The hydrological cycle and its influence on climate

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The uncertainties in assessing the effects of global-scale perturbations to the climate system are due primarily to an inadequate understanding of the hydrological cycle—the cycling of water in the oceans, atmosphere and biosphere. Overcoming this problem necessitates new ways of regarding a field traditionally divided amongst several disciplines, as well as new instrumentation and methods of data collection.

THE hydrological cycle traces the largest movement of any substance on Earth. Water has always had, and will continue to have, a controlling influence on the Earth's evolution. Although the impact of human activities on climate cannot be assessed without including the role of water in all its phases, our quest is handicapped by the lack of quantitative knowledge about the distribution of water and by the need to understand its reciprocal interactions with the climate system.

The hydrological cycle influences climate in a variety of ways. The exchanges of moisture and heat between the atmosphere and the Earth's surface fundamentally affect the dynamics and thermodynamics of the climate system. In the forms of vapour, clouds, liquid, snow and ice, as well as during phase transitions, water plays opposing roles in heating and cooling the environment. Fifty per cent of surface cooling results from evaporation. Water vapour in the atmosphere acts as a powerful greenhouse gas and nearly doubles the effects of greenhouse warming caused by carbon dioxide, methane and all similar gases[1,2]. Clouds control climate by altering the Earth's radiation budget. The release of latent heat of condensation in clouds provides 30% of the thermal energy that drives the Earth's atmospheric circulation.

Given these diverse roles and the complexity of the exchange processes, we must treat the hydrological cycle as a whole, not in parts, to grasp its full behaviour and its intricate nonlinear feedback loops. This approach requires planning and coordination between theory, modelling and observations. It also requires the concerted efforts and expertise of people from many disciplines. At present a full 'systems view' of climate and the hydrological cycle has yet to emerge. This is due, in part, to the fragmented way in which the hydrological cycle has been studied, so that meteorologists, oceanographers, biologists and civil engineers all perceive it differently. The study and teaching of climate needs to integrate these disciplines.

Current efforts to improve our understanding of the hydrological cycle remain focused on observations and modelling. Coupling of land surface models with atmosphere and ocean models is a primary step towards climate prediction. To accomplish this coupling we face many conceptual and computational difficulties. Among them is the need to learn how to combine the dynamic effects of hydrological processes on different space and timescales in the presence of enormous natural heterogeneity. Progress in many areas is limited by a dearth of accurate data. The Earth-observing satellite systems soon to be deployed by many nations will provide many of the necessary observations. Yet even these systems may fall short of providing some of the key observations not only of precipitation and atmospheric winds, but also of clouds, evaporation and ocean salinity. An international programme known as the Global Energy and Water Cycle Experiment (GEWEX)[3,4] is being implemented to observe and characterize the full hydrological cycle. This programme will endeavour to provide the essential remotely sensed and *in situ* measurements and will undertake modelling and field studies of the hydrological cycle.

My aim here is to provide an appraisal of our current theoretical and observational understanding of the roles of the hydrological cycle in the climate system, and its intimate connection to the energy cycle. I hope to show why the hydrological cycle has emerged as the central element in studies of climate change, and to anticipate the main advances expected in modelling and observations in the coming decade, along with areas where improvements will still be required.

The hydrological cycle

Figure 1 shows the main known reservoirs and fluxes of water[5]. Not surprisingly, the oceans are the dominant reservoir in the global water cycle, holding over 97% of the world's water. In contrast, the atmosphere holds only 0.001%, and the rest is locked up in ice caps, snow and underground storage. The hydrological cycle is indeed global, because continents and oceans exchange water. Over the oceans, evaporation exceeds precipitation and the difference contributes to precipitation over land. Over land, 35% of the rainfall comes from marine evaporation driven by winds, and 65% comes from evaporation from the land. As precipitation exceeds evaporation over land, the excess must return to the oceans as runoff.

The mean residence time of water in the atmosphere and oceans is an important climate parameter. As Fig. 1 indicates, the atmosphere recycles its entire water content 33 times per year (total yearly precipitation divided by atmospheric storage),

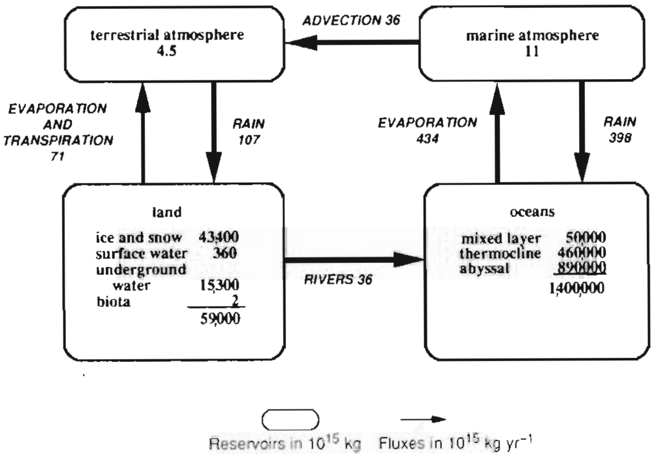

FIG. 1 Estimates of the global water cycle and its reservoirs. The accuracy of several of its components is poor, resulting in a closure error for the whole cycle of about a factor of two. The obvious interactive nature of the cycle makes it impossible to reduce current closure errors without studying the whole cycle. This diagram is based on Fig. 1 from ref. 5.

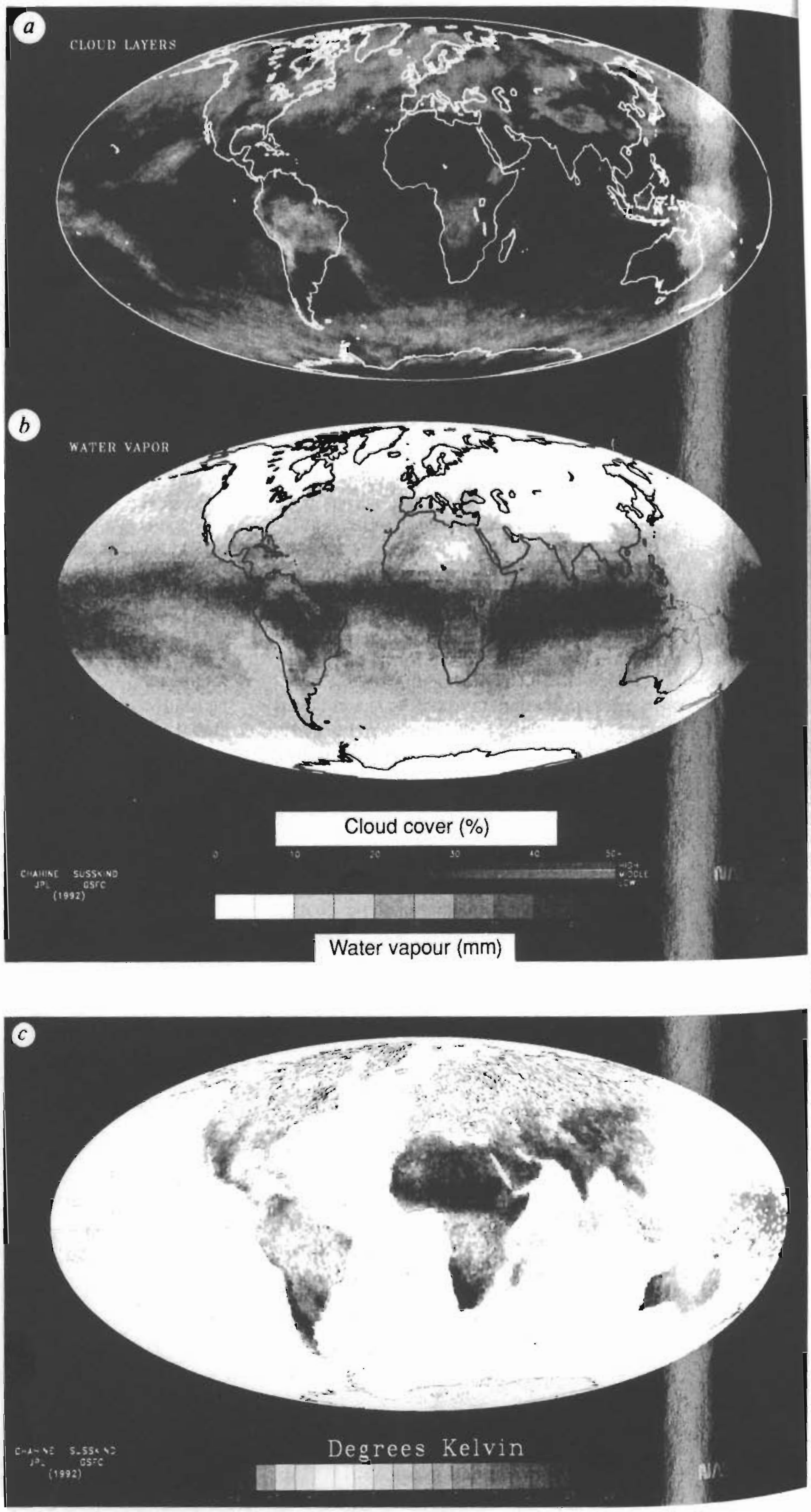

FIG. 2 *a*, Mean cloud cover and altitude for January 1979. Colours indicate cloud heights: blue for low clouds below 4 km (surface to 600 mbar), green for 4–8 km (600–300 mbar) and red for clouds above 8 km (300 mbar to tropopause). Shades of colours indicate variations in the infrared cloud amounts (opacity) as seen from satellites. The intertropical convergence zone (ITCZ) appears clearly as a region of a large amount of high (red) clouds that extends nearly continuously around the Equator. It shows several typical cloud streamers extending south-eastward into the western Pacific and northeast of Australia. In particular, the intense, high-level clouds above India, Indonesia, northern Australia and the western equatorial Pacific define the 'stratospheric fountain', where cold tropospheric air enters the stratosphere. *b*, Mean precipitable water vapour for January 1979. Most evaporation occurs in the tropics (dark purple) and is strongly driven by the amount of solar energy deposited at the surface. Comparison with *a* clearly shows the strong correlation between the distributions of water vapour and clouds. Among the driest regions on Earth are the Tibetan Plateau and Antarctica (light blue), which always appear dry in all seasons. The satellite data were acquired by the High Resolution Infrared Sounder (HRIS) and Microwave Sounding Unit (MSU), both instruments flying on-board the National Oceanic and Atmospheric Administration (NOAA) weather satellites. *c*, Inhomogeneity of land surfaces is clear in this image of temperature difference for day minus night, observed at 2 p.m. and 2 a.m. local time, for January 1979. A striking contrast exists between oceans (mostly white, denoting differences in the range ±1 K) and continental areas. In fact, one can sketch the contours of all continents from this image simply on the basis of the inhomogeneity of the day/night temperature difference of the land surface.

BOX 1 The Global Energy and Water Cycle Experiment (GEWEX)

GEWEX, one of the world's largest geoscience experiments, was initiated in 1988 by the World Climate Research Programme (WCRP) to observe and model the hydrological cycle and energy fluxes in the atmosphere, at the land surface and in the upper oceans. The ultimate goal of the programme is to acquire the necessary knowledge to predict variations of the global hydrological regimes as well as changes in regional hydrological processes and water resources.

Because of the magnitude of the effort, GEWEX will collate information from several ongoing process studies and will initiate investigations of its own, as needed, to improve modelling accuracy and the surface–atmosphere coupling in general circulation models. A build-up phase from 1993 to 1998 (or later) will be followed by a global observing phase coinciding with the deployment (around 1998) of global Earth-observing systems by the world's space agencies. The central activity of the build-up phase will be the GEWEX continental-scale international project (GCIP) and process studies designed to provide the parametric formulation of clouds, radiation and surface forcing factors.

The goals of GCIP are to determine the variability of the hydrological and energy budgets over a continental scale, to develop and validate coupled atmosphere–surface hydrological models and to provide a basis for translating the effects of future climate change into impacts on water resources on a regional basis. GCIP will be located in the Mississippi, one of the world's largest river basins. The effort will collect wind and rain data at high temporal and spatial resolution, satellite cloud and radiance data, cloud properties and radiation fluxes and other relevant hydrological data. GCIP will cover several annual cycles of hydrological processes; the overlapping period between GCIP and the global space-based observations from 1998 to 2000 will serve to validate information retrieval schemes for the new space observations and provide first-hand understanding of the relationship between direct *in situ* data and the data retrieved from space.

giving water vapour a mean residence time in the atmosphere of about 10 days. In contrast, the mean residence time for the oceans as a whole is over 3,000 years, but it is not the same at all ocean depths. In the ocean surface layers, it is only a few days or weeks, increasing to centuries and longer for the deep ocean levels. Over land, the mean residence time of water in vegetation and soil and in aquifers is difficult to determine but ranges from 6 years for the former to 10,000 years for the latter[6].

These two domains of residence time, days-to-weeks and decades-to-centuries, control the Earth's climate system in two distinct ways. The fast regime, consisting of the atmosphere, upper ocean layers and land surface, determines the amplitude and regional patterns of climate change. The slow regime, consisting of the bulk of the ocean, land glaciers and ice caps, modulates the transient responses of the climate system and introduces considerable delay. The fast component of the hydrological cycle has a critical role in predicting climate change and is the primary focus of GEWEX (see Box 1).

Modelling the hydrological cycle

A continuous exchange of water among the reservoirs shown in Fig. 1 occurs mainly through evaporation and precipitation. The driver for this exchange is the Sun's differential heating, which varies with latitude, but the exchange pathways are controlled by surface properties and atmospheric and ocean circulation. Energy and hydrology in the climate system cannot be modelled separately, as they are linked by many atmospheric and surface processes. When an energy imbalance occurs in the atmosphere or at the surface, the atmosphere–surface system reacts to re-establish the balance. In the atmosphere, balance is most efficiently re-established by means of transport of latent heat through evaporation and condensation.

The basic tools for studying these exchanges are general circulation models (GCMs), which have been developed to depict the behaviour of the atmosphere. Over the past decade atmospheric GCMs have improved substantially and are now valuable for forecasting weather up to 10 days. At present, however, this level of confidence does not extend to climate forecasts. Climate models must still be developed to account for the full hydrological cycle and its interactions with the atmosphere, oceans and land. Considerable difficulty arises because the hydrological processes that must be integrated are nonlinear and function over widely different scales in space and time.

Scaling of nonlinear behaviour is a difficult problem. For example, x cm of precipitation falling on 10% of a model grid square may produce a very different response from $0.1x$ cm uniformly falling over the entire square. The issue of the quantitative relationships between identical processes occurring at different scales of space and time is commonly encountered in calculating the fluxes of moisture and heat from a microscale (1×1 km^2) land surface model to a GCM with a grid size of 100×100 km^2. Similar problems are encountered when inferring subgrid properties from the output of a GCM.

When atmospheric and surface models are coupled, they should be able to interact with each other dynamically at the interface. Achieving this will require advances on three fronts. First, we must improve our understanding of the physics, chemistry and dynamics of processes themselves, which requires accurate observations and carefully designed field experiments. Second, we must resolve the problem of representing great natural inhomogeneity; this fundamental statistical–dynamical problem remains basically unsolved. Third, we must translate the results of process studies to the global scale. These advances will be aided by growth in computer power allowing the use of climate models with smaller grid sizes. The task is enormous, but tangible progress is expected over the next decade.

Interactive hydrological processes

I will focus here on five main components of the hydrological cycle: clouds and radiation, atmospheric moisture, precipitation, ocean fluxes and land surface processes. Other components such as snow and ice, underground water storage and river runoff, volcanic eruptions and aerosols, as well as products of pollution, are important but will be incorporated in the five components discussed here. These five components place the discussion of the hydrological cycle within the conceptual framework of climate research, outside the classical surface hydrology framework (precipitation, evaporation, runoff, stream discharge, soil moisture, groundwater discharge and movement).

Clouds and radiation

Clouds, together with water vapour, influence the thermal structure of the atmosphere and the partitioning of energy between surface and atmosphere. Although globally there is a near balance in the net radiation at the top of the atmosphere when averaged over seasons, the regional distribution shows nonuniformities on all scales. These nonuniformities represent sources and sinks of energy that modulate the atmosphere and ocean circulations. Clouds play multiple roles as scatterers and absorbers of radiation. They reflect incoming solar radiation, reducing the direct solar energy input to the environment, but at the same time trap part of the Earth's emitted energy, reducing the net outflow of heat energy from the environment to space. The net effect depends on a range of cloud properties including their microphysical characteristics, their vertical and horizontal extent, and the dynamics of their interaction with the atmosphere. There is general agreement that the current, annual, global mean effect of clouds is to cool the climate system[7], but the exact magnitude and sign of cloud feedback in climate simulations is controversial because of uncertainties in predicting what types of cloud will increase as a consequence of increased CO_2.

Cloud structure and dynamics. Foremost among the microphysical properties are the size distribution, shape and phase of the cloud particles. These variables determine how the incident and emitted radiant energy in the clouds are redistributed. Numerical simulation studies[8] have shown that cloud microstructure and

TABLE 1 Sensitivity of downwelling longwave flux

Parameter	Current uncertainties	Effect on downwelling longwave flux (W m^{-2}) Subarctic summer	Tropics
Specific humidity	20%	11	15
Atmospheric temperature	2 K	5	8
Cloud base height*	100 mbar	11	7
Fractional cloud cover*	0.1	6	3
Doubling CO_2 with 0.50 cloud cover†		0.8	0.2
Doubling CO_2 with no cloud cover†		1.2	0.3

Sensitivity of the downwelling longwave flux at the surface to uncertainties in atmospheric and cloud parameters and the contrast with the effects of doubled CO_2. Uncertainties are ± the figure given. Effects on flux are calculated by adding uncertainties to best estimate.

* Cloud base at 400 mbar.

† No feedbacks.

nucleation are important determinants in formulating cloud radiative processes. Cloud droplets (and aerosol particles), with radii from 0.001 to 10 μm, affect the radiation budget through scattering and absorption of solar and infrared radiation. Their influence is difficult to assess because concentrations vary by orders of magnitude in space and time and because observations of their size distributions, shape and chemical composition are poor. When changes in the state of the cloud water content were introduced into the model, used in ref. 8, the resulting simulations, associated with a doubling of the CO_2 concentration, showed a reduction of global warming from 5.2 °C to 1.9 °C. This result shows the importance of cloud microstructure and the need for a more quantitative determination of their effects.

Cloud height and albedo are also important factors. An increase in the effective cloud top height (with cloud cover and cloud albedo fixed) leads to an increase in surface temperature at all latitudes[9]. Thus, if doubling CO_2 leads to higher clouds, then clouds will produce a positive feedback (surface warming)[10,11]. If, however, the resulting clouds have larger water content, their albedo will be higher and they will reflect more solar radiation, thereby providing a negative feedback leading to cooling of the surface[12–14]. Special attention must be given to dimethyl sulphide emissions from the oceans, SO_2 emissions from fossil-fuel burning and smoke emissions from biomass burning. In the troposphere, SO_2 is converted to sulphate particles which, in addition to smoke aerosols, directly reflect solar radiation and act as cloud condensation nuclei[15], thereby increasing cloud albedo. The resulting cooling may nearly balance the current anthropogenic greenhouse warming[16–18].

Cloud dynamical processes play an important part in determining the vertical distribution of water vapour and the release of latent heat. Observational studies[19] of the interactions between ocean surface temperature and large-scale transport of moisture during the 1987 El Niño showed that ocean surface warming also enhanced deep convective activity and the formation of cirrus clouds with high albedo, reflecting more of the incident shortwave solar radiation. This shortwave forcing acted like a thermostat, shielding the ocean from solar radiation and regulating the sea surface temperature, capping it at a maximum value of 30 to 32 °C. Subsequent studies, however, have stressed the roles of large-scale dynamical processes[20] and evaporation[21] in regulating sea surface temperature in the Pacific.

The cloudiness factor. Climate models use a general parameter often called 'cloudiness' to account for the effects of clouds. When we observe the Earth from space we see certain horizontal inhomogeneities (clouds and aerosols) which we call cloudiness. This factor is quantitatively defined by measuring cloud horizontal extent or opacity relative to a specified background. The multilayer clouds shown in Fig. 2*a*[22] are derived from infrared observations in the 15-μm CO_2 band, and the background is defined by microwave observations in the O_2 cluster at 50 GHz. The resulting infrared cloud distribution is thus a measure of the cloud infrared forcing. The infrared cloud distribution is, on average, less opaque by a factor of 3/4 than the cloud distribution in the visible[23], yet shows the same basic features as the cloudiness obtained from the visible part of the spectrum.

Satellite observations of clouds provide an indispensable overview of cloud systems, letting us directly observe the effects of clouds on the Earth's radiation balance at the top of the atmosphere. The International Satellite Cloud Climatology Project (ISCCP) aims to provide detailed global cloud properties and statistics from geostationary and polar orbiting satellites. Present satellite observations cannot, however, provide information such as the height of the cloud base and the vertical structure of clouds. Current satellite observations are sensitive to the properties of clouds as seen from above whereas the longwave radiation flux reaching the surface is determined by the water vapour and cloud optical depth as seen from below.

Atmospheric humidity

Interactions between water vapour, clouds and radiation constitute one of the most controversial feedback processes in the atmosphere. Although a very small fraction of water resides in the atmosphere, the rapid recycling of atmospheric water vapour makes it exert disproportionate control over the energetics of the climate system. Small changes in the amount of water vapour on all scales produce significant changes in cloudiness and hence radiation. Most of the atmospheric water vapour resides near the surface and its concentration varies by several orders of magnitude within the troposphere. Our knowledge of its vertical distribution and horizontal variability is uncertain, and model prediction of water vapour remains untested.

Feedback controversies. Raval and Ramanathan[2] used observational data to show a correlation between sea surface temperature and total water vapour, and concluded that an increase in water vapour is one of the main positive feedbacks in the atmosphere, amplifying the enhanced greenhouse effect. But Lindzen[24] argued that such a feedback may not actually develop. The warming initiated by increased CO_2 enhances convection and thereby changes the total water vapour and its vertical distribution. Lindzen suggested that although rapid mixing in the lower atmosphere will increase the specific humidity as surface temperature increases, greater convection will lead to decreased specific humidity in the upper troposphere, resulting in a negative feedback. Rind *et al.*[25] have observed that the water vapour density in the upper troposphere is higher in the summer season than in the winter, supporting the argument for the positive feedback of moisture. In addition, I have recently analysed data from the NOAA weather satellites (unpublished results) which show that, independent of seasons, the water content of the atmosphere increases throughout the troposphere as a function of increased sea surface temperature. This issue is still being debated, but it is certain that we need both better observations and further modelling and theoretical studies.

Despite the importance of atmospheric water vapour in weather and climate processes, most models do not make use of current data. Recent studies (E. Kalnay, personal communication) show that weather prediction models are sensitive to small changes in atmospheric moisture and that the impact of these changes on model predictions can be positive or negative depending on how the physics and dynamics of moisture processes are represented. To validate model outputs, we require consistent and more accurate measurements of humidity.

A recent approach to model validation (S. A. Clough, M. J. Iacono and J.-L. Moncet, manuscript submitted) makes use of the strong correlation between the outgoing spectral radiance to space and the spectral cooling rate. High-spectral-resolution measurements of the outgoing radiance can provide unique information about the state of the atmosphere that cannot be deduced from broadband data. In particular, emission to space by strong water-vapour bands is a climate feedback mechanism that may be a good diagnostic of climate change. Of particular interest are the strong contributions to the radiance from the upper troposphere in the 1,400 to 1,700 cm^{-1} region and from the lower troposphere in the 800 cm^{-1} region. The debate about water vapour feedback might be resolved through observations with high spectral resolution (R. Goody, personal communication). Different humidity feedbacks would result in different predictions of the comparative emission of strong water lines and of medium-strength CO_2 lines as a function of latitude and seasons.

Observational studies. Observational difficulties from both space and the surface are the main hindrance in generating climatological data sets for atmospheric water vapour. Patterns of the distribution of total precipitable water vapour (Fig. 2*b*) strongly resemble the distributions of clouds (Fig. 2*a*) despite the fact that current satellite-derived moisture data is accurate only to ~10-20% over the geographical oceans and 20-30% over land[26]. Space observations of water vapour are indispensable, especially over the oceans where radiosonde observations are sparse. Even over land, problems are present. Current instruments are incapable of accurate measurement at temperatures below 230 K and at low moisture concentrations. Inconsistencies in the calibration of radiosonde data (bias changes due to changes in the sensors, and variation from country to country in processing algorithms and instrument packages) also make long-term trends difficult to establish[27]. A much more comprehensive system of monitoring atmospheric moisture is needed to derive humidity profiles throughout the entire atmosphere. Such a system would necessarily include measurements of the outgoing radiance with high spectral resolution to resolve water vapour lines[28]. In addition, improved occultation observations will be needed to measure water vapour with greater accuracy in the very highest regions of the troposphere and in the stratosphere so that radiative heating rates can be studied. Climatological data sets of atmospheric water vapour profiles derived from satellites and from upper air sondes are too poor in vertical resolution to be of much practical use. Vertically integrated water vapour (precipitable water vapour) from satellites is available but no consistent climatological data sets have yet been produced.

Poor knowledge of water vapour continues to hamper the determination of the surface radiation budget which requires, in addition to water vapour profiles, accurate knowledge of atmospheric temperature profiles, aerosols and clouds. Table 1 demonstrates the effects of current uncertainties in moisture, clouds and temperature on the computation of the downward longwave flux at the surfaces (A. Arking and M. D. Chou, unpublished results). These effects are contrasted with the effects corresponding to simple doubling of CO_2 (with no feedbacks) for two cases: 50% clouds and no clouds. Because of current uncertainties, the errors in calculating the downwelling longwave flux remain too large (by about one order of magnitude) to let us determine the impact of increased CO_2 on global warming.

Precipitation

The average annual global precipitation is equivalent to 95-115 cm each year or about 0.3 cm per day. But precipitation is highly variable, with two-thirds of the global precipitation occurring between latitudes of 30° N and 30° S. This variability not only has a tremendous influence on vegetation, droughts and floods but also has a controlling effect on the large-scale circulation of the atmosphere and oceans. In spite of this extreme variability, long-term, time-averaged precipitation fields reveal large-scale patterns that are of great significance in maintaining the hydrological cycle and the climate system.

The atmospheric forcing caused by spatial variation in the release of latent heat of condensation is the main driver of the dynamics of the interactions between the atmosphere, oceans and land. The annual variability of tropical rainfall is strongly related to the annual variability of the sea surface temperature, reflecting the strong coupling between the ocean and the atmosphere. The three key parameters controlling this coupling are sea surface temperature, rainfall and wind stress. Even though the amplitude of the annual cycle of sea surface temperature is small, the thermal coupling is strongly amplified by the latent heat released by large- and small-scale regimes of precipitation. This influences the surface wind field, which changes the ocean upwelling and current system and, in turn, induces further changes in the sea surface temperature in an interactive feedback loop.

These interactions are frequently associated with the evolution of monsoons, tradewind systems and oceanic convergence zones, and with the El Niño/Southern Oscillation (ENSO) cycle which occurs at intervals of 2 to 7 years[29]. The ENSO warm phase in 1991-92 was preceded by one in 1986-87 and another in 1982-83, the strongest this century. In general, ENSO is the most noticeable case of climatic hydrological variability, affecting marine ecosystems along the west coast of America as well as regional and global food production. There is also considerable coherent atmospheric variability on timescales of ~40-50 days, which markedly resembles the low-frequency ENSO cycle[30]. These oscillations are particularly evident in rainfall and wind fluctuations over the low-latitude tropics, from the eastern Indian Ocean to the central equatorial Pacific[31].

Tropical rain systems affect both the upper troposphere and the lower stratosphere. Convective tropical rain provides the energy for fluxes from the troposphere to the stratosphere, known as the 'stratospheric fountains'[32]. The advection of water vapour into these regions provides the moisture needed for the formation of tropical cirrus clouds. From these tropical regions moisture spreads worldwide.

Over land, understanding the interactions between rainfall and surface processes is important on all scales, from microscale (1×1 km^2) to continental. For example, there is a high degree of recycling between rainfall and evapotranspiration in regions like the Amazon, whereas in desert areas the absence of significant sources of surface water vapour may help to maintain the desert itself[33]. In the latter case, it is believed that the dry conditions are initiated by large-scale atmospheric factors and reinforced by surface processes.

Precipitation data. Precipitation is one of the most difficult processes to model and predict. Cloud microphysics and particle growth, as well as the regional and global patterns of temperature, humidity and winds, control the intensity, scales and timing of rainfall. Figure 3 illustrates the uncertainty in our knowledge[34]. The solid and dashed curves represent best interpretations from rain-gauge measurements. The other symbols refer to the results of numerical models. The models succeed in reproducing the extensive rainfall in the tropics but differ in determining the latitude and magnitude of the peak. Differences as large as a factor of five occur in their prediction of the global monthly rainfall at the peak point. Regionally, the variations between the leading models are even worse[35]. The simplistic parameterization of rain processes in global models is the main reason for these poor results. Efforts to improve these models are hampered by the lack of reliable data.

New analyses of infrared and microwave data from space are being undertaken to fill the gap in our knowledge of the global distribution of precipitation. Visible and infrared data are most commonly used today for estimating precipitation. Because precipitation is a product of a complex combination of thermodynamic and dynamic processes, it is possible to formulate a rainfall index from features of cloud and radiation fields derived from satellite observations and then relate the index, through regression equations, to rain-gauge observations of rainfall.

The Tropical Rainfall Measurement Mission[36] is a joint satellite mission between Japan and the USA. It will be launched (around 1997) into a low-inclination orbit from which it will observe mostly ocean areas, and will fly a complement of four instruments: a radar, a microwave radiometer, a visible-infrared radiometer and an Earth radiation budget instrument. The results should establish the necessary link between deterministic and stochastic models of rainfall fields. We need global measurements of precipitation over both land and oceans to close the hydrological cycle by accurately determining the partition of precipitation between ocean and land areas, thereby improving the representation of the balance between runoff and evaporation[37].

Ocean fluxes

The oceans contribute to the global hydrological cycle in two ways. First, they provide long-term memory by storing heat and releasing water vapour. Second, in the subtropics the oceans transport heat polewards at a rate equal to the heat transported by the atmosphere. Improved understanding of the interactions of the oceans with the atmosphere will, it is hoped, allow us to describe and predict the behaviour of the upper oceans accurately enough to close the global hydrological cycle. Oceans move both horizontally and vertically under the influence of winds and density differences. These density differences are related to changes in water salinity which can be generated by evaporation, precipitation, runoff and ice melting. The combination of low surface temperature and high salinity makes water more dense than the deep water below, setting up convection which affects even the deep ocean layers.

Heat transport. Salinity modulates the interactions of the oceans with the hydrological cycle. In the thermohaline circulation of the northern Atlantic Ocean, warm surface water flows northward, becoming more dense through increased salinity and cooling. It then sinks and flows south. The addition of fresh water reduces the density of the upper ocean layers and represses sinking, thereby creating a cap over the ocean which could eventually lead to vastly different thermohaline circulation patterns[38]. Lower surface salinity in the northern Atlantic could be brought about by increased precipitation, melting of the ice caps or changes in the flow of low-salinity water from the Arctic Ocean. This affects the transport of heat to high latitudes in the Atlantic basin and possibly the upper ocean currents over the world. Model simulations indicate that small changes in the Atlantic thermohaline circulation could have prolonged effects on the whole climate system[39].

Despite its importance, the fresh water flux at the ocean surface is poorly known. Rainfall measurements over the oceans are almost non-existent and evaporation is typically estimated from an empirical 'bulk' formula requiring ocean surface temperature, near-surface humidity and wind speed[40]. The difference between these poor estimates of evaporation and precipitation is used to derive even poorer estimates of the distribution of fresh water at the ocean surface, except across international shipping routes in the North Atlantic[41].

Present estimates of heat transport by the oceans are deficient in other ways, resulting in a discrepancy known as the 'mystery' of the missing 1.6 pW ($1\ \mathrm{pW} = 10^{15}\ \mathrm{W}$) in the heat balance of the climate system[42]. The poleward transport of heat at 24° N by the Pacific and Atlantic oceans has been estimated[43] to be 2.0 pW (the Indian Ocean does not extend past latitude 24° N, so it does not have to be considered here). This is comparable to the value of 1.7 pW estimated for the heat transport by the atmosphere[44]. The oceans and the atmosphere together thus transport 3.7 pW northwards, far less than the 5.3 pW required to balance the Earth radiation budget according to satellite data[45].

Ocean observations and modelling. Modelling the effects of atmospheric forcing on the upper ocean layers is very different from modelling interactions between the atmosphere and land surface, because of differences in the rates of vertical and horizontal transfer of heat and fresh water in the two media. In the extratropics, the fluxes of water vapour and energy from the ocean surface to the atmosphere are strongly affected by ocean eddies on a scale of about $100 \times 100\ \mathrm{km}^2$; unless climate models can deal with these scales they cannot closely reproduce the larger motions. To improve the models further we need to increase their resolution and refine the parameterizations of heat transport by ocean currents, deep convection and other aspects of the annual cycle. Two current experiments addressing these issues are the Tropical Ocean Global Atmosphere (TOGA) experiment and the World Ocean Circulation Experiment (WOCE). Together, these will provide a more comprehensive understanding of the hydrological cycle over the oceans.

Land surface hydrological processes

Studies of land surface interactions must address surface inhomogeneities on all scales. Figure 2*c* illustrates an aspect of this inhomogeneity: it shows the difference between day and night temperatures of ocean and land surfaces. Because water has a high heat capacity, the oceans show little change in temperature between day and night. Dry land surfaces such as deserts show extreme differences in temperature, whereas wet, forested or vegetated areas show intermediate levels of change in temperature between day and night.

Evaporation and precipitation over land are major components of the global hydrological cycle. Energy is needed to convert soil water to vapour. Most of this energy comes from radiation absorbed by the surface, which depends on surface albedo and other factors. Surface albedo itself is determined by vegetation and bare soil conditions. Changes in vegetation and soil moisture alter the partition between evaporation and runoff which, in turn, changes surface conditions. Land surfaces affect

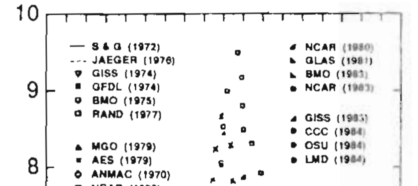

FIG. 3 Mean zonally averaged precipitation for January (see ref. 34 for details of models). The uncertainty in the estimates of global precipitation is typified by the scattering of the data between rain-gauge measurements and among simulations by different models. The solid and dashed curves were put together by different authors from surface-based rain-gauge data. The other symbols refer to results from some of the best models.

the hydrological cycle in various additional ways. For example, in the extratropics, which experience large seasonal fluctuations, the soil stores some of the precipitation it receives in winter and returns it to the atmosphere in summer. Snow and land ice must be included in land surface parameterization[46]. This is particularly important in high latitudes where they have a considerable effect on surface heating. Because of the multiple interactions between climate and surface conditions it is difficult to foresee the effect of human-induced changes (such as deforestation or changes in land use) on either local or global-scale climate.

A few quantitative studies have been made of the effects of land surface processes, using atmospheric GCMs[47]; they indicate that these processes are essential in maintaining climate and controlling its temporal variation.

The physical aspects. Given a knowledge of soil properties and moisture content, the most important surface parameters determining evaporation are albedo and roughness length. The first soil model was the reservoir representation by Manabe[48], known as the 'bucket' model. This model is limited by a moisture capacity of 15 cm. Precipitation in excess of this value becomes runoff. In Manabe's model, evaporation proceeds first at the potential rate (the atmospheric vapour transport capacity) until a critical value of soil moisture is reached, then continues at a linear rate proportional to the soil moisture. In reality, the relationship between rainfall, runoff and evaporation is highly nonlinear and requires more complex representation schemes[49]. Hanson *et al.*[50] introduced geographical variations in surface albedo, roughness length and root depth. Dickinson[51] and Sellers *et al.*[52] developed more elaborate schemes. Soil models must now be combined with their counterparts for vegetated surfaces before testing in a GCM.

The biological aspects. Vegetated surfaces complicate the problem of representation of the land surface[53]. For plant transpiration, the shape and physiology of vegetation are important. Morphology determines the absorption and reflection of radiation and the physiology controls the latent heat flux.

Although the need for GCMs to include vegetated surfaces is well accepted, attempts have so far been limited. Dickinson[51] and Dickinson *et al.*[54] proposed the biosphere-atmosphere transfer schemes, and Sellers *et al.*[52] proposed the simple biosphere model. These models are based on the 'big leaf' concept[55], in which the vegetation is represented by a layer of negligible heat capacity. In model grid cells with incomplete vegetation cover, the model assigns a proportion of the cells to bare soil and others to vegetation; thus the determination of surface energy flux of sensible and latent heat includes contributions from both bare soil and vegetation canopy.

Recent studies[56–58] have tested climate model responses to deforestation in Amazonia. Vegetation and soil characteristics were changed to represent those typical of deforested regions in Amazonia. Evaporation over the deforested region decreased as a result of increased albedo. The first results[56] showed little effect on the overall precipitation but later work[57,58] indicated a larger reduction, suggesting sensitivity to model formulation.

Land surface observations and modelling. Realistic modelling of land surface processes is essential for successful simulation of climate[59], but there are many obstacles. To improve land surface hydrological models for GCMs we must now learn how to combine the effects of processes from local to GCM grid scales in a rigorous manner. Analyses of data from coordinated field experiments will assist our progress in this area[60].

Global data and space observations

Satellites will have an important, but by no means exclusive, role in the observation of the hydrological cycle. Global observations must be a combination of traditional operational weather data and future Earth-observing satellites. The required data fall into five specific categories: basic meteorological parameters such as temperature and moisture; tropospheric wind vectors; precipitation; radiation and clouds; and land surface data. In each of these areas, new instrument capability is needed: high-spectral-resolution infrared spectrometers for high-vertical-resolution sounding of atmospheric temperature and humidity; Doppler lidar measurements of tropospheric winds; global measurement of precipitation from space, using rain radar; determination of the complete hemispheric distribution of the Earth's radiance and its angular distribution by means of a radiation budget radiometer, as well as cloud base height and vertical structure from radar measurements; and high spatial resolution observations of surface vegetation and cloud structure by means of multispectral imaging.

Emerging new community

Determining the manifestation of future climate change begins with assessing our understanding of the components of climate. Progress is being made, but much remains to be done. Even if great accomplishments are made in each of the separate areas discussed here, they must still be integrated to solve the problem of climate change.

In the short span of about 10 years, the hydrological cycle has emerged as the centrepiece of the study of climate, but basic changes are still required in this field. Hydrological science must adjust itself to become a discipline not unlike atmospheric science or oceanography. Rather than fragmented studies in engineering, geography, meteorology and agricultural science, we need an integrated program of fundamental research and education in hydrological science. As Frank Press, president of the US National Academy of Sciences, has stated: "the scientific and educational base in hydrology is incompatible with the scope and complexity of many current and emerging problems"[61]. The shape of the emerging discipline is still evolving[62]; there are difficult mental adjustments to be made, and the transition has only just begun. ☐

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ARTICLES

Continuum of overlapping clones spanning the entire human chromosome 21q

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A continuous array of overlapping clones covering the entire human chromosome 21q was constructed from human yeast artificial chromosome libraries using sequence-tagged sites as landmarks specifically detected by polymerase chain reaction. The yeast artificial chromosome contiguous unit starts with pericentromeric and ends with subtelomeric loci of 21q. The resulting order of sequence-tagged sites is consistent with other physical and genetic mapping data. This set of overlapping clones will promote our knowledge of the structure of this chromosome and the function of its genes.

HUMAN genome mapping consists of ordering genomic DNA fragments on their chromosomes using several methods, such as fluorescence *in situ* hybridization (FISH), somatic cell hybrid analysis or random clone fingerprinting[1-10]. When the fragments correspond to polymorphic sites they can be ordered by genetic linkage analysis[11]. Distances between polymorphic loci are estimated by meiotic recombination frequencies. Such a genetic map allows the localization of any polymorphic trait gene.

Human chromosome 21 (HC21) represents a model for physical mapping of the human genome and is the smallest and one of the best-studied human chromosomes. Several genetic diseases are associated with this chromosome[12], including Down's syndrome (the most frequently occurring mental retardation in humans), some forms of Alzheimer's disease and other neurological diseases, such as progressive myoclonus epilepsy and amyotrophic lateral sclerosis. A map of contiguous units (contigs) covering this chromosome will speed the identification of the cause of these diseases. Indeed, it provides an immediate access to the genomic segment, including any pathological locus, as soon as it has been localized by genetic linkage or cytogenetic analysis.

The process of developing such a long-range contig map involves the identification and localization of landmarks in cloned genomic fragments. When there are enough landmarks for the size of the cloned fragments, contigs are formed, and the landmarks are simultaneously ordered[13]. Yeast artificial chromosome (YAC) cloning provides the means to isolate large, but manageable, DNA fragments of 100 to 2,000 kilobases (kb);

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