Water Vapor Feedback During an Enhanced Hydrological Cycle

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The presence of a hydrological cycle on the Earth greatly moderates the climate, making this planet hospitable to a wide variety of life. It also greatly complicates understanding and prediction of climate since the water and energy cycles interact in a non-linear way on all time and space scales. In general circulation model simulations of global warming, the water vapor feedback greatly enhances the projected temperature increases originated by anthropogenic greenhouse gasses. Many of these models also suggest that the hydrological cycle will be enhanced in a warmer climate leading to a higher frequency of large-scale floods and droughts. Although there is little controversy that the lower tropospheric water vapor equilibriates rapidly to the underlying surface temperature, there is considerable controversy about how the upper tropospheric water vapor may change. Changes in the upper tropospheric water vapor, particularly within the dry areas of the tropics and subtropics, have a very large influence on the longwave radiation budget. An analysis of the variability of global upper tropospheric water vapor from satellite data during the last 20 years shows great variability in water vapor feedback in the tropics as deduced from studies of HIRS channel 12 data. These observations suggest that water vapor cycling through the global monsoons acts to constrain the hydrological cycle and climate within rather narrow bounds.

In the past 20 year, during which we have global observations provided continuously by the NOAA operational satellites, the ENSO events of 1982-83 and 1997-98 clearly stand out as the most dramatic examples of an enhanced hydrological cycle. During these events, extreme droughts occurred in southern Africa, southern India and Sri Lanka, and in the Australian-Indonesian region. Devastating floods occurred in Ecuador and Peru, in California and along the U.S. Gulf coast, and exceptionally heavy snowfall occurred in the mountainous areas of the U.S. Great Basin. The southern oscillation index recorded its greatest values this century.

Figure 1a shows the leading EOF mode of amomalous precipitation [*Xie and Arking*, 1997] during the past 20 years. During ENSO warm events, precipitation is enhanced in the central and eastern equatorial Pacific and precipitation is decreased in the western equatorial Pacific and in the South Pacific convergence zone. Figure 1b shows the spatial pattern of the leading EOF mode of interannual variability of an HIRS channel 12 derived from NOAA polar-orbiter satellite data [*Bates et al.*, 1996]. This index is a measure of upper tropospheric humidity and shows the spatial re-arrangement of the tropical monsoon-desert system during ENSO warm and cold events. The spatial pattern shows an increase in the upper tropospheric humidity over the central and eastern equatorial Pacific, over western Australia and extending west into the southern Indian ocean, and over smaller regions in the North and South Atlantic. Decreases in the upper tropospheric humidity are found in the north and south sub-tropics of the Pacific, over the western equatorial Pacific over northeast Brazil, and over the Gulf of Guinea. Of these, however, the largest decrease is found over the subtropical North Pacific between Hawaii and Baja California. This is an area where the upper tropospheric humidity is already low.

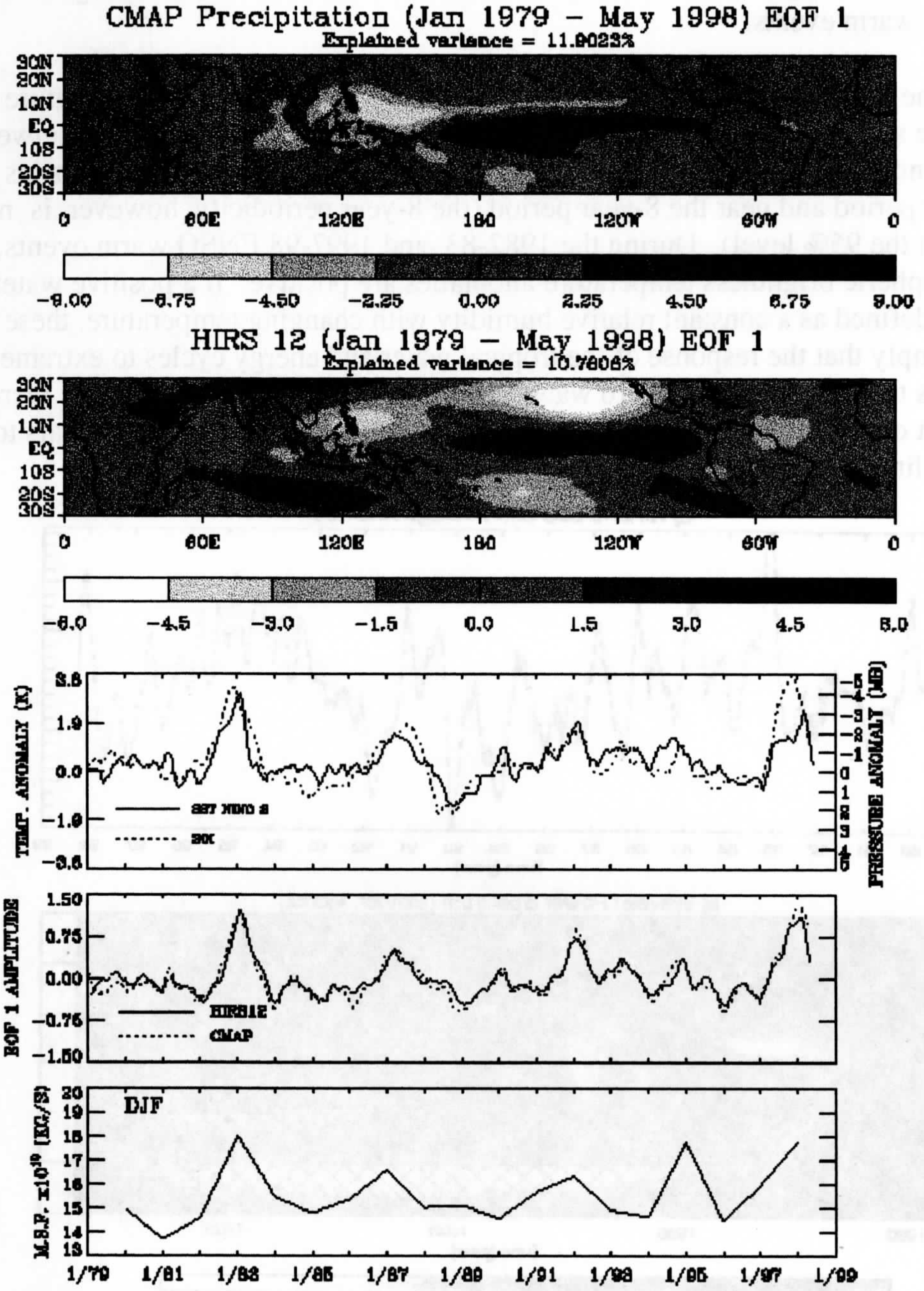

Figure 1. Leading mode EOF of the interannual precipitation (a), leading mode EOF of the interannual tropical upper tropospheric humidity index (b, time series of sea surface temperature anomalies for the central equatorial Pacific Niño 3 region and southern oscillation index (c), time series of leading mode EOF of the interannual upper tropospheric humidity index (d), and time series of December-January-February average meridional mass stream function (e).

The time series of sea surface temperature anomalies in the central equatorial Pacific, the Nino 3 area (Figure 1c), and the southern oscillation index (SIO) are highly correlated with the leading EOF mode principle component time series of precipitation and HIRS channel 12 (Figure 1d). A measure of the intensity of the tropical Hadley cell overturning (Figure 1e), or hydrological cycle, has been computed from NCEP re-analysis data [*Kalnay*, 1996]. This meridional mass stream function has been computed for the northern winter season (December-January-February) when the effects of ENSO warm events are most pronounced in the northern hemisphere mid-latitudes. This index shows that the tropical hydrological cycle intensifies during ENSO warm events and that it was very intense during the 1982-83 and 1997-98 warm events.

Anomaly time series of tropical average (30N-30S) HIRS 12 brightness temperature animalies are shown in Figure 2. There is, however, no significant correlation between this time series and those in Figure 1. There is significant variability at high frequencies and also at the 4-year period and near the 8-year period (the 8-year periodicity, however, is not significant at the 95% level). During the 1982-83 and 1997-98 ENSO warm events, the upper tropospheric brightness temperature anomalies are positive. If a positive water vapor feedback is defined as a constant relative humidity with changing temperature, these positive anomalies imply that the response of the tropical water and energy cycles to extreme ENSO events seems to be a negative or zero water vapor feedback. Since the radiance increases, the net effect on the clear sky outgoing longwave radiation is negative and appears to restore the current climate balance.

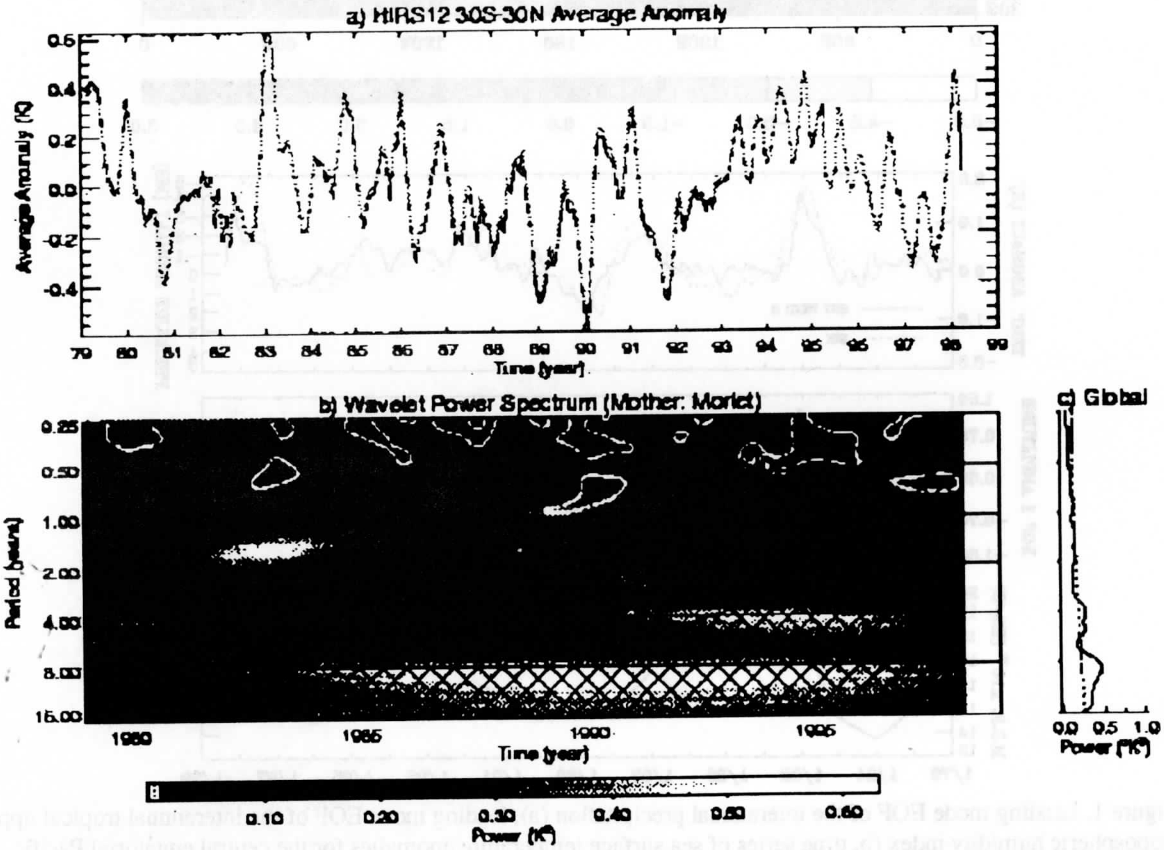

Figure 2. Anomaly time series of tropical (30N-30S) average HIRS channel 12 brightness temperature (a), wavelet spectra (b), and total power spectra (c).

Although the response of the tropical atmosphere is not symmetric for ENSO warm and cold event extremes, these observations suggest that the cycling of water vapor through the tropical hydrological cycle provides a natural humidistat on the water and energy cycles. I propose the following hypothesis to explain these observations. During extreme ENSO warm events, the upper troposphere above the anomalous deep convection becomes saturated and thus the upper tropospheric humidity and clear-sky outgoing longwave radiation anomalies reach a limit. In the descending branches of the Hadley cell, however, there is not such a strict limit and the upper troposphere can become extremely dry. Since the clear-sky outgoing longwave radiation is a strong function of base upper tropospheric humidity, drying already dry areas has a much greater impact on the radiation budget than moistening already moist areas. The net result is that as the intensity of the Hadley cell exceeds some threshold, the water vapor feedback becomes negative and provides a natural limit to the radiation budget within the tropics. ENSO cold events are not symmetric with warm events. Nevertheless, I propose that during the 1988-89 cold event the suppression of convection caused the tropical upper troposphere to be much less saturation limited. During this time, water vapor is still supplied to the upper troposphere by deep convection but the drying of the dry areas is not intense, leading to a net increase in the clear-sky greenhouse. Thus, the tropical clear-sky greenhouse is a function of how water vapor is cycled through the monsoon-desert system and this provides a natural humidistat that keeps the tropical climate within narrow bounds.

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