*J Water SRT — Aqua* Vol. 47, No. 3, pp. 119–124, 1998

# Geophysics, natural selection, and hydrological forecasting

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ABSTRACT: This paper demonstrates how to reduce the uncertainty in long range hydrological forecasting through the use of models based on the interactions between the oceans and the atmosphere, and the land surface and the atmosphere. The numerical models are on a regional and global scale and provide the geophysical justification necessary for the confident use of these 'teleconnections' for climate/hydrological forecasts.

## INTRODUCTION

Over the last 30 years, hydrology has evolved from a field focused on engineering problems of rainfall–runoff and irrigation scheduling at the scale of the small watershed to a field struggling with global-scale issues which demand a geophysical perspective. This shift of viewpoint, emphasising the geosciences, is essential both to understanding the environmental consequences of climate change, and to developing the practical tools for long-range forecasting of water availability.

## EARTH SURFACE–ATMOSPHERE FEEDBACK

The fundamental difference between the hydrologic system at small geographical scale and that at large geographical scale lies in the relative sensitivity of the precipitation to the feedback of moisture and heat from the surface to the atmosphere. Figure 1 is a 'clinical' diagram of this feedback for water within a column of atmosphere in which:

$Q_{in}$, $Q_{out}$ = rates of inflow and outflow of atmospheric moisture

$R$ = net total rate of surface and groundwater runoff of water from the land

$W$ = stored atmospheric moisture

$S$ = stored soil moisture

$E$ = rate of evapotranspiration

$P$ = total rate of precipitation = $P_m + P_a$

$P_m$ = rate of precipitation of 'recycled' (i.e. evaporated within the column) moisture

$P_a$ = rate of precipitation of moisture convected atmospherically into the column.

We will call the average horizontal displacement of a recycled water molecule from '$E$' to '$P$', the '*hydrologic scale'*; it changes with climate. The horizontal dimension of the column in Fig. 1 is that of the problem of interest (i.e. watershed, river basin, continent, etc.) and we call it the '*geographical scale*'. $P$ may be assumed independent of $E$ whenever the hydrologic scale exceeds the geographical scale. Such is the case for small watersheds except perhaps in the tropics where horizontal atmospheric motion is weak. This independent precipitation, in which the surface is decoupled from the atmosphere, is the dynamic situation corresponding to the classical hydrologic model in universal use through the middle of this century. It is represented by the simple linear cascade illustrated in Fig. 2.

At the large geographical scales necessary to consider issues such as global change, the feedback fluxes are important

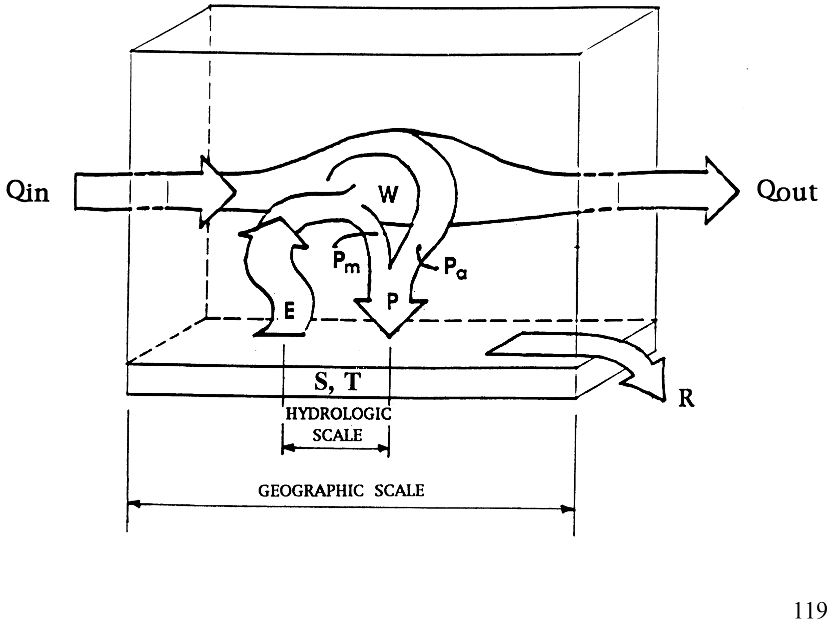

**Fig. 1** The flow paths of atmospheric moisture [10].

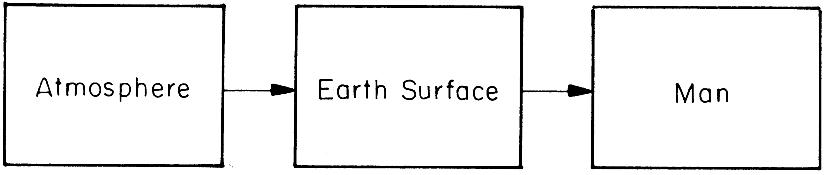

**Fig. 2** Classical concept of the hydrologic system [12].

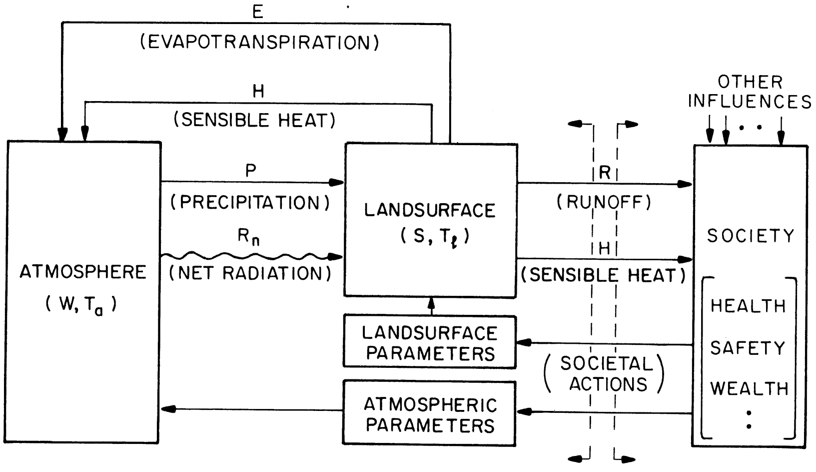

**Fig. 3** Modern concept of the hydrologic system [11].

determinants of the precipitation, so the atmosphere and surface must be considered as a coupled (often highly non-linear) system. This is the modern model of the hydrologic system and is illustrated here in Fig. 3.

## HYDROLOGIC TELECONNECTIONS

The complex dynamics of Earth's coupled fluids, oceans–atmosphere–soil moisture, contain a wide spectrum of periodic components. The higher, multi-year periods (i.e. low frequencies) originate in the response of the large ocean masses to their forcing by solar heating and planetary motions while constrained by the size and shape of the ocean basins. The lower periods (i.e. high frequencies) are characteristic of the low density, low heat capacity, thermodynamically active atmosphere. The response characteristics of these very different fluids are most closely matched in the tropics due to the sharp ocean stratification and deep atmospheric convection there. It is there that their primary dynamic coupling occurs. Being the principal moisture and solar energy reservoirs for the hydrologic cycle, the tropical oceans force hydrologic responses at corresponding periods in the tropical atmosphere. The atmosphere then transfers energy and water mass down a cascade of thermodynamically induced internal motions of ever-diminishing scale and period, as it transports energy and water mass rapidly over great distances and into higher latitudes. In contrast, the land surfaces constitute relatively immobile energy and moisture reservoirs whose dynamics are 'over-damped' in that they have negligible natural oscillations of their own. As such they respond and feedback to the local atmosphere with a decreasing intensity as the excitation period shortens. The dynamic connection of ocean forcing atmosphere followed by atmosphere forcing distant landsurface is called a hydrologic 'teleconnection' after the pioneering observations of Namais [1], and it has obvious potential for long-range forecasts having great economic value. The allied teleconnection arising from land surface forcing atmosphere at point 'A' followed by atmosphere forcing landsurface at pont 'B' also has forecasting utility. However, in comparison with the former, it is: (i) shorter in temporal and spatial range due to the absence of oceanic involvement; and (ii) weaker due to the dispersal of energy and water mass across a spectrum of forcing frequencies. The variable dependence of the local land surface precipitation upon the local land surface moisture state raises the interesting possibility of dynamically generated persistence in the climate of land surfaces [2].

Several hydrologic teleconnections have been empirically recognised for some time. Regional and global scale numerical models of the coupled land surface, atmosphere, and ocean are now providing the geophysical justification necessary for confident use of these teleconnections for forecasting purposes.

## OCEAN–ATMOSPHERE COUPLING

Principal among the recognised oceanic teleconnections is 'El Niño', the quasi-periodic appearance of a warm surface water anomaly in the Eastern tropical Pacific Ocean due to ocean–atmosphere coupling. Associated with El Niño through atmo-

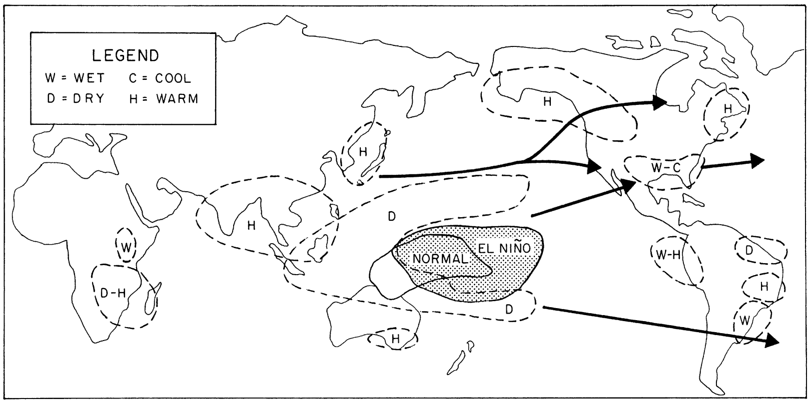

**Fig. 4** The long reach of El Niño [3].

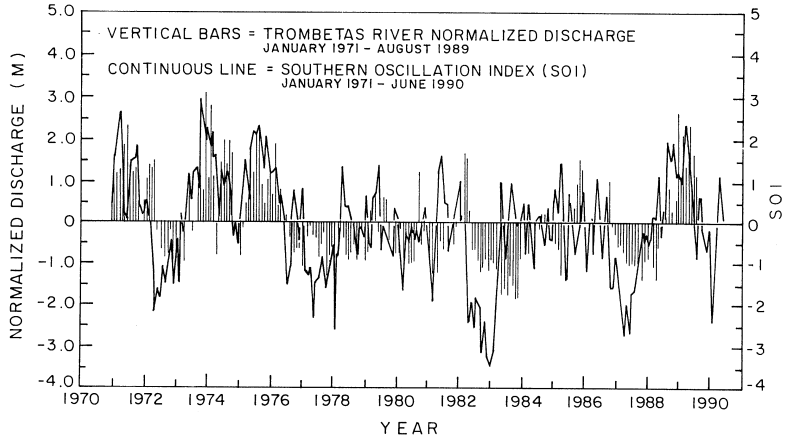

**Fig. 5** Correlation of Trombetas River flow and the SOI [4].

spheric teleconnections are anomalous moisture and temperature conditions at distant locations as is shown in Fig. 4 [3]. One of these teleconnections, which illustrates the practical importance of large-scale hydrologic understanding, is the El Niño-induced area of dry conditions in Eastern Brazil containing the headwaters of the Trombetas River. Figure 5 [4] shows the strong correlation between the normalised monthly flow in the Trombetas River (vertical lines) and the Southern Oscillation Index, SOI (continuous line), which is the normalised difference in surface atmospheric pressure between Tahiti and Darwin. Large negative values of the SOI indicate the presence of El Niño. In addition to the approximately 6-month time lag between the SOI and the streamflow apparent in Fig. 5, numerical models of the El Niño mechanism can forecast its appearance by nearly 2 years [5]. There is thus the potential for 2-year forecasts of monthly streamflow in the Trombetas which could have great utility in engineering activities such as reservoir management.

In a similar fashion Eltahir [6] has shown a high negative correlation between the average annual flow in the Nile River and the SOI as is shown in Fig. 6.

## LAND SURFACE–ATMOSPHERE COUPLING

Strong observational evidence exists of land surface teleconnections driven by regional snow cover [1,7]. As an example, the Indian summer monsoon rainfall and the Himalayan snow cover of the previous winter are compared in Fig. 7.

The theoretical explanation for this and other observed land surface teleconnections is not obvious and will be found only with the aid of large-scale numerical models of the coupled land surface and atmosphere. In these models, the hydrologic states and fluxes at the land surface are necessary boundary conditions to the fluid and thermodynamic equations governing the atmospheric physics. At vegetated land surfaces these boundary conditions involve biological states and fluxes which are not determined by the familiar conservation equations of fluid dynamics, and the geometrical structure of the plant canopy modulates the biophysical interaction of the atmosphere–plant–soil system. Our research suggests that we can formulate in physical terms the natural selection processes that determine the canopy configuration and that fix the average vegetal fluxes under equilibrium conditions. These

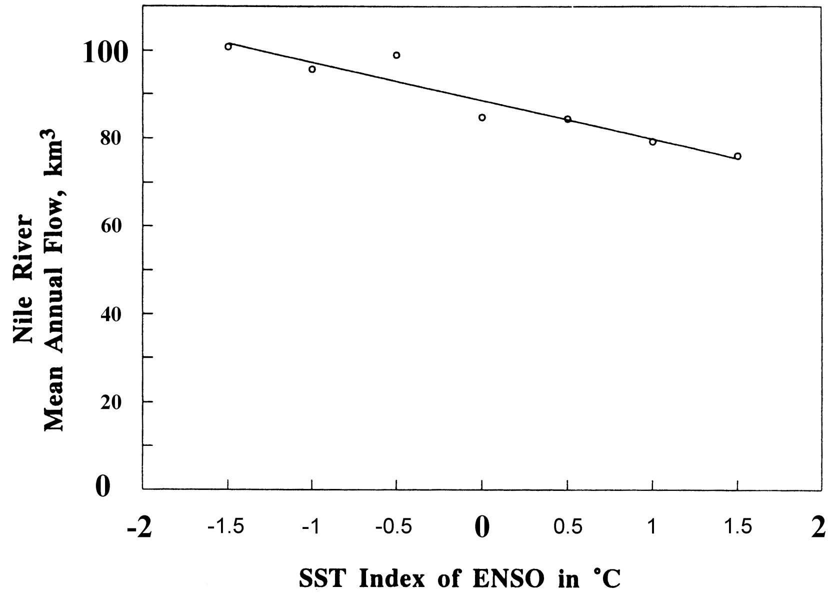

**Fig. 6** Correlation of Nile River flow and the SOI [6].

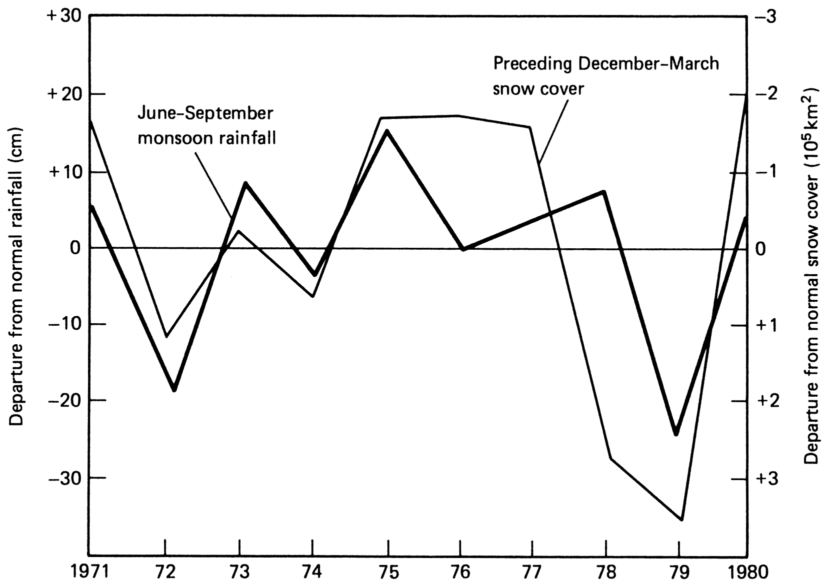

**Fig. 7** Correlation of Indian summer monsoon rainfall and Himalayan snow cover of preceeding winter [7,13].

additional equations should facilitate writing an approximate dynamic land–surface boundary condition in which the canopy structure is not prespecified but is instead determined by the climate and soil in a truly interactive process. Such capability is needed in order to deal realistically with climate change.

## BIOPHYSICAL BOUNDARY CONDITIONS AT THE LAND SURFACE

We describe the average rate of transpiration of the plant community in terms of its two primary state variables: (i) the fractional coverage or 'canopy density', $M$, and (ii) the species-dependent transpiration efficiency, $k_v$, which is the ratio of transpiration to bare soil potential evaporation, $E_p$. These take their place in the expression of long-term average (i.e. climatic) water balance as

$$P = (1 - M)\,\beta(S)\,E_p + M\,k_v\,E_p + R(S), \qquad (1)$$

in which $\beta$ is the bare soil evaporation efficiency. How does nature select the values of $M$ and $k_v$ for a given climate and soil?

If we choose a particular vegetation type $k_v$ is fixed, and with a given climate and soil, Eqn 1 gives a single soil moisture state, $S$, and a single evapotranspiration, $P - R(S)$, for each value of

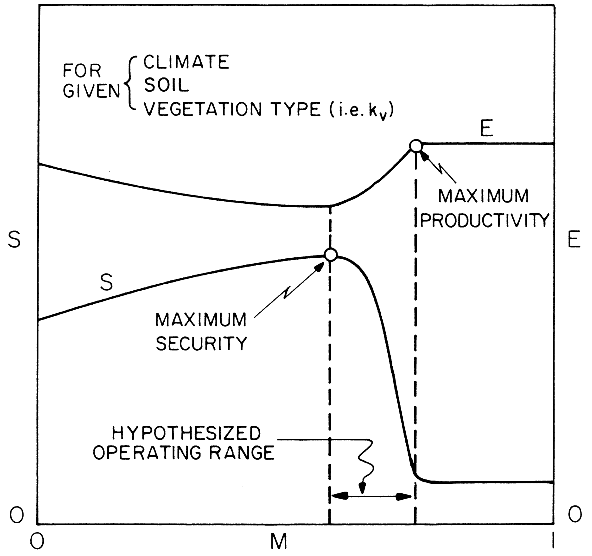

**Fig. 8** Solutions of the climatic water balance equation in water-limited case [9].

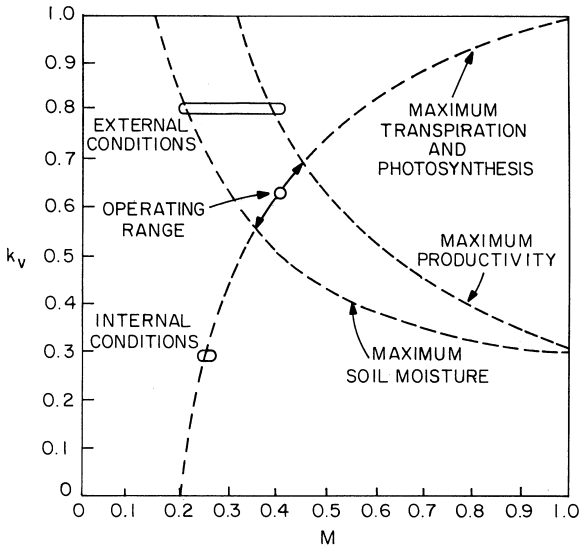

**Fig. 9** Canopy state variables as determined by natural selection (fixed climate, soil and vegetal species).

*M* as is shown in Fig. 8. The intermediate *M* at which *S* is a maximum is a condition of maximum security for the canopy since it implies minimum water-demand stress and hence high resistance to disease. The different, intermediate *M* at which *E* is a maximum is a condition of maximum biological productivity since the latter is directly proportional to canopy water use [8]. Accordingly, it seems reasonable to assume that natural selection will fix the canopy equilibrium value of *M* for a given species at a value within the 'operating range' given by these two maxima; in seeking to maximise reproductivity, the plant will maximise biological productivity to the extent that proves compatible with its own security given the local variability of climate. Limited observations support this hypothesis [9] which we call the *external conditions* of optimality.

For a given canopy density, our research suggests that the transpiration efficiency, $k_v$, is selected by an *internal condition* of canopy structure which maximises the transfer of both moisture and light between canopy and atmosphere; this too assures the maximisation of biomass production.

Finally, natural selection will satisfy both the internal and external conditions simultaneously thereby fixing both *M* and $k_v$ as is illustrated in the sketch of Fig. 9.

## CONCLUSION

Exploiting the natural determinism of climate can reduce the uncertainty in long-range hydrological forecasting. This is possible through global-scale numerical models that capture the essential couplings of the land surface and atmosphere as well as those of the oceans and atmosphere. Vegetation plays a key role in the land surface–atmosphere interaction, but its 'equation of state', which is a boundary condition for the equations governing the atmospheric motion, is unknown. Ongoing research determines the canopy equilibrium state from natural selection hypotheses.

## BIBLIOGRAPHY

1 Namais J. Influences of abnormal surface heat sources and sinks on atmospheric behavior. *The Proceedings of the International Symposium on Numerical Weather Prediction*, Tokyo, 1960, Meteorological Society of Japan, 1962: 615.
2 Rodrguez-Iturbe I, Entekhabi D, Bras RL. Non-linear Dynamics of Soil Moisture at Climate Scales. *Water Resources Res* 1991; **27**(8): 1899.
3 Kerr A. A successful forecast of an El Niño winter. *Science* 1992; **255**: 402.
4 WMO–UNEP. *The Global Climate System: Climate System Monitoring, December 1988–May 1991*. Geneva, 1992: 41.
5 Cane MA, Zebiak SE. A theory for El Niño and Southern Oscillation. *Science* 1985; **228**: 1085.
6 Eltahir EAB. El Niño and the natural variability in the flow of the Nile River. *Water Resources Res* 1996; **32**(1): 131.
7 Dey B, Branu Kumar OSU. Himalayan winter snow cover area and summer monsoon rainfall over India. *J Geophys Res* 1982; **88**: 5471.
8 Rosenzweig ML. Net primary production of terrestrial communities: prediction from climatological data. *Am Nat* 1968; **102**: 67.
9 Salvucci GD, Eagleson PS. *A test of ecological optimality for semiarid vegetation*. R.M. Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, MA, USA, Report 335, 1992.
10 Brubaker KL, Entekhabi D, Eagleson PS. The Implementation and Validation of Improved Land-Surface Hydrology in an

Atmospheric General Circulation Model. *J Climate* 1993; **6**(6): 1077.

11 Eagleson PS. The evolution of modern hydrology (from watershed to continent in 30 years). *Adv Water Resources* 1994; **17**: 3.

12 National Research Council. *Scientific basis of water resource management*, National Academy Press, Washington, DC, 1982: 32.

13 Walsh JE. Snow cover and atmospheric variability. *Am Scientist* 1984; **72**: 50.