

The Emergence of Global-Scale Hydrology

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Emerging problems of environmental change and of long range hydrologic forecasting demand knowledge of the hydrologic cycle at global rather than catchment scale. Changes in atmosphere and/or landscape characteristics modify the earth's metabolism through changes in its biogeochemical cycles. The most basic of these is the water cycle which directly affects the global circulation of both atmosphere and ocean and hence is instrumental in shaping weather and climate. Defining the spatial extent of the environmental impact of a local land surface change, or identifying, for forecasting purposes, the location and nature of climatic anomalies that may be causally linked to local hydrologic persistencies requires global scale dynamic modeling of the coupled ocean-atmosphere-land surface. Development, evaluation, verification, and use of these models requires the active participation of hydrologists along with a wide range of other earth scientists. The current state of these models with respect to hydrology, their weaknesses, data needs, and potential utility are discussed.

INTRODUCTION

For the last century the development of hydrology has been largely in the hands of civil and agricultural engineers working on the classic problems of water supply and natural hazard reduction. The scale of their interest has been primarily that of the catchment with the atmosphere being considered an independent driver of the hydrologic processes.

In recent years, however, the important hydrologic problems of the temperate zones have expanded to a scale commensurate with that of the atmospheric water cycle in those latitudes, and interest is growing in the tropics where the atmospheric and catchment scales are comparable. Hydrologists are now being forced to consider the atmosphere and the land surface as an interactive coupled system, a perspective which draws us closer to the geophysicist's viewpoint of global scale processes. In this paper I hope to make the case for a global scale hydrologic perspective.

GLOBAL ENVIRONMENTAL CHANGE

The atmosphere, hydrosphere, and surface layers of the Earth have arrived at their present characteristics through a coevolution of living and nonliving components. The picture as revealed by paleoclimatologists is one of large-scale natural processes undergoing cycles of dynamic change on a wide spectrum of time scales, from years to hundreds of thousands of years, accompanied synergistically by the evolutionary development of life forms. An example of the evidence for this natural change is offered by the fossil pollen record in North America since the peak of the last ice age 18,000 years ago as determined by Webb and coworkers (Webb et al., unpublished manuscript, 1977) see, for example, *Bernabo and Webb* [1977] and is presented in Figure 1 as taken from *Kerr* [1984]. An increase in summer solar radiation and the retreat of the ice sheet caused the oak and northern pine forests to withdraw to the north and at the same time developed our southern pine forests.

Humans have been altering the environment over large geographic areas for over 10,000 years through their domesti-

cation first of fire and then of plants and animals [*Saga et al.*, 1979]. Early civilizations destroyed the temperate forests of China and the Mediterranean Basin, and modern civilizations have greatly reduced the temperate forests of Europe and North America.

In the last 500 years the hand of man has been increasingly felt on the biogeochemical cycles that control the Earth's metabolism. Energy production, farming, urbanization, and technology have altered the albedo of Earth, the composition of its soil and water, the chemistry of its air, the amount of its forest, and the structure and diversity of the global ecosystem. Approximately 40% of the Earth's land area is now under the active management of man with more than 10% being under cultivation [*Olson et al.*, 1983, pp. 20-21]. Chemical compounds having no analogs in nature are being introduced into both air and water at increasing rates.

Most recently the tropical forests have come under attack. *Meyers* [1979] estimated that Latin America has lost 37% of its original rain forest (largely to agricultural development), Southeast Asia has lost 38% (principally to logging), and Africa has lost over 50% (primarily to slash-and-burn agriculture).

The alteration of ground cover affects surface albedo and runoff, changes the ratio of sensible to latent heat transport, alters surface winds and erosion rates, and changes the thermal and moisture state of the surface. The microclimates of forested and cleared areas differ markedly. In tropical regions such as the Amazon basin where soils are typically poor, their exposure to sunlight may produce chemical and structural changes that inhibit either agriculture or reforestation and introduce erosion in the presence of the heavy precipitation. In subtropical regions, such as central Africa, where precipitation is limited, a forest ecosystem appears to be unstable [*Eagleson and Segarra*, 1985] and its destruction leads to a stable tree-grass savanna. Such has been the fate of 40% of the African equatorial forests as a result of slash-and-burn agriculture [*Phillips*, 1974].

The global cycle of water is perhaps the most basic of all the biogeochemical cycles. In addition to its strong influence on the other cycles (e.g., carbon, nitrogen, phosphorus, sulfur), it directly affects the global circulation of both atmosphere and ocean and hence is instrumental in shaping weather and climate. Planning and/or construction is underway on various macroengineering water projects which, through their modifi-

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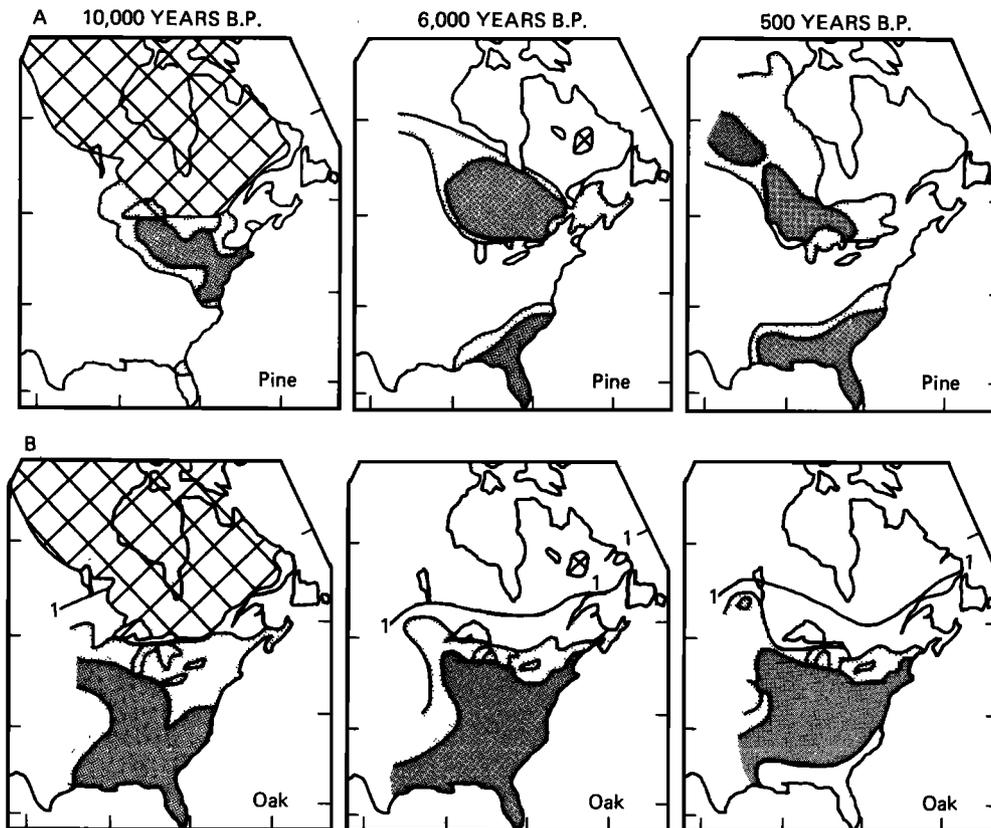


Fig. 1. Vegetation change in eastern North America during the past 10,000 years. Crosshatched area is ice sheet. Contour is 1% oak. Light stippling is 5–20% oak or 20–40% pine. Heavy stippling is greater than 20% oak or greater than 40% pine. (From Kerr [1984], *Climate since the ice began to melt*, *Science*, 226, 326–327, copyright 1984 by the American Association for the Advancement of Science.)

cations of regional hydrology, promise to contribute their own distortions to the course of environmental change.

One example is the drainage of the immense swamps of the White Nile's Sudd region in order to capture for downstream uses some of the water now lost by evapotranspiration. The permanent swamps are on the order of 34,000 km² in surface area and if solely the dry-season evaporation from this surface could be captured it would amount to some 25×10^9 m³ annually, which is more than the current annual flow of the White Nile at Khartoum [Chan and Eagleson, 1981]. The loss of this atmospheric water and its associated latent heat would surely be felt climatically. The first phase of this project, the 360-km Jonglei canal, is nearly complete.

Another project is the diversion of several Soviet rivers away from their current northward flow. The project has two parts: a European portion now under way which will divert the Sukhona and Onega Rivers southward, away from the White Sea, to irrigate 2.5 million acres in the northern Caucasus, and a Siberian portion which if undertaken would send the Ob and Irtysh rivers to the arid regions around the Aral Sea instead of into the Kara Sea. By depriving the Kara Sea of a large fresh water inflow, this latter diversion may alter the ice cover and thus change the regional albedo.

Both the deforestation and the proposed macroengineering projects act to create anomalous regional moisture and/or heat sources (or sinks) the effects of which may, in theory at least, propagate to distant regions via atmospheric dynamics [Webster, 1982]. As possible examples of such "tele-

connections," as they have come to be called, we cite first the striking negative correlation between the winter snow cover over Eurasia and the intensity of the following summer monsoon in India. As was pointed out by Walsh [1984], this inverse relation (see Figure 2) is consistent with the argument that widespread snow cover leads to lower springtime air temperatures and hence to higher sea level pressures over southern Asia which oppose the normal monsoonal pressure gradients. Of course, the correlation does not establish causality. A similar correlation has been found both observationally and with atmospheric general circulation model (GCM) experiments between drought in northeast Brazil and positive sea surface temperature anomalies in the tropical Atlantic.

Much similar evidence has been assembled to support teleconnections between sea surface temperature anomalies in the eastern tropical Pacific Ocean (El Niño) and middle-latitude atmospheric circulation in the winter hemisphere (see, for example, Horel and Wallace [1981]), and between sea surface temperature anomalies in the Atlantic Ocean off West Africa and sub-Saharan drought [Lamb, 1978].

The climatic effects of anomalies in land surface conditions have been established observationally at local and regional scale as a result of urbanization [Landsberg, 1974] and irrigation [Schickedanz, 1976; Stidd, 1975]. At continental and global scale the sensitivities have been established through numerical simulations as summarized by Mintz [1984].

The evidence is overwhelming that regional anomalies in the surface state of the Earth as given by its albedo, temper-

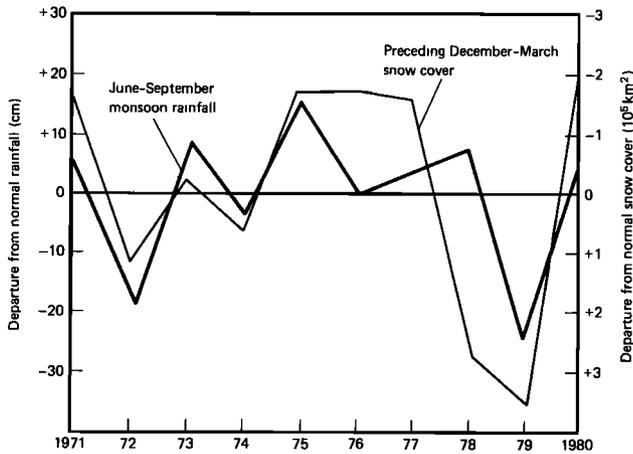


Fig. 2. Indian summer monsoon rainfall and Himalayan snow cover of preceding winter (from Walsh [1984] as adapted from Dey and Kumar [1983]).

ature, and wetness have local and sometimes also far-reaching effects upon the atmospheric temperature, humidity, and precipitation.

But man's effect on the hydrologic cycle is not limited to these physical issues. His use of the atmosphere for disposal of civilization's gaseous wastes has altered the chemistry of precipitation with serious consequences for fish and other aquatic organisms, crops, forests, wetlands, soils, and even buildings. There is a potential here for damage to human health as well and this is beginning to attract serious study [Maugh, 1984]. The acidification of water supplies brings increased concentration of potentially toxic metals such as lead, cadmium, mercury, and aluminum in that water; the metals are leached from the soil and from sediments and from the pipes and fixtures used in water supply systems. Of particular concern are lead, which is in widespread use as a liner in the cisterns of rural roof catchment systems, and aluminum, which comprises about 5% of the Earth's crust.

Aluminum is practically insoluble in water of neutral or low (alkaline) pH and thus has not been historically available biologically. Within the last decade however high concentrations of aluminum have been found in brain, muscle, and bone tissues of patients who have been under long-term dialysis at centers where there is significant aluminum in the water. With the advent of nuclear magnetic resonance (NMR) scanning, high concentrations of aluminum have been found in the brain tissue of many patients with Alzheimer's disease and with senile dementia. Autopsies on victims of certain other central nervous system disorders at isolated locations having abnormal incidence rates have shown similar high concentrations of aluminum. Whether there proves to be a causal relation in these examples or not, the specter of unsafe drinking water adds further motivation to understand the pathways for the global dispersal of atmospheric pollutants.

QUESTIONS OF LARGE-SCALE HYDROLOGY

The case for global-scale hydrology can be made at small scale. Consider the question of the local environmental impact from local land surface change. Will drainage of the swamps reduce the local precipitation? The portion of local precipitation derived from local evapotranspiration was estimated at about 10% Budyko and Drozdov [1953] for the European

U.S.S.R., and at about the same percentage by Benton *et al.* [1950] for the Mississippi valley. However, Lettau *et al.* [1979] found places in the Amazon basin where as much as 71% of the precipitation appeared to come from locally evaporated water. Salati and Vose [1984] estimate 48% recycling for the Amazon Basin as a whole. As was concluded by Shukla and Mintz [1982], evaporation change can affect local precipitation but the strength of the recycling will vary from region to region depending on how the large-scale circulation is modified. The recycling can be verified only through tracer experiments or estimated using global-scale modeling.

An allied question seeks the geographical influence function of a local land surface change; that is, What locations will feel the effects of a land surface change here? Reduction of evaporation in the Sudd will reduce the precipitation where? By how much? Answers call for tracer studies in global-scale models.

The inverse of this question is of interest for those concerned with identifying the source of their precipitation; that is, Where was the water last evaporated that falls locally as precipitation? Where can we look for climatic anomalies that may be linked to local hydrologic persistencies?

Again, we need global-scale models to define this atmospheric moisture replacement distance. As was pointed out by Eagleson [1982], the lateral scale of a proposed land surface change will have to exceed this replacement distance before the feedback loop can close to create a downwind amplification of the original disturbance.

These hydrologic scales and feedbacks are seasonally as well as geographically variable. During the winter months, the continental land surfaces are net sinks for atmospheric moisture picked up over the oceans, while in the summer, when thermal convection is the primary precipitation mechanism, the depletion of soil moisture by evaporation and transpiration transforms the continents into net sources of atmospheric water. Understanding these scales is critical to forecasting the location, size, and strength of anomalies in the cycle and in defining the environmental impacts of land surface changes. These scales are largely unknown and should be determined for all regions of the globe and for all seasons of the year.

The hope for significant improvement in the accuracy and lead time of local long-range hydrologic forecasting, so important to agriculture, lies in establishing teleconnections to the climatic flywheel: the oceans. The GCM with coupled dynamic ocean provides these teleconnections implicitly.

Conditioned as we are by the traditional engineering demands of water supply and flood protection, hydrologists often lose sight of the broad definition of their field [Federal Council of Science and Technology, 1962] which includes that part of the hydrologic cycle involving the oceans. Actually, the distribution of precipitation and evaporation over the ocean plays an important role in establishing ocean circulation and hence global climate. An example is the formation of deep water in the northern Atlantic Ocean.

The best estimates available suggest that evaporation exceeds precipitation and continental runoff on the North Atlantic Ocean and its adjacent seas by about 15%, this deficit being replaced by ocean circulation. The excess evaporation results in a salinity and hence density increase which must be balanced by an exchange for less salty water from another ocean. It is thought that the exchange occurs through a sinking and southward flow of the saline surface waters in the North Atlantic accompanied by a shallow northward return flow of less salty water from the Antarctic. Warmed as it

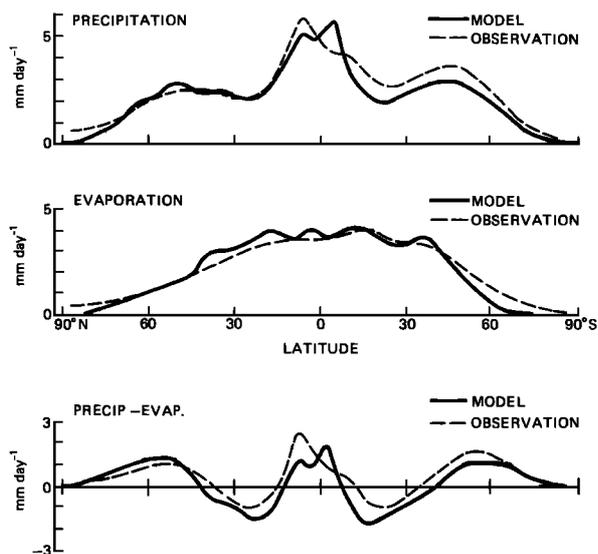


Fig. 3. Zonally averaged mean annual precipitation and evaporation; comparison of model and observations [from Mitchell, 1983].

passes through the tropics, this returning surface water carries heat to the North Atlantic and upon evaporation transfers much of this to the atmosphere where it becomes responsible for the moderate climate of northern Europe.

Our quantitative knowledge of the oceanic branch of the global hydrologic cycle is quite poor. What are the water balances of the various ocean basins? We have very poor knowledge of the oceanic fluxes due to precipitation and evaporation let alone those due to continental groundwater discharge and to sea floor vents. Observational difficulties suggest that in the short term at least global models will provide our best estimates of oceanic precipitation and evaporation.

GLOBAL HYDROLOGIC MODELING

Atmospheric general circulation models are based on the fundamental equations that describe the dynamics and energetics of fluid motion. These include the equations of motion (conservation of momentum), the first law of thermodynamics (conservation of energy), the continuity equations for air mass and water vapor (conservation of mass), and the ideal gas law (approximate equation of state). These equations are solved numerically on a grid having a horizontal resolution on the order of 5° (i.e., several hundred kilometers) and with as many as 12 vertical layers up to an atmospheric limit of, say, 10 mbar. The computational time step at this resolution is about 7 min. Of course, each of the "prognostic" (i.e., independent) atmospheric variables, wind, temperature, pressure or density, and humidity, must be given an initial condition at each node of the solution net, and a boundary condition at each surface node. Early models prescribed fixed boundary values but more recently interactive boundary conditions of progressive sophistication have been introduced; first, for the land surface [Manabe, 1969], second, for the oceans [Manabe and Bryan, 1969], and currently for the vegetation [Mintz *et al.*, 1983]. For example, at the ground surface current GCMs calculate the temperature and soil moisture concentration using approximations of the surface heat and water balances. Other "diagnostic" variables such as cloudiness, precipitation, surface radiative flux, surface sensible heat flux, evaporation,

runoff, and snow cover are estimated from parameterizations which relate these subgrid-scale processes to the large-scale variables that are resolved by the model [Gates, 1983].

After the global solution of these equations has been advanced in time for a period of perhaps several years, the time-averaged prognostic variables approach constant values which define the model climate. At this time comparisons with global distributions of observed average annual and average seasonal quantities can be made. At the current state of model development typical comparisons of zonally averaged (i.e., circumferentially averaged) annual average precipitation and evaporation agree quite favorably with observation (Mitchell [1983]; see Figure 3) and the global distribution of the local annual averages shows basic agreement in the location, if not in the intensity, of regions of high and low precipitation (Hansen *et al.* [1983]; see Figure 4). There are local discrepancies of up to 100% in annual totals mostly in tropical regions. The models are also used to simulate the average seasonal cycle of precipitation including monsoons and the movement of the tropical rain belt following the intertropical convergence zone (ITCZ).

The atmospheric GCMs have the potential of realistically simulating the interannual variability of the hydrologic cycle also because of the unstable transient cyclones arising primarily at mid-latitudes in solution of the equations of motion.

There is much room for improvement in the formulation of GCMs, particularly in the parameterization of subgrid-scale hydrologic processes, but there is also need for additional basic understanding of some critical hydrologic phenomena. For example, consider the following.

Precipitation arising from moist convection is acknowledged to be spatially variable at subgrid-scale when calculating the mass falling on the GCM gridsquare. The usual parameterization of land surface hydrology distributes this mass uniformly over the gridsquare when calculating the subsequent soil moisture fluxes [e.g., Hansen *et al.*, 1983]. This simplification produces such low rainfall intensities that the infiltration capacity is seldom exceeded and hence GCMs typically yield little or no direct runoff. Furthermore, current soil moisture flux parameterizations are of the Thornthwaite-Budyko type [Thornthwaite and Mather, 1955] in which the flux is linearly related to soil moisture concentration. Current parameterization efforts are directed toward incorporating more realistic nonlinear moisture flux relations. In improving upon these simplifications, the spatial averaging question becomes crucial. How do we represent the spatial average dynamic hydrologic behavior of mesoscale areas in the presence of inputs and physical parameters which are spatially variable at smaller scale and in a manner which is at best only generically known? This is an unsolved problem that arises wherever in nonlinear dynamics disparate scales must be coupled.

Vegetation cover has a profound influence on the heat and moisture budgets of the land surface and yet in current GCMs it is a prescribed boundary condition. Such prescription does not account for the synergism among climate, soil, and vegetation that determines such parameters as canopy density and type and hence albedo and water use. Of particular importance in this regard is the prognostic distinction between deciduous and evergreen vegetation. It is thus important to develop and use in GCMs vegetation models which are truly interactive. This is beginning insofar as the water use and albedo of prescribed vegetation types are concerned. If the interaction is to include model specification of vegetation type, however, it will first be necessary to understand the climate

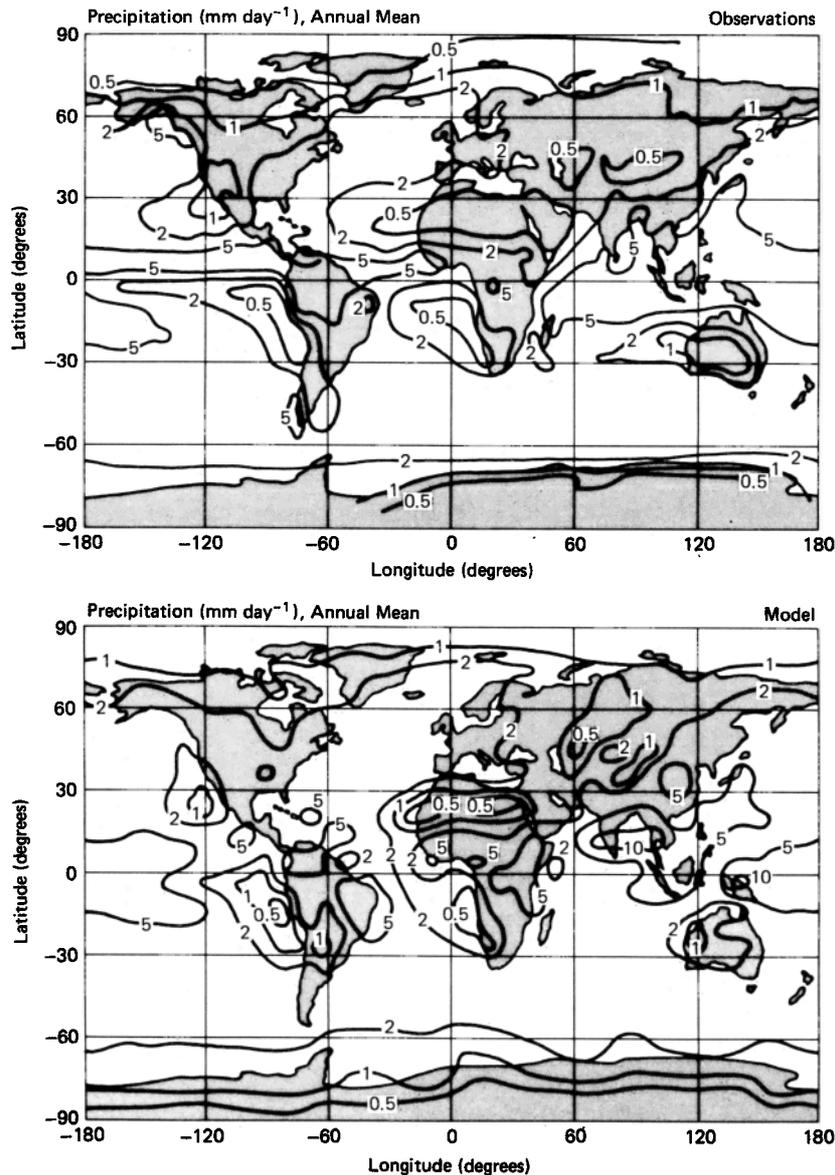


Fig. 4. Global distribution of mean annual precipitation; comparison of model and observations (from Hansen *et al.* [1983]; reproduced with the permission of the American Meteorological Society.)

and soil conditions that determine one type in preference to the others. There is ample empirical evidence (for example, see Perrier [1982; Figure 5]) that the primary types of world vegetation are arranged, to a significant degree, according to variations in the availability of water and energy, contemporary understanding of the role of humans, pests, and fire notwithstanding. Ultimately, the soil too should be made interactive as its physical and chemical character are part of the synergism. As modeling of global biogeochemical cycles moves into the planning stages this becomes a serious consideration [National Research Council, 1985].

Location of the time-varying snow line and sea ice boundary is critical to the magnitude and distribution of Earth's albedo. Additional work is needed on the snow and ice melt problems to be able to define these boundaries with reasonable accuracy.

Coming back now to the spatial scale of the hydrologic

cycle and its exploration using atmospheric GCMs, we will present some preliminary results of R. D. Koster (unpublished manuscript, 1985) as a demonstration of the power and utility of these models as a hydrologic research tool. Using the GCM of the NASA Goddard Institute for Space Studies (GISS) with medium resolution ($8^\circ \times 10^\circ$ grid), Koster "tagged" the water in a 1-day impulse of evaporation from selected grid squares and followed this water for 2 months to see where it precipitated. The GCM initial conditions were those corresponding to a particular month. The characteristic time for precipitation of the evaporated water varied from 2 to 5 days for the grid squares tested. Only three of the most environmentally interesting grid squares are presented here.

Figure 6 follows the water evaporated in March from the grid square most closely representing the Amazon basin and marked here by the solid shading. The lighter shaded grid squares show where most of the evaporated water was subse-

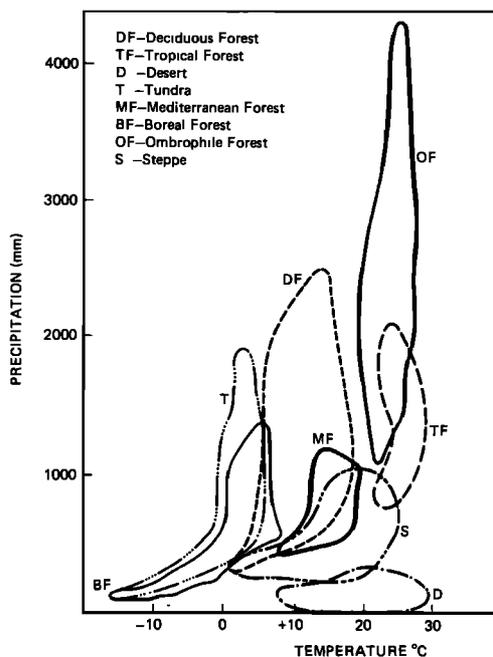


Fig. 5. Climatic limits of major zoniomes (from Shuttleworth, 1983]; reproduced with the permission of Cambridge University Press).

quently precipitated. Grid squares receiving less than an arbitrary small amount are considered to have received none. Notice in this case that the evaporation apparently gets caught in the Southern Hemisphere Hadley cell and is carried primarily to the south with relatively little east-west dispersion. This preliminary study indicates that the South American continent would be the primary area affected by precipitation change due to Amazon deforestation. The study also

shows that 37% of the water evaporated from the Amazon basin in March is recycled as subsequent precipitation on the same grid square.

Figure 7 follows in the same fashion the water evaporated in March from another site of extensive deforestation, Southeast Asia. In this case there is a strong west-to-east advection of the moisture added to the expected poleward movement. The "influence radius" of this location is enormous as far as evaporation is concerned, and 52% of the evapotranspiration is recycled into local precipitation.

The final evaporation example is that of Sudan's Sudd region discussed earlier and is presented here as Figure 8. The precipitation resulting from January evaporation is largely confined to the African continent with some being advected onto the Atlantic Ocean by the Easterly winds of these latitudes. About 19% of the Sudd evaporation during this month falls back on the Sudd as precipitation.

These results are far from definitive of course: being impulsive rather than steady state; being for only one season of the year, being for only a single sample of the possible initial conditions, and most importantly; being subject to all the approximations and inaccuracies of GCMs at their current state of development. At the least, however, they do have qualitative, comparative value; they are eloquent testimony to the potential utility of these models in hydrology, and they serve as valuable guides to the design of field programs.

EXPERIMENTAL SUPPORT

Science advances on two legs, analysis and experimentation, and at any moment one is ahead of the other. At the present time advances in hydrology appear to be data limited; not the micrometeorological measurements of the laboratory taken to learn about the one-dimensional physics of isolated processes, but rather those macroscale field observations needed to understand the hydrologic coupling of mesoscale precipitation events with het-

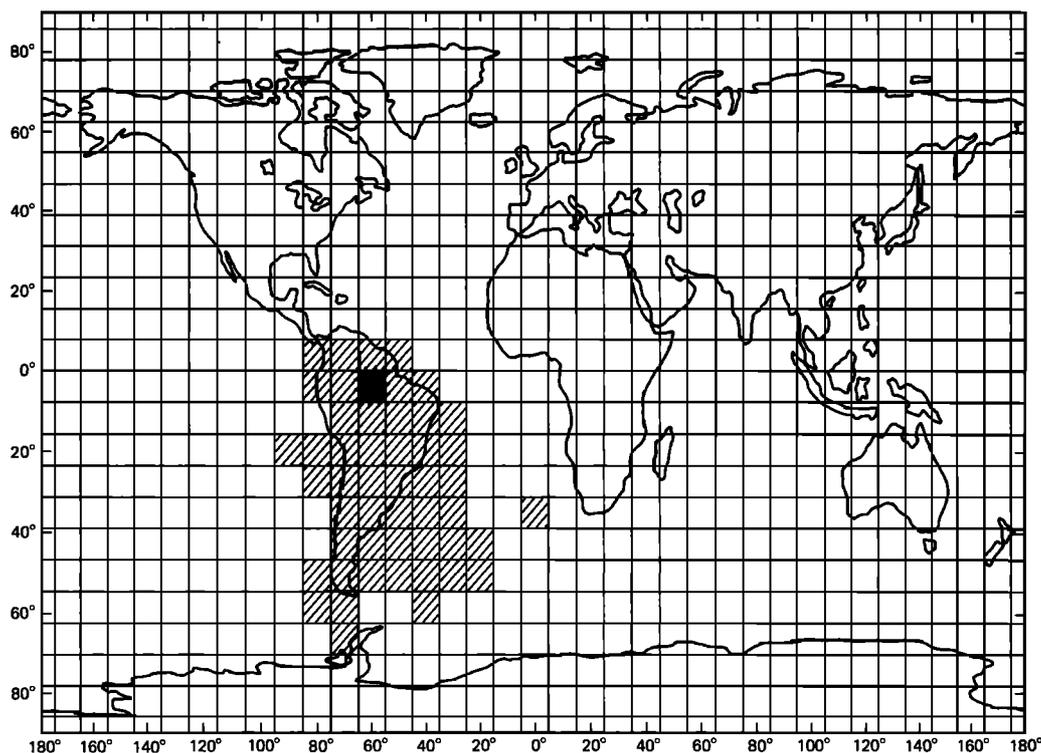


Fig. 6. Region of influence of Amazon March evaporation [Koster, 1985].

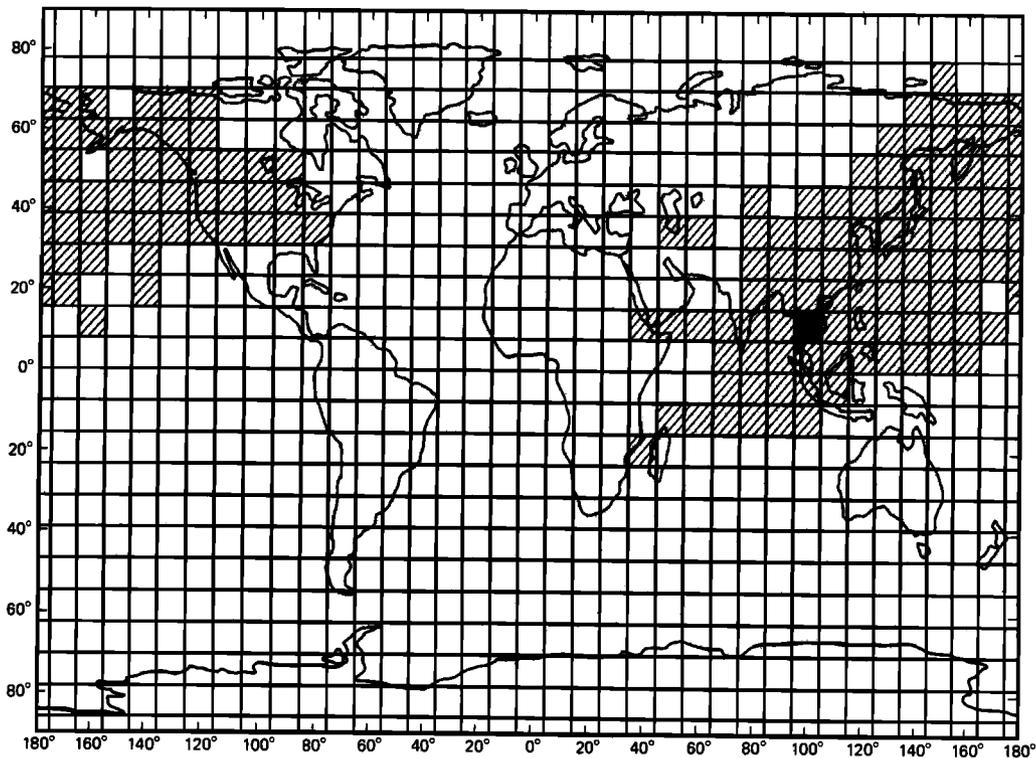


Fig. 7. Region of influence of Southeast Asia March evaporation [Koster, 1985].

erogeneous land surfaces, and the global-scale assessments necessary for monitoring the changing inventory of Earth's waters.

We have already mentioned the importance of the meso-scale measurements to subgrid-scale parameterization in GCMs and, of course, they lie at the core of conventional catchment hydrology as well. Measurements of the bulk energy and water fluxes over inhomogeneous mesoscale areas (i.e., 10^2 to 10^4 km²) are badly needed to learn how best to parameterize these fluxes in the presence of different vegetation types and in different climates. Planning is underway for such experiments by two international groups [*International Association of Meteorology and Atmospheric Physics (IAMAP)* and *Committee on Space Research (COSPAR)*, 1983; *World Meteorological Organization*, 1984] and hopefully the U.S. interagency STORM project [*Interagency Team for STORM Central*, 1984] will be modified to include these hydrologic objectives. It is important that hydrologists play an active role in both the planning and the conduct of these enormously expensive experiments to ensure that the broadest objectives are met.

Implementation, verification and utilization of these meso-scale parameterizations in global models requires periodic estimation of key hydrologic parameters and variables for the global network of gridsquares. Economy demands that these estimates be made from space yet progress is limited by lack of measurement technology. For the land surface gridsquares research is needed particularly with respect to the critical quantities: precipitation; evapotranspiration; sensible heat flux; soil moisture and temperature (some bulk measure in terms of which the fluxes can be estimated); hydraulic and thermal properties of the soil; vegetation type and canopy structure; and snowpack mass. For water surface gridsquares estimation of precipitation and evaporation is badly needed.

The inventory measurements are called for because of our surprisingly poor quantitative knowledge of the global water cycle. We need to observe the various global reservoirs on time scales appropriate to their dynamics: days for atmospheric and soil water; weeks for lakes and snow pack; weeks to years for sea ice; and years to millenia for ground water and glaciers. Clearly, this is a formidable task of great cost and calls for increased efforts to make these measurements possible from space.

EDUCATIONAL IMPLICATIONS

The development of GCMs has quite appropriately been carried out by meteorologists, climatologists, and oceanographers who first foresaw the need for and potential of the global-scale approach to study climate change and to improve long range weather forecasting. Their early assumption that the land surface was a passive and weak participant in the atmospheric action led to a hydrologic parameterization consisting of prescribed surface moisture state, either bone dry or saturated, and produced an overactive model hydrologic cycle. Subsequent numerical experiments demonstrated the high sensitivity of model climate to the land surface moisture state and brought concerted effort to incorporate more realistic hydrologic algorithms within the very real (but continuously expanding) constraints of computation time. This effort has come primarily from within the meteorological community and from physicists interested in achieving the potential for remote sensing in this application. Sincere attempts to involve hydrologists have been largely unsuccessful.

Hydrologists have much to offer this modeling effort and have even more to gain by being active participants. They bring an accumulated experience with the hydrologic behavior of inhomogeneous, mesoscale catchments that allows them to define the most important parameters and processes in specific

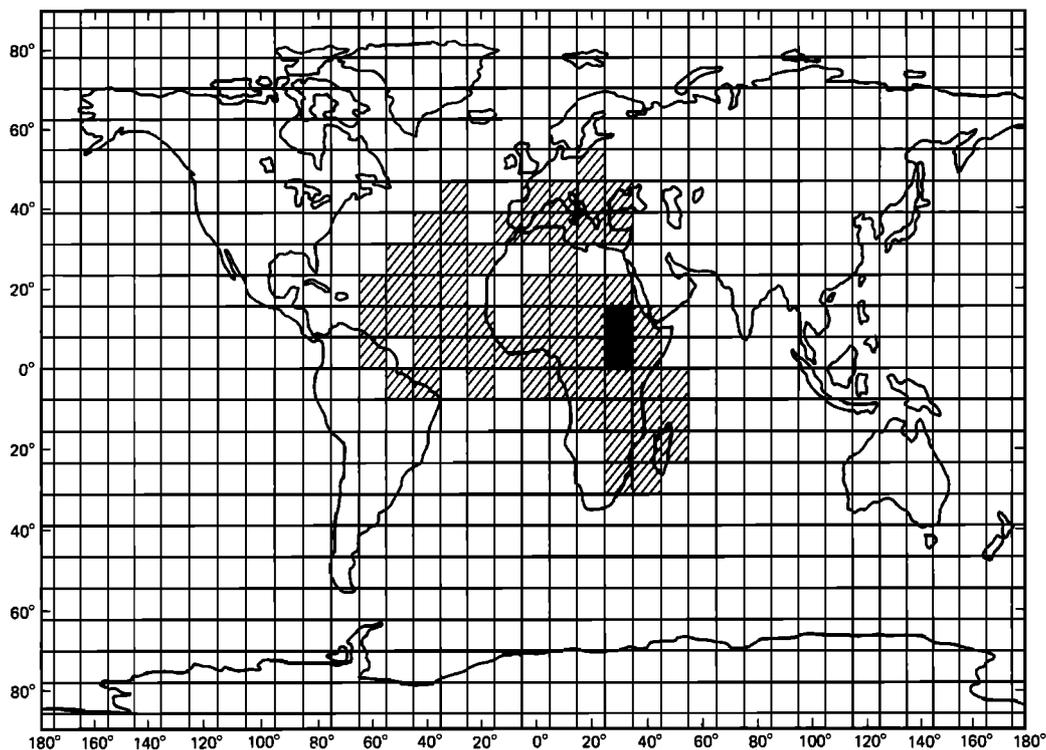


Fig. 8. Region of influence of Sudd January evaporation [Koster, 1985].

climatic and geologic circumstances. More importantly, perhaps, they bring the engineering motivation for solving the problems of people and an understanding of the water needs of man's agricultural, urban, and industrial life support systems. Hydrologists should know the important environmental questions to be asked of a verified model, and their participation in model development will help ensure the model's ultimate capability to be of appropriate benefit.

To be effective in such an interdisciplinary partnership the hydrologist will need a familiarity with subject areas that are seldom a part of his current educational program. These include radiation physics, planetary fluid dynamics, precipitation processes, micrometeorology, plant physiology, natural and managed ecosystems, and the analysis of random fields. The design of such educational programs is an important task and a significant challenge.

SUMMARY AND CONCLUSION

Because of humanity's sheer numbers and its increasing capacity to affect large regions, the hydrologic cycle is being altered on a global scale with consequences for the human life support systems that are often counterintuitive. There is a growing need to assess comprehensively our agricultural, urban, and industrial activities, and to generate a body of knowledge on which to base plans for the future. It seems safe to say that these actions must come ultimately from global-scale numerical models of the interactive physical, chemical and biological systems of the earth. Of central importance among these systems is the global hydrologic cycle and its representation in these models presents many analytical and observational challenges for hydrologists.

We must devote more attention not only to the technical issues of hydrology raised by the model builders but also to encouraging and preparing more young hydrologists to build

a career in this direction. He who controls the future of global-scale models controls the direction of hydrology.

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