitation derived from extreme and heavy events increased at the expense of more moderate events. Kunkel et al. (1999) show that extreme precipitation events of 1–7-day duration in the United States increased at a rate of about 3% decade⁻¹ from 1931 to 1996. Trenberth (1998) and Dai (1999) presented patterns of changes in frequency of hourly precipitation across the United States and showed relationships with El Niño. Other evidence for increasing precipitation rates occurs in Japan (Iwashima and Yamamoto 1993) and Australia (Suppiah and Hennessy 1996).

While enhanced rainfall rates increase the risk of flooding, mitigation of flooding by local councils, the Corps of Engineers, and the Bureau of Reclamation in the United States is continually occurring, and flooding records are often confounded by changes in land use and increasing human settlement in flood plains. Nevertheless, great floods have been found to be increasing in the twentieth century (Milly et al. 2002). However, the main way to test these ideas would be to track the hourly precipitation data.

HOW SHOULD PRECIPITATION CHANGE AS THE CLIMATE CHANGES? Changes in radiative forcing associated with increasing greenhouse

gases in the atmosphere produce increased heating at the surface. We assume climate changes associated with aerosols are dealt with elsewhere. The actual amount of heating depends critically on all sorts of feedbacks, including water vapor feedback, ice–albedo feedback, and effects of changes in clouds. Uncertainties result in sensitivity of climate models to doubling of carbon dioxide in global mean surface temperature of 1.5° to 4.5°C (IPCC 2001). However, the Intergovernmental Panel on Climate Change (IPCC) models predict that the change in the hydrological cycle (e.g., in total precipitation) overall is about 1%–2% K^{−1}. It is not known how good this range is and, given concerns over how well models simulate the diurnal cycle, it may be quite uncertain (see also Allen and Ingram 2002).

Generally, evaporation at the surface cools and hence acts to “air condition” the planet, and therefore increased surface evaporation would be expected to moderate temperature increases. In fact a very robust finding in all climate models (IPCC 2001) with global warming is for an increase in potential evapotranspiration. In the absence of precipitation, this leads to increased risk of drought, as surface drying is enhanced. It also leads to increased risk of heat waves and wildfires in association with such droughts; because once the soil moisture is depleted then all the heating goes into raising temperatures and wilting plants.

Nevertheless, a very well determined value is the change in water-holding capacity of the atmosphere, governed by the Clausius–Clapeyron equation,³ of about 7% K^{−1}. Moreover, models suggest that changes in relative humidity are small, presumably because of precipitation physics, and this is borne out by limited observations (e.g., Soden et al. 2002). Hence, the actual moisture content of the atmosphere should also increase at something like this rate, which is again consistent with observations in areas of the world not dominated by major pollution clouds. However, it is unlikely that the moisture changes will be uniform even though models predict increases in surface tem-

peratures almost everywhere after a few decades with increases in greenhouse gases. Atmospheric dynamics play a role through favored regions of convergence and subsidence. In spite of larger increases in surface temperatures projected at high latitudes, the nonlinear dependence with temperature encapsulated by Clausius–Clapeyron means that there is a bigger absolute increase in moisture amount in lower latitudes. Hence, much of the moisture may not be within reach of extratropical storms. So it is a research question to examine the universality of this heuristic argument. Nevertheless, it is worthwhile pursuing the implications to provide a conceptual basis for interpreting observations and models.

We have argued that because heavy rainfall rates greatly exceed evaporation rates and thus depend on low-level moisture convergence, then the rainfall intensity should also increase at about the same rate as the moisture increase, namely 7% K^{−1} with warming. In fact the rate of increase can even exceed this because the additional latent heat released feeds back and invigorates the storm that causes the rain in the first place, further enhancing convergence of moisture. This means that the changes in rain rates, when it rains, are at odds with the 1%–2% K^{−1} for total rainfall amounts. The implication is that there must be a decrease in light and moderate rains, and/or a decrease in the frequency of rain events, as found by Hennessey et al (1997). Thus, the prospect may be for fewer but more intense rainfall—or snowfall—events. Of course these general arguments must be tempered by regional effects and changes in teleconnections, such as those discussed in section 2c (see also Trenberth 1998).

Typically neither observational nor model data have been analyzed in ways that can check on these concepts, although some recent model analyses are moving in this direction. Often daily mean amounts are used and may be analyzed in terms of the “shape” and “scale” parameters of a gamma distribution fit to the data. Wilby and Wigley (2002) use this approach to demonstrate increases in extremes of precipitation with anthropogenic forcing in the NCAR Climate System Model and the Hadley Centre Coupled Model (HadCM2) in spite of quite different spatial patterns of precipitation change. Expectations outlined here are realized in the ECHAM4/OPYC3 model (Semenov and Bengtsson 2002). Another recent check of this was performed in the Hadley Centre model (Allen and Ingram 2002) and it indeed shows at the time of doubling of carbon dioxide in the model simulations that rainfall intensities less than about the 85th percentile decrease

³ The Clausius–Clapeyron equation can be written as $de_s/de_s = LdT/RT^2$, where e_s is the saturation vapor pressure at temperature T , L is the latent heat of vaporization, and R is the gas constant. Hence, it is natural to express changes in moisture as a percentage of the current value. Changes in saturation-specific humidity also involve the ratio of the gas constant of dry air to that of water vapor (0.622) and range from 6.0% K^{−1} at 300 K to 7.4% K^{−1} at 270 K. Global mean temperatures at 850 and 700 mb are about 7.5° and 0°C, so that 7% K^{−1} is a reasonable approximation overall.

in frequency, while heavy events increase at close to the Clausius–Clapeyron rate.

In extratropical mountain areas, the winter snowpack forms a vital resource, not only for skiers but also as a freshwater resource in the spring and summer as the snow melts. Yet warming makes for a shorter snow season with more precipitation falling as rain rather than snow, earlier snowmelt of the snow that does exist, and greater evaporation and ablation. These factors all contribute to diminished snowpack. In the summer of 2002 in the western parts of the United States, exceptionally low snowpack and subsequent low soil moisture likely contributed substantially to the widespread intense drought because of the importance of recycling. Could this be a sign of the future?

QUESTIONS AND ISSUES. Climate change is certainly very likely to locally change the intensity, frequency, duration, and amounts of precipitation. Testing of how well climate models deal with these characteristics of precipitation is an issue of significant societal importance. The foremost need is better documentation and processing of all aspects of precipitation. Trenberth (1998) has argued for the creation of a database of frequency and intensity using hourly precipitation amounts. It is compatible with the time steps in global models, which are typically two or three steps per hour. Ricciardulli and Sardeshmukh (2002) estimate the mean duration of convective events in the Tropics to be 5.5 h. Hence, this time interval averages over individual cells within a storm but typically allows the evolution of a storm to be grossly captured. It is viable from a data management standpoint. It is also viable from many observations, from recording rain gauges and from radar [e.g., Next Generation Weather Radar (NEXRAD), see Carbone et al. 2002] and satellite estimates. Mohr and Zipser (1996) and Mohr et al. (1999) exploited Special Sensor Microwave Imager (SSM/I) 85-GHz data to describe size, intensity, and geographic distribution of cloud clusters and mesoscale convective systems and their contributions to rainfall. Nesbitt et al. (2000) utilized different sensors on the Tropical Rainfall Measuring Mission (TRMM) to identify and classify precipitating clouds and to provide insight into intensities of precipitation and lightning. Sorooshian et al. (2002) similarly exploited the Geostationary Operational Environmental Satellite (GOES) measurements combined with TRMM multisensor observations using artificial neural network algorithms to estimate hourly precipitation at 1° resolution. In fact, remote sensing measures the in-

stantaneous rain rate, not cumulated amount over time, and this has generally been converted into a daily amount (e.g., by fitting of lognormal distributions; Short et al. 1993a,b; Shimizu et al. 1993). Instead it would be better if converted into an hourly rate, and histograms of the rate as a function of time would then provide the basic information observation database. Climate model archives seldom include hourly data, but such data are essential for precipitation.

We have argued (Trenberth 1998, 1999a) that increasing the moisture content of the atmosphere should increase the rate of precipitation locally by invigorating the storm through latent heat release and further by supplying more moisture, although what happens to the total amount is less clear, as the duration of a storm may be shortened. Some analyses of model results support this view but most analyses have used daily and not hourly or higher frequency data, so they also highlight the need for more attention to the nature of the analysis of both models and observational datasets. There is also a need for improved analysis of the frequency of precipitation and changes in weather systems, as would be expected from changes in the moisture content of the atmosphere.

Other issues include increased understanding of the efficiency of precipitation and how it changes with environmental conditions. Efficiency certainly depends on instability, water loading, vertical shear, entrainment, and system type, and may well depend on microphysical and aerosol influences on precipitation, discussed in the first section. Such investigations require accurate knowledge of the transport of water vapor in storms. An example of the incredible richness of the variability of water vapor in the atmosphere is given in Fig. 6. There is clearly a need for improved parameterization of convection in large-scale models. Parameterization of convection needs to be improved to appropriately allow convective available potential energy (CAPE) to build up as observed and likely involves both the improvement of “triggers” and the suppression of convection by the presence of convective inhibition (CIN). Parameterizations are a scale interaction problem in part, as the triggers are often subgrid scale (e.g., outflows and other small-scale boundaries, gravity wave motions, and convective rolls, etc.) while larger-scale motions may suppress or enhance the magnitudes of CAPE and CIN. Some processes are difficult to include in global climate models, where convection occurs at grid points in single columns that are not directly related to events at adjacent grid point columns, while in the atmosphere, mesoscale convective systems can be long-lasting and may move from one grid column

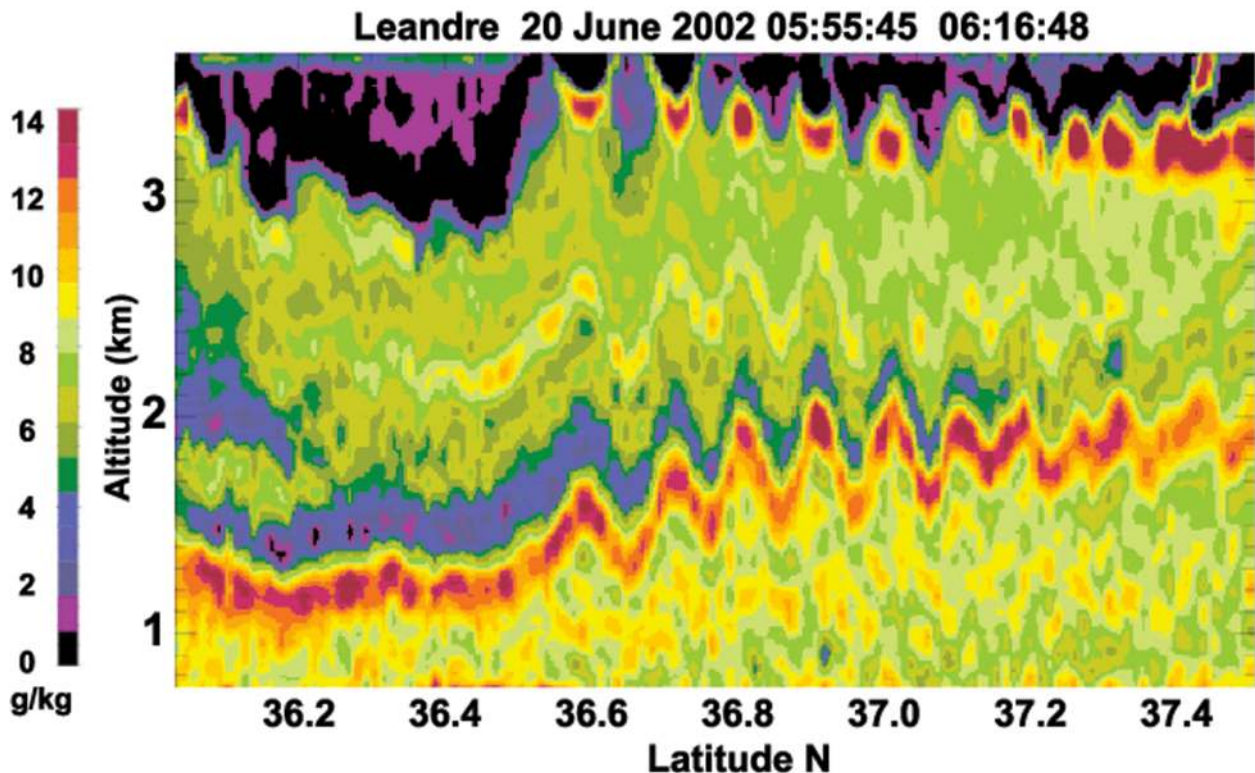


FIG. 6. An example of water vapor variability from the IHOP 2002 project. The figure shows a vertical cross section of water vapor mixing ratio as measured by the French LEANDRE 2 water vapor differential absorption lidar (DIAL) aboard the U.S. Naval Research Laboratory P-3 aircraft. The cross section is oriented N-S as the aircraft flew toward a nocturnal convective system. The moisture deepened with wavelike perturbations in response to circulations produced by the system. (This preliminary image is courtesy of Dr. C. Flamant, University of Paris.)

to another (e.g., Carbone et al. 2002). We also call for improved observations and modeling of sources and sinks of moisture for the atmosphere, especially over land. This relates to recycling and the disposition of moisture at the surface in models, and whether the moisture is or is not available for subsequent evapotranspiration. It relates to improved and validated treatment of runoff, soil infiltration, and surface hydrology in models including vegetation models.

Recognition of the need to better characterize the four-dimensional distribution of water vapor in the lower atmosphere for the purposes of improving understanding and prediction of convection initiation and precipitation amounts is an objective of the International H₂O Project (IHOP 2002) that conducted a major field program in the southern Great Plains of Oklahoma, Kansas, and the Texas Panhandle in the summer of 2002. Unprecedented water vapor datasets were collected in conjunction with kinematic and thermodynamic data, but have yet to be fully analyzed (see, e.g., Fig. 6). The importance of water vapor variations has been argued in several panel reports [e.g., the National Research Council (NRC) 1998] and the

U.S. Weather Research Program Prospectus teams (Emanuel et al. 1995; Dabberdt and Schlatter 1996).

Finally, we believe that improved simulation of the diurnal cycle of precipitation in models is essential. This probably also requires improved simulation of the diurnal cycle of temperature, cloud amount, and atmospheric circulation as well, and especially the build up and release of CAPE. We believe the best approach is a hierarchical one using models ranging from a single-column model, to cloud-resolving models, to mesoscale regional models, to global atmospheric models, and coupled climate models. Land surface processes and atmosphere–ocean–land interactions are clearly important. The replication of the diurnal cycle and the associated precipitation is a key framework for testing these different models.

Accordingly, at NCAR we have established a “Water Cycle Across Scales” initiative to address the issues outlined above, among others. The initiative made modest supplements to the IHOP 2002 experiment to make it more relevant to the “across scales” nature of this effort. However, an initial focus of the initiative is on the warm season diurnal cycle in

North America. Hence, the diurnal cycle is being exploited as a test bed to examine systematic timing and duration of precipitation events and as a vehicle to improve model performance. More information about the water cycle initiative is available online at www.rap.ucar.edu/projects/watercycles/.

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