CONCEPTUAL FRAMEWORK FOR CHANGES OF EXTREMES OF THE HYDROLOGICAL CYCLE WITH CLIMATE CHANGE

KEVIN E. TRENBERTH
National Center for Atmospheric Research[1], *P. O. Box 3000, Boulder, CO 80307, U.S.A.*

Abstract. A physically based conceptual framework is put forward that explains why an increase in heavy precipitation events should be a primary manifestation of the climate change that accompanies increases in greenhouse gases in the atmosphere. Increased concentrations of greenhouse gases in the atmosphere increase downwelling infrared radiation, and this global heating at the surface not only acts to increase temperatures but also increases evaporation which enhances the atmospheric moisture content. Consequently all weather systems, ranging from individual clouds and thunderstorms to extratropical cyclones, which feed on the available moisture through storm-scale moisture convergence, are likely to produce correspondingly enhanced precipitation rates. Increases in heavy rainfall at the expense of more moderate rainfall are the consequence along with increased runoff and risk of flooding. However, because of constraints in the surface energy budget, there are also implications for the frequency and/or efficiency of precipitation. It follows that increased attention should be given to trends in atmospheric moisture content, and datasets on hourly precipitation rates and frequency need to be developed and analyzed as well as total accumulation.

1. Introduction

The character of precipitation, with highly variable rain rates and enormous spatial variability, makes simply determining mean precipitation difficult let alone how it will change as the climate changes. For instance, a detailed examination of spatial structure of daily precipitation amounts by Osborne and Hulme (1997) shows that in Europe the average separation distance between climate stations where the correlation falls to 0.5 is about 150 km in summer and 200 km in winter — the more convective nature of summer precipitation is responsible for the difference. In addition, this complexity also makes it difficult to model precipitation reliably, as many of the processes of importance can not be resolved by the model grid (typically 200 km) and so sub-grid-scale processes have to be parameterized. Yet there are some overall aspects of precipitation related to the hydrological

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cycle that can be clarified and for which expectations as to how they will change are physically based. Here the processes involved that influence precipitation and link it to evaporation and heating are outlined along with the importance of dealing not just with accumulated amounts, but also precipitation rates (or intensity) and precipitation frequency. The relative roles of moisture stored in the atmosphere, its advection, and resupply have been examined in detail in Trenberth (1998), and only a brief summary of those aspects are included here.

The term "global warming" is often taken to refer to global increases in temperature accompanying the increases in greenhouse gases in the atmosphere. In fact it should refer to the additional global heating (sometimes referred to as radiative forcing, e.g., by the IPCC (1996)) arising from the increased concentrations of greenhouse gases, such as carbon dioxide, in the atmosphere. Increases in greenhouse gases in the atmosphere produce global warming through an increase in downwelling infrared radiation, and thus not only increase surface temperatures but also enhance the hydrological cycle, as much of the heating at the surface goes into evaporating surface moisture. This occurs in all climate models regardless of feedbacks, although the magnitude varies substantially (see section 3).

Temperature increases signify that the water-holding capacity of the atmosphere increases and, together with enhanced evaporation, the actual atmospheric moisture should increase, as is observed to be happening in many places (Hense et al., 1988; Gaffen et al., 1991; Ross and Elliott, 1996; Zhai and Eskridge, 1997). Of course, enhanced evaporation depends upon the availability of sufficient surface moisture and over land, this depends on the existing climate. However, it follows that naturally-occurring droughts are likely to be exacerbated by enhanced potential evapotranspiration. Further, globally there must be an increase in precipitation to balance the enhanced evaporation but the processes by which precipitation is altered locally are not well understood.

It is shown that precipitating systems of all kinds feed mostly on the moisture already in the atmosphere at the time the system develops, and precipitation occurs through convergence of available moisture on the scale of the system. Hence, the atmospheric moisture content directly affects rainfall and snowfall rates, but not so clearly the precipitation frequency and thus total precipitation, at least locally. Thus, it is argued that global warming leads to increased moisture content of the atmosphere which in turn favors stronger rainfall events, as is observed to be happening in many parts of the world (Karl et al., 1995), thus increasing risk of flooding. It is further argued that one reason why increases in rainfall should be spotty is because of mismatches in the rates of rainfall versus evaporation. The arguments assembled here imply the need for new observations, datasets, and ways of analyzing both model and observed data. Trenberth (1998) discusses these aspects more fully.

2. Atmospheric Moisture Cycling

New estimates of the moistening of the atmosphere through evaporation at the surface and of the drying of the atmosphere through precipitation are given in Trenberth (1998). These are simple estimates based on the precipitable water and average local evaporation and precipitation rates, which ignore transport. Overall for the global annual mean, the e-folding residence time (the time for amounts to fall by a factor $e = 2.718$) for atmospheric moisture is just over 8 days. For precipitation, local values of e-folding residence time of the atmospheric depletion rate of moisture are less than a week in the tropical convergence zones but they exceed a month in the dry zones in the subtropics and desert areas. Time constants for depletion and restoration rates of atmospheric moisture are fairly similar overall, but this conclusion does not take account of the fact that rain falls only a small fraction of the time. In midlatitudes precipitation typically falls from zero to 30% of the time, and so rainfall rates, conditional on when rain is falling, are much larger than evaporation rates. The depletion rate time scale is about 4 hours in the tropics when rain is falling. In middle latitudes, typical unconditional rainfall rates are 3 mm/day, but with rain falling about 10% of the time and precipitable water amounts of 15 mm, the depletion rate time scale of 5 days drops conditionally on rain falling to about 12 hours (Trenberth, 1998). This inferred imbalance in the drying versus moistening of the atmosphere implies that most of the moderate and heavy rain that falls comes directly from the precipitable water already in the atmosphere at the time the storm responsible for the precipitation developed, not directly from evaporation, and so the lifetime of moisture in the atmosphere and its availability to rain systems is a limiting factor. However, atmospheric depletion of moisture by light rain could easily be restored by evaporation.

These above aspects do not take moisture transport into account. Therefore new estimates have also been made of how much precipitated moisture comes from evaporation from within versus transport from outside a domain, called recycling. Approximate values of recycling are computed following the approach of Brubaker et al. (1993), as detailed in Trenberth (1998). Equilibrium conditions are assumed, so that there are no changes in atmospheric moisture content but changes in moisture storage in the atmosphere do not impact the results for seasonal or longer averages. A domain of length L aligned along the trajectory of the air is considered. An important assumption is that the atmosphere is well mixed so that the ratio of precipitation that falls arising from advection versus local evaporation

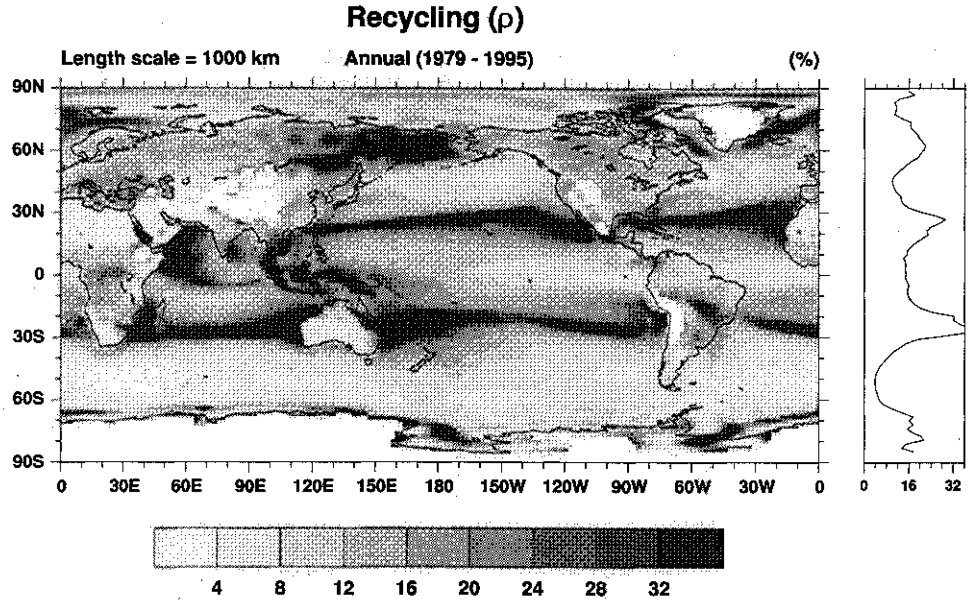

Figure 1. The recycling, for annual mean conditions, for length scales of 1,000 km, and using E and moisture flux from the NCEP reanalyses (Kalnay et al., 1996) and P from CMAP (Xie and Arkin, 1997). Values are set to missing (white) where the surface pressure is less than 800 mb.

is equal to the ratio of average advected to evaporated moisture in the air. While interest has often been on recycling estimates for large drainage basins, the heterogeneity of the land surface is such that the recycling clearly varies substantially over the basins. The regions of mountains (where surface pressures are less than 800 mb) are screened out from the calculation, as those are regions where the moisture flux is small and there are huge variations over short distances owing to orographic effects on rainfall.

In Trenberth (1998) recycling results for annual means are presented for $L = 500$ km. Here results presented for $L = 1000$ km (Fig. 1) reveal recycling percentages of about 8 to 20% over land typically. For 500 km scales the global mean is 9.6%, consisting of 8.9% over land and 9.9% over the oceans and for 1000 km scales the mean recycling is 16.8% globally, 15.4% over land and 17.3% over the oceans. Over the Amazon, the average is about 10% and over the Mississippi basin about 12%. These values prove to be compatible with most previous extimates (e.g., Brubaker et al., 1993) once the different scales of the basins are taken into account. It is worth pointing out that the larger values previously obtained for the Amazon versus the Mississippi are mostly a result of the scale of the domain.

The recycling fraction depends greatly on the magnitude of the total moisture flux. In the computations, this includes advection by the mean flow as well as the transient eddies. Relatively high values (>30%) of recycling occur either in the subtropical highs, where evaporation E is high and the advective moisture flux is small, or in convergence zones where, again, the advective moisture flux is small. Low values occur over the southern oceans, the North Pacific, and the eastern equatorial Pacific, where the moisture flux is at a maximum. All of these recycling values show that on average less than 20% of the precipitation that falls comes from evaporation within a distance of about 1000 km. Therefore the results reinforce the arguments given above concerning the importance of transport of moisture and local storage in feeding precipitating systems.

The dominant storm-scale process in both thunderstorms and extratropical storms is the convergence of moisture by the storm-scale circulation. The latter determines how much moisture is available to the system and can vary in size from a few tens of kilometers to over 2000 km spatial scales. The advected moisture may combine with the in situ moisture to feed the storm but it is not all available as the relative humidity can not be reduced to zero, except perhaps approximately in strong down drafts very locally. The efficiency of thunderstorms is observed to vary from about 20% to 50%. "Precipitation efficiency" is defined as the ratio of the water mass precipitated to the mass of water vapor entering the storm through its base (e.g., Fankhauser, 1988) or the ratio of total rainfall to total condensation in modeling studies (e.g., Ferrier et al., 1996).

In the United States, much of the moisture for precipitation, especially in the winter half year, comes from moisture transported out of the subtropics often in a southwesterly flow ahead of cold fronts. For storms east of the Rockies, moisture flows northwards from the Gulf of Mexico or subtropical Atlantic. At advection rates of 12 m s^{-1} (which is the standard deviation of the northward velocity component at 850 mb just north of the Gulf of Mexico in January), the moisture travels over 1,000 km in a day, so that moisture from the Gulf can be readily precipitated out over the Great Plains or Ohio Valley just a day or so later. In major storms, transient northward advection rates often exceed 20 m s^{-1} at 850 mb. In the western United States, the moisture comes from the subtropical Pacific. Therefore much of the extratropical precipitation originates from moisture advected from the Gulf of Mexico and subtropical Atlantic or Pacific a day or so earlier and it is estimated that about 70% to 75% of the moisture in an extratropical storm comes from moisture that was stored in the atmosphere at the beginning of the storm and brought into the region by the storm-scale circulation. For thunderstorms, whose life is a few hours, nearly all of the precipitated moisture comes from moisture that was already in the atmosphere at the time the storm began.

3. Relevance to Climate Change

The above discussion reveals the mismatch between precipitation rates and evaporation, so that moderate and heavy precipitation, which contributes most to the total accumulation, depends upon the moisture already in the atmosphere and the advection and resupply of moisture by the storm circulation. These points are pertinent to climate change experiments with global climate models. However, most climate model studies have not analyzed the results in a way that throws light on these aspects. The surface heat budget is especially relevant.

There are many feedback processes in nature that can either amplify or diminish the climate response to increases in greenhouse gases. The net radiative forcing or "warming" at the surface depends critically on these and the surface heat budget. In every case it seems that at the surface there is an increase in downwelling infrared radiation associated with both the greenhouse effect from carbon dioxide and other greenhouse gases, as well as changes in water vapor and clouds. In some models, changes in clouds produce an offset by reducing shortwave radiation, but the net energy available from radiation at the surface is increased in spite of the greater surface emissions associated with the higher temperatures. Moreover, changes in the sensible heat flux also act to warm the surface because of stabilization of the lower atmosphere (Boer, 1993; Roads et al., 1996).

This leaves only the latent heat flux through increased evaporation to compensate and balance the surface heat budget. The latent heat flux, which ranges from 3 to 10 W m^{-2} for CO_2 doubling for the four models considered by Boer (1993), determines the global enhancement of the hydrological cycle and average precipitation rate (of about 3 to 10%). However, the atmospheric moisture content increases by about 20% (Mitchell et al., 1987) or more (in the case of the CCM2, Roads et al., 1996) although with very little change in model relative humidity. With other things kept constant, moisture convergence would be enhanced by the same amount and should lead to similarly enhanced precipitation. But a 20% increase in precipitation cannot occur because of the limitations associated with the surface energy budget. Nevertheless such mechanisms should take place for individual storms, whether thunderstorms, or extratropical cyclones, leading to increased rainfall rates. If this is the case, however, there are implications for the frequency of storms or other factors that must come into play to restrict the total precipitation.

One factor clearly of importance is that the moisture increases are not uniform. Generally, evaporative cooling is more important in the tropics and subtropics. Bigger increases occur in lower latitudes because of the nonlinear nature of the Clausius-Clapeyron equation in spite of larger increases in surface temperatures at high latitudes. Thus much of this moisture may not be within reach of many extratropical storms. Another factor is the precipitation efficiency, discussed above. How precipitation efficiency might change with climate change is not known and this is not a factor that can be dealt with by current climate models. Warmer conditions could imply that more moisture might remain in the atmosphere if this is determined by relative humidity, as is likely. Therefore the rainfall may not increase in direct proportion to the moisture convergence, because more moisture is left in the atmosphere.

In most models, surface temperature increases with increased greenhouse gases are greatest in the Arctic, in part because of ice-albedo feedback, so that the meridional surface temperature gradient and baroclinicity is reduced, although this may not be the case above the surface. Therefore another factor relates to extratropical storms and the overall baroclinicity, as argued by Held (1993). Held notes that one effect of increased moisture content in the atmosphere is to enhance the latent heating in such storms and thereby increase their intensity. But he also notes that more moist air would be transported polewards, reducing the required poleward energy transports normally accomplished by baroclinically unstable eddies and the associated poleward down-gradient heat transports. He therefore argues that this would contribute to "smaller eddies" and a decrease in eddy amplitudes. While recognizing that both effects are important, Held suspects that the latter is dominant. There are other possibilities not considered by Held. In particular, individual storms could be more intense from the latent heat enhancement, but fewer and farther between. Changes in the vertical temperature structure (the lapse rate) will also play a role in such storms.

Therefore the other major factor worth considering in more detail is the frequency of precipitation events. The above discussion suggests that for rain rates to increase faster than rain amounts, then the frequency of rain should decrease. However, this would only apply globally. A preliminary examination of trends in frequency of precipitation events for the United States computed over the period 1963 to 1994 in Trenberth (1998) shows that the most notable statistically significant trends are for increases in the southern United States in winter and decreases in the Pacific Northwest from November through January, which may be related to changes in atmospheric circulation and storm tracks associated with the trend toward more El Niño events (Trenberth and Hoar, 1996). For instance, an example has been the 1997-98 El Niño winter which featured heavy rains across the southern states from California to Florida, while somewhat drier conditions generally prevailed across the northern states.

These aspects have been explored only to a limited extent in climate models. None deal with true intensity of rainfall, which requires hourly (or higher resolution) data, as the analysis is of daily rainfall amounts. Cubasch et al. (1995) and Hennessy et al. (1997) have analyzed changes in intensity and frequency in coarse resolution models with increased CO_2. Cubasch et al. note that while precipitation change does not display a clear signal, increases in rain intensity and dry periods are simulated in the ECHAM3 model. The UKHI and CSIRO9 models (Hennessy et al., 1997) are consistent in showing heavier rainfall events with doubled CO_2, a general decrease in the probability of moderate precipitation, and an increase in no or light precipitation. Return periods for extreme events whose period is greater than one year decrease by factors of 2 to 5. Hennessy et al. further argue that the frequency of precipitation should be expected to decrease with increases in intensity, and find this to be true in the model simulations for the most part.

An analysis by Mearns et al. (1995) used a nested regional model with 60 km resolution for regions of the United States for control and doubled-carbon dioxide results. They explored the frequency and intensity of modeled precipitation but only for daily values, not the true precipitation rates. Results revealed increased daily rainfall variability under doubled CO_2. There are some areas where frequency of precipitation decreases but precipitation mean daily amounts increase. Overall, however, they find both increases and decreases of both precipitation frequency and intensity. Jones et al. (1997) produced results over Europe using a similar technique and a nested model with 50 km resolution. They find a substantial increase in precipitation intensity in extreme events, and were able to trace most of that increase simply to the increased atmospheric moisture concentrations in the models. While moderate precipitation decreased, the frequency of dry days also increased along with an increase in evaporation, and so these were all symptoms of an increased hydrological cycle.

4. Conclusions and Recommendations

The arguments on how climate change can influence moisture content of the atmosphere, and its sources and sinks are assembled in the schematic in Fig. 2. This provides the sequence described earlier. The sequence given is simplified by omitting some of the feedbacks that can interfere. For example, an increase in atmospheric moisture may lead to increased relative humidity and increased clouds, which could cut down on solar radiation (enhance shortwave cloud forcing) and reduce the energy available at the surface for evaporation. Those feedbacks are included in the climate models and alter the magnitude of the surface heat available for evaporation in different models but not its sign. Figure 2 provides the rationale for why rainfall rates and frequencies as well as accumulations are important in understanding

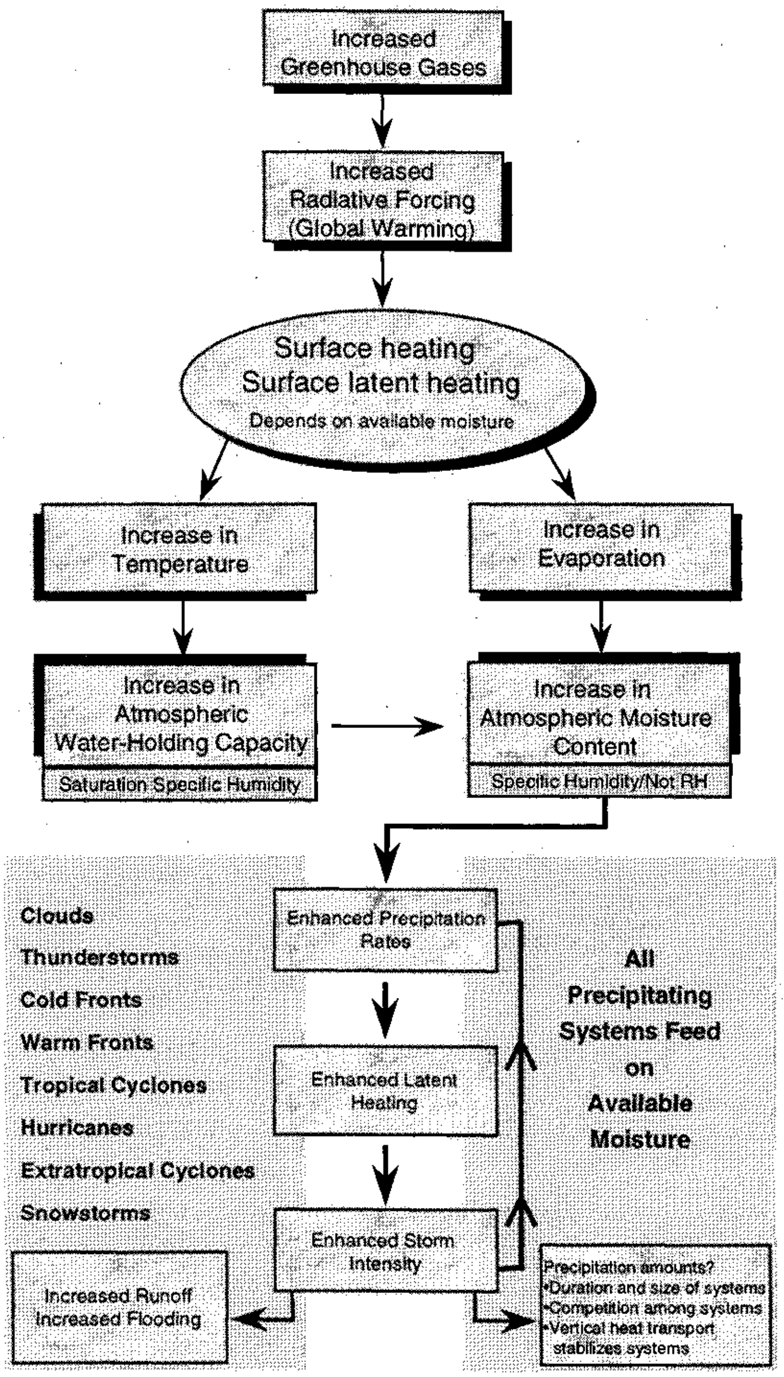

Figure 2. Schematic outline of the sequence of processes involved in climate change and how they alter moisture content of the atmosphere, evaporation, and precipitation rates. All precipitating systems feed on the available moisture leading to increases in precipitation rates and feedbacks.

what is going on with precipitation locally. The accumulations depend greatly on the frequency, size and duration of individual storms, as well as the rate (Byers, 1948) and these depend on static stability and other factors as well. In particular, the need to vertically transport heat absorbed at the surface is a factor in convection and baroclinic instability both of which act to stabilize the atmosphere. Increased greenhouse gases also stabilize the atmosphere. Those are additional considerations in interpreting model responses to increased greenhouse gas simulations.

Another clearly important factor in interpreting observed and modeled changes, not explored here, is the changes in atmospheric circulation which can alter the location and intensity of storm tracks and thereby lead to dipole structures in precipitation changes, with decreases in rainfall in some areas and increases in others. For example, Trenberth and Guillemot (1996) show how storm tracks changed across North America to help bring about the spring-summer 1988 drought and 1993 floods.

There is firm evidence that moisture in the atmosphere is increasing. In the Western Hemisphere north of the equator, annual mean precipitable water amounts below 500 mb are increasing over the United States, Caribbean and Hawaii by about 5% per decade as a statistically significant trend from 1973 to 1993 (Ross and Elliott, 1996), and these correspond to significant increases in relative humidities of 2 to 3% per decade over the Southeast, Caribbean and subtropical Pacific. Precipitable water and relative humidities are not increasing significantly over much of Canada, however, and are decreasing slightly in some areas. In China, recent 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 in the western Pacific. A claim for recent drying in the tropics by Schroeder and McGuirk (1998) using TOVS data is questionable owing to the changes in instruments and satellites. Clearly, there is a need to obtain more reliable atmospheric moisture trends over the entire globe.

Moreover, there is clear evidence that rainfall rates have changed in the United States. The incidence of heavy rainfall events has steadily increased at the expense of moderate rainfall events throughout this century. This has been shown by an analysis of the percentage of the U.S. area with much above normal proportion of total annual precipitation from 1 day extreme events, where the latter are defined to be more than 2 inches (50.8 mm) amounts (Karl et al., 1996). The "much above normal proportion" is defined to be the upper 10%. This quantity can be reliably calculated from 1910, and the percentage has increased steadily from less than 9 to over 11%, a 20% change. Karl and Knight (1998) have provided further analysis of U.S. precipitation increases and show 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 is increasing at the expense of more moderate events. Other evidence for increasing precipitation rates occurs in Japan (Iwashima and Yamamoto, 1993) and Australia (Suppiah and Hennessy, 1996).

It has been argued that increased moisture content of the atmosphere favors stronger rainfall and snowfall events, thus increasing risk of flooding. As noted, there is a pattern of heavier rainfalls observed in many parts of the world where the analysis has been done. However, flooding records are confounded by changes in land use and increasing settlement of flood plains. Moreover, because there is a disparity between the rates of increase of atmospheric moisture and precipitation, there are implied changes in the frequency of precipitation and/or efficiency of precipitation (related to how much moisture is left behind in a storm).

These arguments may help to explain the exceptional rain and snow falls over the U.S. in the winter of 1996-97. These included heavy rains and flooding in the Pacific Northwest in early January, where observed increases in moisture content of the atmosphere at Hawaii and in the subtropical Pacific (Ross and Elliott, 1996) are especially pertinent. Also, heavy snowfalls in the Great Plains and Upper Mississippi Basin led to extensive flooding in the spring of 1997 as snows melted, and heavy rains in the Ohio River Valley which, along with snow melt, also produced extensive flooding. Note that the primary argument here is not that these flooding events would not have occurred but that they have probably been enhanced, perhaps by as much as 10%, because of the increased moisture in the atmosphere, over what would have occurred two decades ago.

The above arguments suggest that there is not such a clear expectation on how local total precipitation amounts should change, except as an overall global average. With higher average temperatures in winter expected, more precipitation is likely to fall in the form of rain rather than snow, which will increase both soil moisture and run off, as noted by the IPCC (1996) and found in many models. In addition, faster snow melt in spring is likely to aggravate springtime flooding. In other places, dipole-like structures of precipitation change should occur in places where storm tracks shift meridionally. Beyond this, it is suggested that examining moisture content, rainfall rates and frequency of precipitation and how they change with climate change may be more important and fruitful than just examining precipitation amounts in understanding what is happening in model projections. To be compatible with life times of significant rain events, yet still deal with whole storms rather than individual rain cells, hourly precipitation data are recommended. Such data are also retrievable from climate models.

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References

Boer, G. J.: 1993, 'Climate change and the regulation of the surface moisture and energy budgets.' *Clim. Dyn.* **8**, 225–239.

Brubaker, K. L., Entehabi, D., and Eagleson, P. S.: 1993, 'Estimation of continental precipitation recycling.' *J. Clim.* **6**, 1077–1089.

Byers, H. R.: 1948, 'The use of radar in determining the amount of rain over a small area.' *EOS Trans. AGU* **29**, 187–196.

Cubasch, U., Waszkewitz, J., Hegerl, G., and Perlwitz, J.: 1995, 'Regional climate changes as simulated in time-slice experiments.' *Clim. Change* **31**, 273–304.

Fankhauser, J. C.: 1988, 'Estimates of thunderstorm precipitation efficiency from field measurements in CCOPE.' *Mon. Wea. Rev.***116**, 663–684.

Ferrier, B. S., Simpson J., and Tao, W-K.: 1996, 'Factors responsible for precipitation efficiencies in midlatitude and tropical squall simulations.' *Mon. Wea. Rev.* **124**, 2100–2125.

Gaffen, D. J., Barnett, T. P., and Elliott, W. P.: 1991, 'Space and time scales of global tropospheric moisture.' *J. Clim.* **4**, 989–1008.

Held, I. M.: 1993, 'Large-scale dynamics and global warming.' *Bull. Am. Meteorol. Soc.* **74**, 228–241.

Hennessy, K. J., Gregory, J. M., and Mitchell, J. F. B.: 1997, 'Changes in daily precipitation under enhanced greenhouse conditions.' *Clim. Dyn.* **13**, 667–680.

Hense, A., Krahe P., and Flohn, H.: 1988, 'Recent fluctuations of tropospheric temperature and water vapour content in the tropics.' *Meteorol. Atmos. Phys.*, **38**, 215-227

IPCC (Intergovernmental Panel of Climate Change): 1996, *Climate Change 1995: The Science of Climate Change.* Eds. J. T. Houghton, F. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell, Cambridge Univ. Press, Cambridge, U.K., 572pp.

Iwashima, T., and Yamamoto, R.: 1993, 'A statistical analysis of the extreme events: Long-term trend of heavy daily precipitation.' *J. Met. Soc. Japan* **71**, 637–640.

Jones, R. G., Murphy, J. M., Noguer, M., and Keen, A. B.: 1997, 'Simulation of climate change over Europe using a nested regional-climate model II: Comparison of driving and regional model responses to a doubling of carbon dioxide.' *Quart. J. Roy. Met. Soc.* **123**, 265–292.

Kalnay E, Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K-C., Ropelewski, C., Leetmaa, A., Reynolds, R., and Jenne, R. 1996, 'The NCEP/NCAR Reanalysis Project.' *Bull. Am. Meteorol. Soc.* **77**, 437–471

Karl, T. R., and Knight R. W.: 1998, 'Secular trends of precipitation amount, frequency and intensity in the USA.' *Bull. Am. Meteorol. Soc.* **79**, 231–242.

Karl, T. R., Knight, R. W., Easterling, D. R. and Quayle, R. G.: 1996; 'Indices of climate change for the United States. *Bull. Am. Meteorol. Soc.* **77**, 279–292.

Karl, T. R., Knight, R. W. and Plummer, N.: 1995, Trends in high frequency climate variability in the twentieth century.' *Nature* **377**, 217-220.

Mearns, L. O., Giorgi, F., McDaniel, L., and Shields, C.: 1995, 'Analysis of daily variability of precipitation in a nested regional climate model: comparison with observations and doubled CO_2 results.' *Global Planetary Change* **10**, 55–78.

Mitchell, J. F. B., Wilson C. A., and Cunnington, W. M.: 1987, 'On CO_2 climate sensitivity and model dependence of results.' *Quart. J. Roy. Met. Soc.* **113**, 293–322.

Osborn, T. J., and Hulme, M.: 1997, 'Development of a relationship between station and grid-box rainday frequencies for climate model evaluation.' *J. Clim.* **10**, 1885–1908.

Roads, J. O., Marshall, S., Oglesby R., and Chen, S-C.: 1996, 'Sensitivity of the CCM1 hydrological cycle to CO_2.' *J. Geophys. Res.* **101**, 7321–7339.

Ross, R. J., and Elliot, W. P. 1996, 'Tropospheric water vapor climatology and trends over North America: 1973-93.' *J. Clim.* **9**, 3561–3574.

Schroeder, S. R., and McGuirk, J. P.: 1998, 'Widespread tropical atmsopheric drying from 1979 to 1995.' *Geophys. Res. Lett.* **25**, 1301–1304.

Suppiah, R., and Hennessy, K. J.: 1998, 'Trends in the intensity and frequency of heavy rainfall in troipcal Australia and links with the Southern Oscillation.' *Aust. Meteorol. Mag.*, **45**, 1–17.

Trenberth, K. E.: 1998, 'Atmospheric moisture residence times and cycling: Implications for rainfall rates with climate change.' *Clim. Change*, **36**, (in press).

Trenberth, K. E., and Guillemot, C. J.: 1996, 'Physical processes involved in the 1988 drought and 1993 floods in North America.' *J. Clim.* **9**, 1288–1298.

Trenberth, K. E., and Hoar, T. J.: 1996, 'The 1990–1995 El Niño-Southern Oscillation event: Longest on record.' *Geophys. Res. Lett.* **23**, 57–60.

Xie, P, and Arkin, P. A.: 1997, 'Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates and numerical model outputs.' *Bull. Am. Meteorol. Soc.* **78**, 2539–2558.

Zhai, P., and Eskridge, R. E.: 1997, 'Atmospheric water vapor over China.' *J. Clim.* **10**, 2643–2652.

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