ATMOSPHERIC MOISTURE RESIDENCE TIMES AND CYCLING: IMPLICATIONS FOR RAINFALL RATES AND CLIMATE CHANGE

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Abstract. New estimates of the moistening of the atmosphere through evaporation at the surface and of the drying through precipitation are computed. Overall, the *e*-folding residence time of atmospheric moisture is just over 8 days. New estimates are also made of how much moisture that precipitates out comes from horizontal transport versus local evaporation, referred to as 'recycling'. The results depend greatly on the scale of the domain under consideration and global maps of the recycling for annual means are produced for 500 km scales for which global recycling is 9.6%, consisting of 8.9% over land and 9.9% over the oceans. Even for 1000 km scales, less than 20% of the annual precipitation typically comes from evaporation within the domain. While average overall atmospheric moisture depletion and restoration must balance, precipitation falls only a small fraction of the time. Thus precipitation rates are also examined. Over the United States, one hour intervals with 0.1 mm or more are used to show that the frequency of precipitation ranges from over 30% in the Northwest, to about 20% in the Southeast and less than 4% just east of the continental divide in winter, and from less than 2% in California to over 20% in the Southeast in summer. In midlatitudes precipitation typically falls about 10% of the time, and so rainfall rates, conditional on when rain is falling, are much larger than evaporation rates. The mismatches in the rates of rainfall versus evaporation imply that precipitating systems of all kinds feed mostly on the moisture already in the atmosphere. Over North America, much of the precipitation originates from moisture advected from the Gulf of Mexico and subtropical Atlantic or Pacific a day or so earlier.

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. Global temperature increases signify that the water-holding capacity of the atmosphere increases and, together with enhanced evaporation, this means that the actual atmospheric moisture should increase. 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. Observations confirm that atmospheric moisture is increasing in many places, for example at a rate of about 5% per decade over the United States. Based on the above results, we argue that increased moisture content of the atmosphere therefore favors stronger rainfall or snowfall events, thus increasing risk of flooding, which is a pattern observed to be happening in many parts of the world. 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). However, an analysis of linear trends in the frequency of precipitation events for the United States corresponding to thresholds of 0.1 and 1 mm/h 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 El Niño–Southern Oscillation trends. It is suggested that as the physical constraints on precipitation

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apply only globally, more attention should be paid to rates in both observations and models as well as the frequency of occurrence.

1. Introduction

Characterizing all aspects of the hydrological cycle accurately from observations and analyses is a difficult task, so that there remain substantial uncertainties in precipitation, evaporation, moisture transport in the atmosphere and surface runoff (e.g., Trenberth and Guillemot, 1996b, 1998). These uncertainties become magnified in attempts to project what changes may occur in any of these quantities as the climate changes. Although comprehensive climate system models can be used for these tasks, the complexity of the changes that occur, for example in precipitation, with an increase in carbon dioxide concentrations in the atmosphere, is considerable for a single model. And the complexity becomes even greater when results from different models are compared (e.g., Mitchell et al., 1987; Boer, 1993).

There are reasons for this complexity, of course. Precipitation processes often occur on scales not adequately resolved by climate models. Moreover, observed precipitation fields have tremendous structure on very small scales and there is a large essentially random component to them, so that the details are not reproducible in models run under the same climate forcings, and thus the details are not predictable. But some changes with larger-scale structures can be anticipated; examples include changes in the overall hydrological cycle and changes in monsoons and storm tracks.

How should rainfall, or precipitation, change as climate changes? Why are the patterns predicted from different models under increased greenhouse gas scenarios so different? What is the relationship among changes in evaporation, changes in moisture content of the atmosphere, and changes in precipitation? What are the factors that should be taken into account to explain the changes? The IPCC 1995 report (IPCC, 1996) in dealing with future climate prospects with increased greenhouse gases in the atmosphere states that 'Warmer temperatures will lead to a more vigorous hydrological cycle;[2] this translates into prospects for more severe droughts and/or floods in some places. . . ' 'Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events'. This paper attempts to explain the processes involved that influence these results and addresses some of the questions by noting the importance of rainfall rates (or intensity) and rainfall frequency, not just accumulated amounts. We further examine the relative roles of moisture stored in the atmosphere, its advection, resupply, and how these may change.

One problem with using models for climate change experiments is that the models contain biases in their control climates, and so the observed rainfall patterns may not be well reproduced. Some models include a 'flux adjustment' to