The Role of Water in Climate[1]

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WATER, because of its unique physical properties and its omnipresence on our planet, plays a central role in the workings of the *Earth system* (i.e., the oceans, atmosphere, soils, and biota). The momentary state of the local atmosphere with respect to wind, temperature, cloudiness, moisture, pressure, etc. is known as *weather.* Its predictability is limited to about two weeks due to the intrinsic variability of its components. The average weather over some longer period of time (usually thirty years) is called *climate* and is naturally variable. It fluctuates with periodicities of 100,000, 41,000, and 21,000 years because of predictable variations in Earth's orbit, and it also changes irregularly both as a part of the intrinsic dynamics of the system and from unpredictable influences such as volcanic eruptions and solar flares. Contemporary concern for man's influence on climate is clarified through an understanding of the global water cycle and of man's effect thereon.

THE UNIQUENESS OF WATER[2]

Water has unique physical and chemical properties that give it essential roles in regulating the "metabolism" of our planet along with that of its resident life forms:

- *Elixir of life.* The unusual molecular structure of water makes it an almost universal solvent; no other liquid can dissolve such a wide variety of compounds. Because cell membranes are permeable only to certain dissolved substances, water is often called the elixir of life, essential—as are blood and lymph—both for the nourishment of cells and for the removal of their wastes. It plays this same role at all higher levels of life's organization.

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[1] Read 24 April 1998.

[2] This section is taken from the opening chapter (written by the author) in *Opportunities in the Hydrologic Sciences*, 348 pp., National Academy Press, Washington, D.C., 1991.

- *Global heat exchanger.* The range of temperatures and pressures on Earth's surface are such that water is plentiful in its life-supporting liquid state and yet moves freely and vigorously to its vapor and solid states as well. Such is not the case on the other planets in our solar system. When changing among its liquid, vapor, and solid states (at constant temperature), a gram of water absorbs or yields more heat (called *latent* heat) than do most substances. Latent heat is absorbed for evaporation of water and melting of ice, while latent heat is released upon condensation of vapor and freezing of water. Such phase changes of water on Earth are powered by the Sun. Solar energy stored in water vapor as latent heat during evaporation travels with the vapor in the atmospheric circulation until it is released when and where the vapor condenses into precipitation. In this way both water and heat are redistributed globally.
- *Climatic thermostat.* A gram of water can absorb more heat for each degree of temperature rise than can most other substances. This gives water a correspondingly large "thermal inertia" (i.e., its temperature tends to stay the same), making the oceans the flywheel of the global heat engine.
- *Greenhouse gas.* Water vapor is an efficient "greenhouse" gas in that it is transparent to the incoming short-wave radiation from the Sun but is opaque to the long-wave radiation leaving Earth. At current concentrations it is responsible for about twice as much greenhouse heating as is carbon dioxide! More important, and to the first approximation, a one-degree increase in atmospheric temperature causes a 6 percent increase in water vapor (Mitchell et al., 1987), which leads to further warming and a positive feedback between atmospheric temperature and water vapor (Mitchell, 1989).

THE HYDROLOGIC CYCLE

Water circulates continuously throughout the Earth system in a solar-powered process called the *hydrologic cycle*, which is as important to that system as our circulatory system is to humans (N.R.C., 1991).

While this cycle occurs at all scales from that of a single leaf to the whole planet, its primary elements are typically as follows: evaporation from the liquid state to the vapor state at Earth's surface; vapor transport to a new location by motion of the atmosphere; condensation into the liquid state as a result of cooling in these new surroundings; precipitation of the liquid back to Earth's surface. It is of fundamental importance to remember that the latent heat of vaporization added to the water at its evaporation site is subsequently given up by the vapor to the surrounding dry air at its condensation site as the vapor reverts there to liquid form. This is the heat engine that powers atmospheric motion and thereby redistributes both water mass and solar energy around the globe. At this global scale the hydrologic cycle is the primary determinant of climate and may be simplified as follows:

- Solar energy is absorbed by the surface at the equator where the radiation intensity is maximum and water is plentiful (i.e., 75 percent of the equatorial surface is ocean).
- Strong equatorial evaporation puts lots of water vapor and its accompanying latent heat into the surface air.
- Hot, moisture-laden surface air rises to the upper atmosphere in vertical convective plumes.
- Condensation of some of this moisture at cooler, high elevations causes tropical precipitation and releases the associated latent heat that generates lateral atmospheric motion.
- Remaining water vapor and its latent heat are transported by this high altitude atmospheric motion to higher latitudes where Earth's rotation imparts a west-to-east component to the wind. The maximum of this wind defines what we call the *jet stream*. The tall convective plumes act like boulders in the stream of west-to-east upper air flow (UCAR, 1994), setting up stationary waves in the jet stream that guide the path of storms across Earth's surface as we are shown nightly on the television news.
- Drier air descends in cooler latitudes and as it flows equatorward to complete the large-scale atmospheric circulation, Earth's rotation imparts an east-to-west component to the surface wind. In the tropics these winds are called the *prevailing easterlies*.

We see from the above that water is not just a passenger on the passing breeze, but to a large extent creates the breeze that transports it! Furthermore, the "head bone" of this circulatory system is connected to its "ankle bone." That is, a change in the evaporative conditions *here* will lead to a change in precipitation *there*, providing a mechanism for long-range environmental impact. For example, water evaporated from the forests of Southeast Asia next appears as precipitation in eastern China and over much of the United States.

THE OCEAN–ATMOSPHERE SYSTEM

Solar energy enters the ocean–atmosphere system primarily by heating the upper water of the ocean. From there energy flows to the atmosphere and back to the ocean with losses to space and continual degradation in its ability to do useful work. Because of the great difference in their masses, the ocean and the atmosphere have distinctly different dynamic properties. Like the separate instruments in an orchestra, they will respond at different frequencies when disturbed by external forces. Continuing this convenient (but inexact) musical analogy, we can imagine the atmosphere and the ocean as separate drumheads stretched over the spherical frame of Earth. Each drumhead is "struck" by energy flowing from the other drumhead, and both are perturbed periodically by the motions of Earth and its moon. The atmosphere receives both latent and sensible heat from the ocean as is described above, while the ocean receives mechanical energy from the atmosphere through the frictional drag of wind at the interface. The "heavy" oceans are the bass drums of this ensemble with the major responses having periods of months, while the "light" atmosphere is the snare drum, and responds in days or weeks. This dynamic sluggishness coupled with its thermal inertia makes the oceans responsible for both persistence and long-term periodicity in the seemingly random behavior of the Earth system, qualities that when understood offer the benefits of long-range forecasting.

The ocean surface evaporation–atmospheric moist convection process is so strong at the equator that it acts there to couple the atmosphere and the ocean into a single complex body exhibiting a continuous irregular joint oscillation known as the *Southern Oscillation.* Philander (1998) has called this oscillation the ". . . spontaneous music" of the coupled Earth system, and the score goes something like this (Enfield, 1989; Allan et al., 1996):

- Intense solar heating stratifies the equatorial ocean into a warm (light) surface layer separated by the so-called *thermocline* from the cold (heavy) underlying remainder.
- Hot air rises in the tropics, acquires a west-to-east velocity as it flows poleward at high altitude, descends in colder latitudes, and returns to the tropics with strong prevailing east-to-west surface wind.
- The easterly winds drag the heated surface waters of the equatorial Pacific Ocean toward its Southeast Asian boundary, thereby tilting the thermocline down in the west, up in the east, and forcing the underlying cold water to rise to the surface along that ocean's South American boundary. These widely separated pools, having contrasting surface water temperature, generate evaporation and convective rising of moist air in the west, as well as descending dry air in the east, thereby supporting respectively the moist monsoonal climates of Southeast Asia and the coastal deserts of South America, while augmenting the tropical easterly surface winds.
- So goes the diminuendo phase of the Southern Oscillation, which is sometimes called *La Niña.*

The existence of this phase of the tropical ocean–atmosphere circulation is apparently unstable and, in a manner still to be completely defined, contains the seeds of its own destruction (Enfield, 1989; Picaut et al., 1997).

- On the thermocline there appears a system of waves that, in its successive six- to twelve-month transits and retransits of the Pacific, acts to erode the trans-Pacific slope of the thermocline, thereby weakening the tropical easterly winds and allowing the surface hot spot (generator of the atmospheric convective plumes) to slosh eastward to the central Pacific.
- This shift of the "boulders" in the west-to-east upper air stream causes a reorientation of the jet stream guiding the global atmospheric transport of water vapor and latent heat.
- This crescendo phase of the Southern Oscillation is known by the now-familiar name *El Niño*.
- As the internal waves disperse over one to two years time their effect weakens, La Niña circulation is slowly reestablished, and then the cycle recurs with a three- to seven-year period.

The strength of the tropical circulation associated with the Southern Oscillation and the amount of energy and moisture pumped by it into the upper atmosphere constitute a major determinant of climate in extra-tropical regions, particularly in North America. In particular, the El Niño circulation brings higher than normal precipitation to predictable locations, particularly the southern U.S., Peru, and the headwaters of the river Nile. Other areas are predictably hot and/or dry. Recognition of these long-distance atmospheric "teleconnections," and understanding of the deterministic physics of the causative ocean–atmosphere oscillation allow forecasting the onset and duration of El Niño conditions over a year in advance, thus providing agriculturalists, engineers, epidemiologists, public administrators, insurance underwriters (and even commodity futures speculators!) with valuable advance information (Trenberth, 1997).

Land Surface–Atmosphere Boundary

The interaction between *land* and atmosphere is heavily modulated by the amount of water in the pores of the soil. Some of this water also becomes involved in the evaporative exchange of mass and energy with the atmosphere, although at much lower rates than from the ocean because of the added resistance to water movement provided by the soil.

Vegetation appears on the soil surface with a density dependent upon the soil moisture concentration. In their metabolic processes plants also transfer soil moisture into the atmosphere through evaporation from the pores of the leaves known as *transpiration.* In a given climate, transpiration by plants is more efficient than is evaporation from bare soil as a means of transferring moisture and heat from the land to the atmosphere (Eagleson, 1978). Furthermore, merely 30 percent of Earth's surface is land and only 65 percent of that (20 percent of Earth's surface) is vegetated in one form or another (Perrier, 1982, Table 1, p. 404), so transpiration is clearly a secondary player in the global-scale transfer of heat and moisture. However, it can be an important determinant of local climate, particularly in continental interiors.

SUMMARY

Evaporation of water and its recondensation elsewhere is the primary energy source for atmospheric motion. By this motion, the movement of both moisture and heat from tropical to higher latitudes becomes the primary determinant of climate.

As we learn to identify and express more of the deterministic (as opposed to the random) processes of the Earth system, we can expect improved useful forecasts of climate fluctuations and change.

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