Precipitation in a Changing Climate–More Floods and Droughts in the Future

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Evidence is building that human-induced climate change—or global warming—has a direct influence on changes in precipitation and the hydrological cycle. While precipitation amount is most commonly considered, even bigger changes occur in its intensity, frequency and type (rain vs. snow). A warmer climate increases risks of both drought and flood, but at different times and/or places. These aspects have enormous implications for agriculture, hydrology and water resources, yet they have not been adequately appreciated or addressed in many studies of climate change impacts. Because natural variability in weather provides resilience, the biggest impacts occur through changes in extremes.

The conceptual basis for changes in precipitation is given by Trenberth (1998, 1999), Allen and Ingram (2002), Trenberth et al. (2003), Neelin et al. (2006) and Held and Soden (2006). Increased heating accelerates land-surface drying as heat goes into the evaporation of moisture; this increases the potential incidence and severity of drought, and has been observed in many places worldwide (Dai et al., 2004). However, the water-holding capacity of air increases by about 7 percent per 1° Celsius warming, and moisture in the atmosphere has been widely observed to be increasing. This moisture then gets carried around by atmospheric winds to a point where storms are favored. Typical storms reach out a distance of about four times the radius of the rain dimension, and gather in water vapor to produce precipitation (Trenberth, 1998; 1999). As heavy rainfall rates typically exceed local surface evaporation rates greatly, precipitation depends primarily on low-level moisture convergence. The convergence of increased water vapor therefore leads to more intense precipitation and risk of heavy rain and snow events. This is widely observed to occur in all storms, whether they be individual thunderstorms, extratropical rain or snow storms, or tropical cyclones and hurricanes. But this convergence may also lead to reductions in the duration and/or frequency of rain events, given that total amounts do not change much and dry spells in-between such events also increase in duration. Hence, basic theory, climate model simulations and empirical evidence all confirm that warmer climates, owing to increased water vapor, lead to more intense precipitation events even when the total annual precipitation is reduced slightly. This in turn increases the risk of flooding.

Observations of Change

Observational evidence reviewed by Trenberth et al. (2007) is noted here very briefly. Relative humidity has tended to remain about the same, from the surface throughout the troposphere, and thus actual moisture amounts in the atmosphere increase at the same rate that the Clausius-Clapeyron equation gives, or about 7 percent per Kelvin over the oceans where moisture supply is not limited or slightly less over parts of land. Other changes occur as the patterns of where storms form and track change, and thus global atmospheric circulation plays a key role in the distribution of precipitation (Vecchi et al., 2006). Generally dry areas are becoming drier (mostly throughout the subtropics) and wet areas are becoming wetter, especially in mid-to-high latitudes and in the monsoon trough in the tropics during the wet season. The snow season has become shorter by up to 3 weeks in parts of the boreal high latitudes over the last 50 years, owing to an earlier onset of spring.

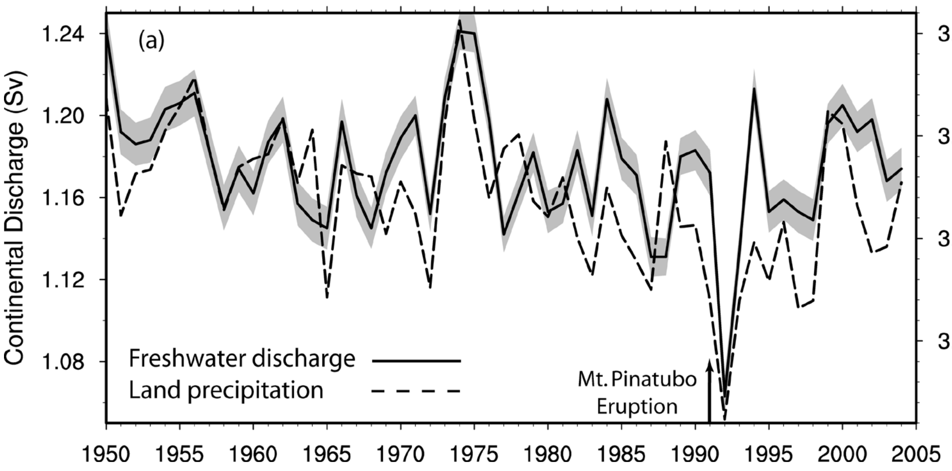
There is also clear evidence of changes in the extremes of precipitation. Globally-averaged over the land area with sufficient data, the percentage contribution to total annual precipitation from very wet days (upper 5 percent) has increased during the past 50 years, even in places where mean precipitation amounts are not increasing. For the contiguous United States, Groisman and Knight (2008) show that even as the top 0.3 percent of heavy rains has increased by 27 percent from 1967 to 2006, so have dry spells increased in most places. The distribution and timing of floods and droughts is most profoundly affected by the cycle of El Niño events, particularly in the tropics and over much of the mid-latitudes of Pacific-rim countries. While enhanced rainfall rates increase the risk of flooding, mitigation of flooding by local councils and government bodies 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).

Increases in drought are associated with a drying trend over many land areas that has taken place since the mid-1950s that is partly associated with decreases in precipitation over land (see figure on page 9) and an overall decrease in runoff and river discharge into the ocean (Trenberth and Dai, 2007; Dai et al., 2009). Large surface warming has also likely contributed to the drying by increasing atmospheric demand for moisture.

Future Prospects

Expectations for changes in overall precipitation amounts are complicated by aerosols. Because particulate aerosols block the sun, surface heating is reduced. Absorption of radiation by some aerosols, notably carbonaceous, directly heats the aerosol layer which otherwise may have been heated by latent heat release in precipitation following surface evaporation. Hence, these aerosols reduce the hydrological cycle. The largest decrease recorded in global land precipitation took place in the year after the Mount Pinatubo volcanic eruption, owing to cooling from aerosols deposited in the stratosphere (Trenberth and Dai, 2007; see figure on page 9). Even as the potential for heavier precipitation occurs from increased water vapor amounts, the duration and frequency of events may be curtailed, as it takes longer to recharge the atmosphere with water vapor.

A very robust finding in all climate models 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 becomes enhanced. It also leads



Annual water year (October–September) continental freshwater discharge (solid line; shading indicates ± one standard error, 1 Sv=10^6 m^3 s^{-1}) into the global oceans from 1950–2004 estimated using streamflow records from the world's largest 925 rivers supplemented with simulated streamflow using a land surface model forced with observed precipitation and other atmospheric forcing. Dashed line is observed precipitation integrated over global land areas. The correlation between the two curves is 0.65. The timing of the Mount Pinatubo eruption is given by the black arrow at the bottom. From Trenberth and Dai (2007).

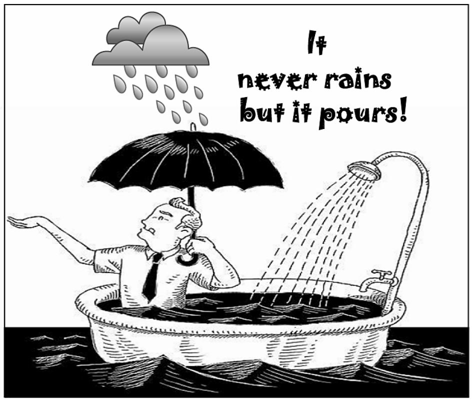
to an increased risk of heat waves and wildfires; once the soil moisture is depleted, all of the heating goes toward raising temperatures and wilting plants.

The global increase in precipitation closely matches the increase in surface evaporation, which depends on the energy available. The evaporation rate is much less than the 7 percent per 1°Celsius increase in water vapor, although Wentz et al. (2007) suggests that this may be underestimated in models. A consequence is that the characteristics of precipitation must change (Trenberth et al., 2003); it is the intensity and duration that are thus most affected. The increase in intensity can even exceed this value because the additional latent heat released feeds back and invigorates the storm that causes the rain in the first place, further enhancing the convergence of moisture. The total precipitation amount increases at a much lower rate, however, so there must be a decrease in light and moderate rains and/or a decrease in the frequency of rain events. We might call this the "it never rains but it pours" syndrome (see figure below). In addition, as heat is transported upwards during precipitation, there is greater latent heat released with the additional moisture and thus less need for the overall circulation to be vigorous (Held and Soden, 2006; Vecchi et al., 2006). Another implication is that large-scale overturning circulations, such as the Hadley and Walker cells, are apt to weaken.

Based on model results, the Intergovernmental Panel on Climate Change (IPCC) (2007) finds that there is a tendency for an increase in heavy daily rainfall events in many regions, including some in which the mean rainfall is projected to decrease. In the latter cases, the rainfall decrease is often attributable to a reduction in the number of rain days rather than the intensity of rain when it does occur. An analysis of future climate simulations by the latest generation of coupled climate models (Sun et al., 2007) shows that for each 1° Celsius of surface warming globally, atmospheric precipitable water increases by about 9 percent, daily precipitation intensity increases by about 2 percent, and daily precipitation frequency decreases by 0.7 percent. For very heavy precipitation (>50 mm day^{-1}), the percentage increase in frequency is much larger than in its intensity (31.2 vs. 2.4 percent) so that there is a shift towards increased heavy precipitation. Thus, extreme weather events such as heavy rainfall and flooding are projected to become much more frequent as climate warms, but with fewer events overall.

Climate model results (IPCC 2007) have become more consistent with regard to projected changes in the patterns of precipitation and can now simulate recent observed patterns of change. Increases in the amount of precipitation are very likely at high northern latitudes, but decreases in precipitation are projected for tropical and subtropical regions outside of the monsoon trough. This is the "rich get richer and the poor get poorer" syndrome (Neelin et al., 2006). However, extratropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation and temperature patterns, continuing the broad pattern of observed trends over the last half-century. Along with a poleward expansion of the subtropical high-pressure systems, this movement leads to a drying tendency in the subtropics that is especially pronounced at the higher-latitude margins of the subtropics.

Future tropical cyclones (typhoons and hurricanes) will also likely become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical sea surface temperatures (IPCC, 2007). Because an intense tropical cyclone takes heat out of the ocean and mixes the ocean, leaving behind a much stronger cold wake than a more modest storm, there may be fewer tropical cyclones as a whole. Possible increases in static stability also lead to fewer tropical cyclones. Nonetheless, increased risk of flooding is a likely outcome from land-falling tropical storms.



As temperatures rise, the likelihood of precipitation falling as rain rather than snow increases, especially at the beginning and end of the snow season and in areas where temperatures are near freezing. Such changes lead to increased rains and, along with earlier snowmelt and greater evaporation and ablation, the result is a reduced snow-pack. In mountain areas, the winter snowpack forms a vital freshwater resource in the spring as the snow melts. A diminished snowpack results in subsequent lower soil moisture, which likely contributes to summer drought due to the importance of recycling of moisture.

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References

Allen, M. R., and W. J. Ingram, 2002. Constraints on future changes in climate and the hydrologic cycle. *Nature,* 419, 224–232.

Dai, A. G., K. E. Trenberth, and T. Qian, 2004. A global data set of Palmer Drought Severity Index for 1870-2002: Relationship with soil moisture and effects of surface warming. *J. Hydrometeorology*, 5, 1117–1130.

Dai, A., T. Qian, K. E. Trenberth, and J. D. Milliman, 2009. Changes in continental freshwater discharge from 1949-2004. *J. Climate*, 22, 2773-2791.

Groisman, P. Ya., and R. W. Knight, 2008. Prolonged dry episodes over the conterminous United States: New tendencies emerging during the last 40 years. *J. Climate*, 21, 1850–1862.

Held, I. M., and B. J. Soden, 2006. Robust responses of the hydrological cycle to global warming. *J Climate*, 19, 5686–5699.

Intergovernmental Panel on Climate Change, 2007: Climate Change 2007. The Physical Science Basis. Contribution of WG 1 to the Fourth Assessment Report of the IPCC. [S. Solomon, D. Qin, et al (eds.)]. Cambridge University Press. Cambridge, U. K., and New York, NY, USA, 1056 pp.

Milly, P. C. D., R. T. Wetherald, K. A. Dunne, and T. L. Delworth, 2002. Increasing risk of great floods in a changing climate. *Nature*, 415, 514–517.

Neelin, J. D., M. Munnich, H. Su, J. E. Meyerson, and C. E. Holloway, 2006. Tropical drying trends in global warming models and observations. *PNAS*, 103, doi: 10.1073/pnas.0601798103.

Sun, Y., S. Solomon, A. Dai, and R. Portmann, 2007. How often will it rain? *J. Climate*, 20, 4801–4818.

Trenberth, K. E., 1998. Atmospheric moisture residence times and cycling: Implications for rainfall rates and climate change. *Climatic Change*, 39, 667–694.

Trenberth, K. E., 1999. Conceptual framework for changes of extremes of the hydrological cycle with climate change. *Climatic Change*, 42, 327–339.

Trenberth, K. E., and A. Dai, 2007. Effects of Mount Pinatubo volcanic eruption on the hydrological cycle as an analog of geoengineering. *Geophys. Res. Lett*, 34, L15702, doi:10.1029/2007GL030524.

Trenberth, K.E., A. Dai, R. M. Rasmussen, and D. B. Parsons, 2003. The changing character of precipitation. *Bull. Amer. Met. Soc.*, 84, 1205–1217.

Trenberth, K. E., et al., 2007. Observations: Surface and Atmospheric Climate Change. In: Climate Change 2007. The Physical Science Basis. Contribution of WG 1 to the Fourth Assessment Report of the IPCC. (S. Solomon, D. Qin, et al.) Cambridge University Press. Cambridge, U. K., and New York, NY, USA, 235–336.

Vecchi, G. A., B. J. Soden, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison, 2006. Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing. *Nature*, 441, 73–76.

Wentz, F., L. Ricciardulli, K. Hilburn, and C. Mears, 2007. How much more rain will global warming bring? *Science*, 317, 233–235.

Increasing Greenhouse Gases Impact Local Water Supplies

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Life on Earth is a water processing system and humans have found many additional uses for water to support a technology-based life. With population and standards of living increasing, demand for water is beginning to exceed supply in some places. In a constant climate, long-range plans for meeting this increased demand can be made. In a changing climate, if we do not know the details of the changes, good plans cannot be made.

There are two conceptual difficulties in understanding water supply. The first is that the amount of water in any given local reservoir at any given location is the result of the balance of fluxes in and transports by the whole climate system. Consequently, the availability of water at one location and time is dependent on a global water circulation system in which local variations are affected by distant changes. Hence local water problems may arise from global-scale variations but global variations can be induced by large local changes. The second difficulty is that, in a complex system like the climate, the amount of water in a reservoir does not necessarily behave in an intuitive or simple way: as examples, reducing our demand for water in response to a drought does not necessarily lead to an increase of water in the reservoir or increasing precipitation does not necessarily produce an increase of water in the reservoir either. Moreover, even small changes of the global atmospheric or oceanic circulations can produce local changes in a local reservoir that are not proportional.

The part of the climate water cycle that is of most concern to people, animals and plants is the net transport of evaporating ocean water by the atmospheric circulation to precipitation over land. However, the net transport of a small amount of water away from the oceans is a consequence of a large energy transfer between the ocean (heated by the sun) and the atmosphere (cooled by thermal radiation to space) and a re-distribution of freshwater by the atmospheric and oceanic circulations. The former constitutes the main part of the energy balance of Earth; subtle changes in the latter can affect the ocean biosphere and chemistry. A substantial fraction of the water precipitating onto the land is lost to evaporation and almost all of the net import of water to the land is returned to the ocean by runoff. Between the time water is temporarily stored near the land surface (a smaller part of the water is stored for longer time periods at greater depths) and its eventual return to the ocean, water passes through the biosphere or through other human usages.

Solar heating of the surface is regulated by clouds; thermal radiative cooling of the atmosphere is regulated by clouds and water vapor. The surface is cooled mostly by evaporation of water vapor into the atmosphere and the atmosphere is heated mostly by precipitation back to the surface. Thus, the water cycle constitutes the main surface-atmosphere exchange of energy. From this description, it is easy to see