

**How should rainfall change as climate changes:  
Prospects for increases in extremes?**

How should rainfall change as the climate changes? This is a key question that could have a substantial impact on society and the natural environment, as it can directly affect availability of fresh water, the quality of potable water, drought and floods. Usually the only measure of rainfall cited is rainfall amount. Yet most of the time it does not rain. So just a little thought makes us realize that we need to be concerned also with how often it rains: the frequency; and how hard it rains when it does rain: the intensity or rainfall rate, as well as the amounts. Also, it turns out that making these distinctions allows us to make more sensible statements about the likely changes and how to examine the data on rainfall. Of course the more general term is precipitation, so we must also include snow and other forms of precipitation in addition to rain.

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) 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 downward infrared radiation. This increase in surface heating can indeed increase surface temperatures but it also increases evaporation. In fact it is more likely to do the latter as long as adequate moisture is around - and over the oceans, which encompass 70.8% of the globe, water is everywhere. For example, after a rain storm, when the sun comes out, the first thing that happens is that the puddles dry up and the surface of the ground dries before the sun's heat goes into raising temperature.

When the temperature increases, so does the water-holding capacity of the atmosphere, at  $7\% K^{-1}$ . This is why we tend to use relative humidity as a measure of moisture as it signifies the percentage of moisture the atmosphere can hold rather than the absolute amount. At very cold temperatures, the atmosphere can hardly hold any moisture, in effect it gets freeze dried, and so liquid water amounts from snow at temperatures below freezing are quite small.

Of course, enhanced evaporation depends upon the availability of sufficient surface moisture and over land, this depends on the existing climate. In fact surface moisture comes directly from evaporation as well as through transpiration in plants, together called evapotranspiration. However, it follows that naturally-occurring droughts are likely to be exacerbated by enhanced potential evapotranspiration (drying).

Thus if the water carrying capacity of the atmosphere increases and there is enhanced evaporation, the actual atmospheric moisture should increase, as is observed to be happening in many places. Over the United States and Gulf of Mexico, for example, moisture amounts in the lowest 20,000 feet of the atmosphere have increased about 10% from 1973-94.

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. Precipitating systems of all kinds (rain clouds, thunderstorms, extratropical cyclones, hurricanes, etc) 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. In other words, when it rains it should rain harder than it used to under similar circumstances. This is exactly what is being observed to be happening in many parts of the world, 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. Evaporation occurs typically at about 0.2 inches per day but moderate or heavy rain can easily be an inch or more per day. Thus rain dries out the atmosphere unless the winds bring in more moisture from remote areas, and the weather system runs out of moisture.

However, because of constraints in the surface energy budget, there are also implications for the frequency and/or efficiency of precipitation. The global increase in evaporation is determined by the increase in surface heating and this controls the global increase in precipitation. Moisture amounts are not limited by this but instead are limited by the moisture carrying capacity, and so precipitation rates are apt to increase more rapidly than amounts, implying that the frequency of precipitation must decrease, raising the likelihood of fewer but more intense events. Hence it is argued that increased moisture content of the atmosphere favors stronger rainfall and snowfall events, thus increasing risk of flooding. Although there is a pattern of heavier rainfalls observed in many parts of the world where the analysis has been done, another factor is increasing settlement of flood plains which changes vulnerability to flooding. Flooding records are confounded by changes in land use, construction of culverts and dams, and other means designed to control flooding.

Another important factor is that with higher average temperatures in winter expected, more precipitation is likely to fall in the form of rain rather than snow, which will increase runoff. In addition, faster snow melt in spring is likely to aggravate springtime flooding. Snow pack in spring is observed to be decreasing and is projected to continue to do so. This makes for less soil moisture in summer, more heat waves and less recycling of moisture, increasing risk of drought, heat waves and wild fires.

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. In other places, complicated patterns of precipitation change should occur where storm tracks shift. Where the storms previously tracked gets drier and where they shift to becomes wetter. 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, both in the real world and in climate models. But many data analyses are not done to illuminate these aspects.

**Reading:**

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## **Background**

Dr. Kevin E. Trenberth is Head of the Climate Analysis Section at the National Center for Atmospheric Research. From New Zealand, he obtained his Sc. D. in meteorology in 1972 from Massachusetts Institute of Technology. He was a lead author of the 2001 IPCC Scientific Assessment of Climate Change and serves on the Scientific Steering Group for the Climate Variability and Predictability (CLIVAR) program and the Joint Scientific Committee of the World Climate Research Programme. He is a fellow of the American Meteorological Society (AMS) and American Association for Advancement of Science, and an honorary fellow of the Royal Society of New Zealand. In 2000 he received the Jule G. Charney award from the AMS and in 2003 he received the NCAR Distinguished Achievement Award.

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