Roles of recycling and memory in the variability of the hydrological cycle

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INTRODUCTION

Fluctuations in the atmospheric hydrologic cycle are one of the primary sources of the observed hydrologic variability. These fluctuations are understood to be generated as internal modes of the atmospheric dynamics (such as the North Atlantic Oscillation) as well as externally driven, such as by the sea-surface temperature (El Nino Southern Oscillation). However, little is known about the roles of recycling and deep layer terrestrial memory in modulating the atmospheric dynamics. This paper discusses results that lead to the following hypotheses:

- Regional atmospheric moisture transport is governed by both the large-scale forcing as well as local recycling, and their relative contributions have important implications in the inter-annual variability of the hydrologic cycle.
- The deep layer terrestrial moisture and energy storage modulate the dynamics of the near-surface layer, thereby influencing the land-atmosphere interaction.

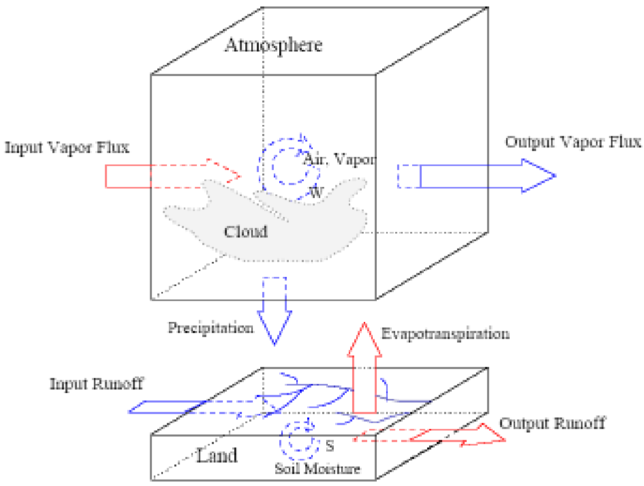

Fig. 1 Schematic diagram of the atmospheric and terrestrial components of the hydrological cycle. W *is the precipitable water in a vertical air column, and* S *is the terrestrial water storage in a soil column.*

MODES OF MOISTURE TRANSPORT AND RECYCLING

Dominguez and Kumar (2003) showed that the modes of moisture flux transport depend in a non-trivial way on climate anomalies, in that often more than one climate anomaly influences moisture transport or the moisture transport can be driven by the sources and sinks of moisture without a distinct climatic pattern playing a role. Therefore, the knowledge of climate anomaly patterns alone is not sufficient to gain an understanding of the moisture flux anomalies. Owing to the tight coupling between the atmospheric and terrestrial branches of the hydrologic cycle (see Figure 1), albeit with several different time scales, the modes of atmospheric moisture transport, which further affect moisture convergence and precipitation, play a crucial role in modulating the terrestrial hydrological response.

Dominguez and Kumar (2003) investigated the principal modes of seasonal moisture flux transport over North America, analysing their possible dependence on large-scale atmospheric circulation patterns. Using 54 years (1948–2001) of vertically integrated six-hourly data from the NCEP/NCAR Reanalysis I Project, orthogonally rotated principal component analysis (RPCA) was implemented to identify the dominant modes. For every season, the characteristic spatial pattern of the most dominant modes was compared to the geopotential height anomaly field. The height field corresponding to the positive phase of the mode was calculated as a composite of the years that score above one standard deviation in the yearly scores of the selected moisture flux mode. The geopotential height patterns were then compared to well known large-scale circulation patterns.

Figure 2 shows an example of the influence of the inter-annual variability on the fluctuations of the Great Lakes in

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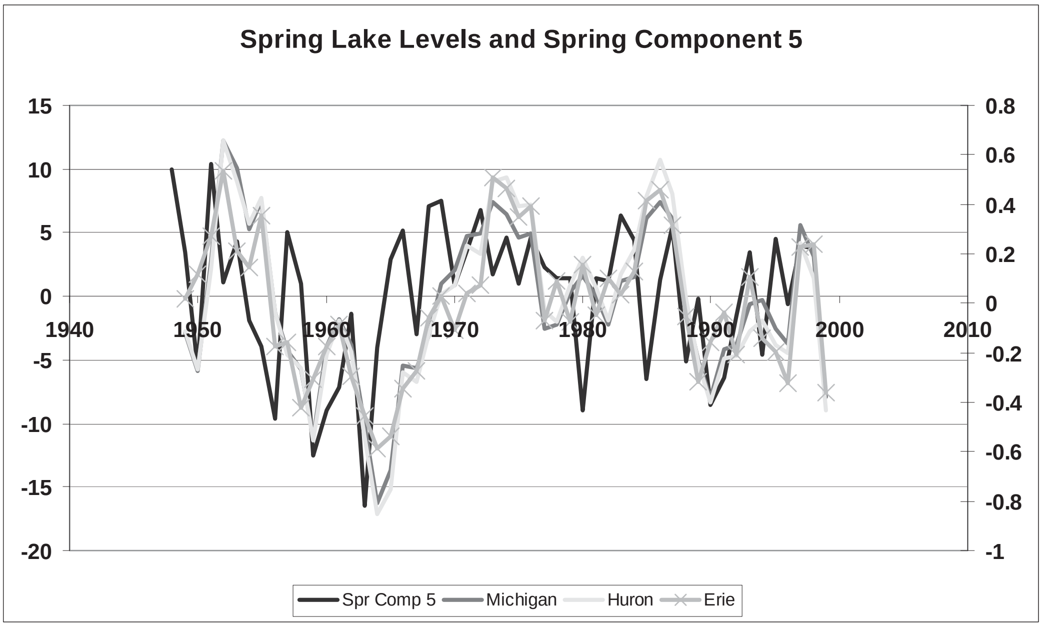

Fig. 2 Correspondence between 5th mode of fluctuation of moisture flux magnitudes for Spring (over North America) and anomalies of lake level fluctuations of the Great Lakes

North America. It can be seen that the anomalies of the lake level (in feet, left axis) correspond closely to one of the modes of variability (spring mode 5, right axis). This mode is strongly affected by tropical variability, demonstrating a teleconnection influence on the inter-annual variability of the lake levels. The lake levels are used here as an integrated response of the basins draining into them, indicating the impact on the terrestrial hydrologic variability. The persistence of fluctuations in the lake levels can also be seen.

In general, over North America the large-scale circulation patterns are an important driving force for moisture transport during winter. During this season the Pacific/North American (PNA) and the North Atlantic Oscillation (NAO) patterns emerge as the dominant mechanisms of transport. The Eastern Pacific (EP), North Pacific (NP) and Pacific/North American (PNA) patterns are important during the spring. The summer is characterised by a smaller influence of large-scale patterns and although the NAO and Arctic Oscillation (AO) are present in the first two modes, some of the geopotential height fields cannot be linked to known patterns. Autumn is also characterised by a weak influence of large-scale patterns. Extreme hydrological events such as the 1993 flood that affected the United States' mid-west region, or the droughts that affected a large area of the United States in the early 1950s, mid 1970s and late 1980s, are captured as specific modes.

The analyses of modes of moisture flux transport over North America, summarised above, show two important characteristics:

1. Several leading modes are a combination of more than one mode of climatic anomalies, and therefore have an identity of their own.
2. Several leading modes do not correspond to climate anomalies and are possibly driven by the feedback process between land and atmosphere. In the warm seasons this feedback is possibly driven by recycling and moisture, whereas in the cold season it is possibly driven by the feedback of radiative processes.

This second issue is currently under investigation.

TERRESTRIAL MEMORY

Several studies have illustrated the role of land-surface moisture storage in modulating the anomalies induced by the SST (sea-surface temperature) dynamics. Anomalous soil-moisture states (wet or dry) take several weeks or longer to dissipate. Recent studies (Dirmeyer, 2001; Koster and Suarez, 2001) have shown that the soil-moisture anomalies may show timescales greater than a month. These issues are related to the identification of the strength of coupling between the terrestrial and the atmospheric processes and how this coupling enhances or dissipates the persistence of anomalies forced externally by the ocean processes.

Using a Large Area Basin scale (LABs) (Chen and Kumar, 2001) land surface model, it was established (Chen and Kumar, 2002, 2004) that the dynamics of the entire moisture profile, not just near-surface, play an extremely important role in the partitioning of precipitation into various moisture reservoirs as well as that of radiation into various energy components. The North American continent was divided into 5020 basins using the HYDRO1k data (Verdin and Verdin, 1999) with an average basin size of 3255 km^2, and the LABs model was implemented for each of these basins with a time step of 30 minutes. The model output is aggregated to monthly timescale for identifying the ENSO-related effects on terrestrial energy profiles. Chen and Kumar (2001), using the ISLSCP (International Satellite Land Surface Climatology Project) two-year data for 1987–1988 over the North American continent, established that the baseflow arising from the sub-surface layers accounts for roughly 60% of the total streamflow in the Mississippi River basin. The modelled streamflow were validated with observation data. During the drier 1988 summer the evapotranspiration was largely supported by drawing on the water storage. The water storage plays a very active role in regulating the dynamics of the water balance and in general is substantially larger in magnitude than the runoff.

In a subsequent study, using a 15-year simulation with ECMWF (European Center for Medium Range Weather Forecast) Re-Analysis 15-year (ERA) data for 1979–1993, it was identified (Chen and Kumar, 2002) that the moisture in deeper layer plays a very active role in the hydrologic manifestation of climatic anomalies such as ENSO. The extremal cross-correlation (and the associated lag) between the time series of ENSO index and the monthly anomaly of the runoff over North America showed that there are three distinct coherent negatively-correlated regions: central Canada, north-western Alaska and south Mexico. The runoff anomalies in the north and north-west regions of the North American continent are most often negatively-correlated with the ENSO signal. In contrast, there are four distinct positively-correlated regions: the centre of the continent, the area around the Gulf of Mexico, the area around the Hudson Bay and the area around California and Nevada. The negatively-correlated regions demonstrate a high probability of low flow during the warm phase of an ENSO year and/or of high flow during the cool phase. The four positively-correlated regions have high flow potential in an El Ninõ year and/or low flow potential in a La Ninã year.

In the regions of ENSO influence, terrestrial hydrological variables such as runoff exhibit a response that has a delay, greater than that of precipitation, to the ENSO signal and this phase lag is caused due to the storage characteristics of soil profile. Study using near surface and total soil-moisture deficit revealed that the influence on runoff is generally communicated through the latter, while the former is more coherent with the rainfall pattern. It is hypothesised in Chen and Kumar (2002) that the relatively slower dynamics of terrestrial moisture serve as a memory in causing the delayed peak in runoff as compared to the precipitation. That is, the higher rainfall during an ENSO episode may not always result in extreme runoff. The infiltrated water could get stored as soil-moisture and less intense rainfall at a later time (possibly a month to a season delay) may cause higher runoff due to the reduced soil-water deficit.

Further study of the temperature profile (Chen and Kumar, 2004) shows that there exist several ENSO-related spatially-coherent correlation regions for soil temperature anomaly over the continent, where the temperature anomaly can propagate down into deep soil. It is shown that this is theoretically plausible due to the long fluctuation period of the signal. The amplitudes of soil temperature anomaly fluctuations decrease from layer one to six (as should be expected). Also, their variability decreases with the increasing soil depth. At these six soil layers (of thicknesses 10, 20, 40, 80, 160 and 320 cms), it is found that there are three wave crests corresponding to the three El Ninõ events and two wave troughs corresponding to the two La Ninã events during the 15-year time period. The pattern of ENSO-related spatially-coherent correlation with terrestrial enthalpy anomaly is primarily consistent with that obtained from soil water enthalpy anomaly, and the coherent correlation regions of ENSO and soil water enthalpy for total soil column are similar to those of soil water deficit. This implies that the variation of the ENSO-related

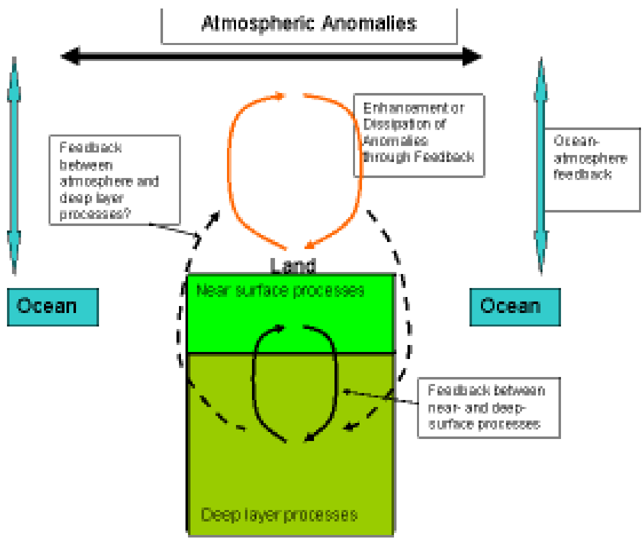

Fig. 3 Schematic showing the interaction between ocean, atmosphere and land, and the context of deep-layer memory in the dissipation or enhancement of atmospheric anomalies. The deep layer is defined as the depth below the terrestrial surface where the timescales of decay of moisture and temperature anomalies is of the order of several weeks (month to season) or longer.

soil water anomaly dominates the variations of the soil water enthalpy and consequently the terrestrial enthalpy anomalies.

These results lead to the hypothesis that the deep layer terrestrial moisture and energy storage modulate the dynamics of the near-surface layer thereby influencing the land-atmosphere interaction (see Figure 3); and that the evolutionary pattern of the deep layer processes is more predictable than that of near-surface. The deep layer in the context of the proposed research refers to the depth below the terrestrial surface where the timescales of decay of moisture and temperature anomalies is of the order of several weeks (month to season) or longer. This issue is currently under investigation.

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