

The Global Hydrologic and Energy Cycles: Suggestions for Studies in the Pre-Global Energy and Water Cycle Experiment (GEWEX) Period

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Abstract

Given the importance of a quantitative understanding of the way in which water and energy are moved from place to place and from component to component of the earth's climate system, it is necessary to obtain reliable estimates of the hydrologic and energy cycles in the global atmosphere. While a number of observing platforms designed to address this problem are anticipated in the coming decade, the theoretical and modeling concepts required to interpret the observations have not yet been well formulated. Therefore, it will be necessary to lay the groundwork for making a reasonable estimate of the global hydrologic and energy cycles on time scales of 1 month to several years. A theoretical and modeling framework must be established in which the observations taken during the Global Energy and Water Cycle Experiment (GEWEX), the Tropical Rainfall Measuring Mission (TRMM), and during the Earth Observing System Experiment (Eos) may be utilized and understood.

The major thrust of such a framework will be to validate the global general circulation models (GCMs) which must be used to predict and understand the mechanisms of global change. Future predictions of climate from these models will be reliable only if they can simulate the observed water and energy cycles, and only then can future predictions of water and energy processes also be considered accurate.

The calculations of the seasonal cycle of water and energy fluxes between atmosphere and ocean, and between atmosphere and land may be carried out in four ways. First, and least expensive, the existing operational analyses of atmospheric data from the National Meteorological Center (NMC) and the European Centre for Medium-Range Weather Forecasts (ECMWF) for the most recent, and hence most reliable, years of record may be used. Second, a set of reanalyzed data must be created from the historical record to broaden the database and to evolve an internally consistent, homogeneous, and multivariate time series of climate observations. Third, a long integration of the most realistic, high-resolution GCM available should be made for comparison with the first two datasets in order to validate the model and identify and eliminate sources of systematic error. And, finally, when they become available, the calculations should be repeated based on observations taken during the GEWEX, TRMM, and Eos missions.

1. Introduction

When considering the earth as a system, the presence

of water represents one of its most important distinguishing features. In its vapor phase, water plays a dominant role in the modulation of solar radiation reaching the surface and in the transport of energy from one place to another. As liquid, water is active in a number of processes, such as cloud–radiation interaction, life support, and mass, energy, and dissolved-particle transport. This activity takes place on a wide range of time scales, from the period of minutes in which a cloud formation may change, to the millions of years over which erosion and continental drift can alter the earth's topography. The solid phase of water, either in the form of snow or ice on land or ocean, contributes substantially to the earth radiation budget by altering its albedo and the surface energy budget by altering the way in which sensible and latent heat are transported from the surface to the atmosphere. Snow and particularly ice play significant roles in the alteration of the earth's land surface characteristics on many time scales. Water on this planet exists in several huge reservoirs, including the world oceans, the atmosphere, the cryosphere, and the biosphere, and there are transports of water from place to place and from reservoir to reservoir which are quite substantial on the seasonal to interannual time scales.

The presence of water in its various phases in the earth-atmosphere system is perhaps the most important factor in determining the earth's mean climate. For example, if there were no water vapor in the atmosphere, the equator-to-pole gradient of the radiative equilibrium mean temperature would be far different from what is observed today. Likewise, in the absence of water vapor, the vertical gradient of the radiative equilibrium temperature would also be very different. The presence of water is therefore one of the most important factors in determining the mean kinetic energy of the earth's atmosphere (Simpson et al. 1988). There is a sizable amount of heat stored in the oceans (and the atmosphere, although of smaller magnitude) which substantially reduces the winter-summer contrast that regions of the earth would experience otherwise. The heat is stored in the summer, and released in the winter, permitting a much smaller

annual temperature cycle. The atmosphere and oceans also transport energy from warm parts of the globe to cold regions thereby further reducing the magnitude of contrasts possible at the planet's surface. Thus, the energy cycle of the climate system provides a vehicle whereby the large swings in temperature from location to location and from season to season at a given point, which would normally be associated with a spherical planet in radiative equilibrium with a distant source of radiant energy, are significantly reduced. Similarly, as in the case of the hydrologic cycle, there are large reservoirs of energy on the planet and transport between them; even tiny fluctuations in those transports can cause major changes in the climate of the earth.

The equations expressing the water and energy cycles have very similar forms. First, they are both governed by conservation laws—conservation of water mass and conservation of energy. Second, the cycles have similar components. There are storage terms representing the great reservoirs of water and energy, and there are transport terms representing the flux of water and energy from reservoir to reservoir or from place to place. And, third, there are changes of form for both water and energy. Water has three phases whose transitions contribute to the energy cycle, and energy has three components, namely, internal, kinetic, and potential. The transitions among the three components of energy have been the focus of much investigation in both atmospheric science and physical oceanography.

As may be seen from the preceding discussion, the two cycles, water and energy, cannot be treated in an independent framework. Most obvious is the role of water in the energy cycle. A substantial contributor to the surface-heat balance is the flux of latent heat which, for short periods and over small regions, can be as large as the solar radiative flux. But a latent-heat flux is also a water-vapor flux, and transport of water vapor can completely alter the nature of the energy balance in the case where evaporation takes place at a given location and the release of latent heat associated with its condensation takes place at a different location, possibly far removed from the point of evaporation. Also, a first-order effect in the modulation of radiative flux reaching the ground is the presence in the atmosphere of water vapor and liquid water in the form of clouds. Clouds are the largest contributor to the planetary albedo in the wavelengths associated with solar radiation and are one of the major emitters in the infrared bands. No less important but less direct is the effect of the energy cycle on the transport of water. Since the energy cycle acts to moderate the climate, the changes in temperature gradients cause changes in the regions of con-

densation of water vapor, and possibly more important, changes in atmospheric winds and ocean currents giving rise to alterations in the transport of water itself.

Even more indirect but of great relevance to plants and animals on earth is the fact that the water and energy cycles make it possible for the planet to support life. This has its own feedback effects. In addition to the very long time scale on which vegetation alters the chemical species present in the atmosphere, there are processes taking place on many other time scales. For example, over a period of seasons, there is strong feedback between vegetation, soil moisture, and the atmospheric conditions near the earth's surface. In this case, prolonged spells without rainfall can cause reductions in the vegetation in a given region which can, in turn, cause reductions in the amount of moisture available for evapotranspiration. The latter is closely linked to the rainfall through the hydrologic cycle, closing the feedback loop both regionally and remotely. On longer time scales, there are hypotheses which relate the process of desertification to the soil moisture and albedo characteristics of the vegetated land surface, giving the possibility of nearly permanent climate change in certain regions.

When considering the possibility of climate change, it should be realized that although we may be interested in making estimates or even predictions of how the climate will change over the next several decades, we must be able to understand and simulate the changes which take place on seasonal and interannual time scales. If one were to try to identify the largest climatic change during this century, one would only have to look 6 months back because the seasonal cycle signal has the largest amplitude of any process on subgeologic time scales. Similarly, in terms of impact on human activity, the prospects of droughts or floods which take place on interannual time scales must be taken very seriously. Further, since the earth has such a complex climate, whose characteristics are established by so many interdependent processes, it is clear that making accurate predictions of climate change will require extremely sophisticated models of the atmosphere, oceans, cryosphere, and biosphere. Such models must be validated over ranges which are realizable and verifiable, such as the seasonal and interannual ranges. Also, these models will not be sufficient unless a substantial amount of new observations can be obtained to certify that the processes which are simulated in the models are indeed the important ones for climate change.

The state of technology has reached a level of maturity which may be sufficient to meet the requirements of modeling and observation mentioned above. Atmospheric general circulation models (GCMs) are

highly useful for short- and medium-range weather forecasting and expected improvements will make climate simulation more accurate as well. Data-assimilation systems have also become quite accurate, so much so that they are capable of identifying observing stations whose reports are inconsistent or inaccurate (Bengtsson and Shukla 1988). Computer resources are anticipated to be available in the next decade which will allow extremely high-resolution models to be used routinely for climate simulation. Space-based sensors are expected to be launched in the 1990s which will provide higher accuracy for atmospheric, oceanic, and land-surface observations.

It must be noted that, while these improvements in engineering and science applications are substantial, they will be poorly utilized unless we make the effort now to examine the ways in which the in situ and satellite data can be used and provide a basic scientific rationale for guiding the observations and modeling efforts; i.e., we must use the datasets we have in hand today and the models and computational resources currently available to provide guidance for the design and deployment of the space-based observing systems of the 1990s. The results of these studies will provide a benchmark against which to measure the products of the space-observing systems after they are launched. As has been implied in the discussion herein, the effort must be highly interdisciplinary because the components of the earth system are so diverse and because, until very recently, there has been very little interaction among the relevant disciplines, particularly as far as land-surface processes are concerned. The proper framework for evaluation of the hydrologic and energy cycles on time scales of one season to several years will require insights from atmospheric dynamics, radiative transfer, physical oceanography, and biosphere studies (including hydrology).

What we wish to provide in the following sections is a conceptual framework within which quantitative estimates of water and energy cycles can be obtained with the existing observational datasets and models. We believe that these goals are quite ambitious and that what we propose will be a multiyear, multiteam effort, but we also believe that the fundamental ideas must be discussed here and now in order to prepare properly for the coming decade.

This concept is distinct from other ongoing national and international programs in that *here we are concerned with obtaining a quantitative estimate of the seasonal and interannual variations of the hydrologic and energy cycles rather than the individual physical processes at the earth's surface and in the atmosphere which contribute to the modulation of the hydrologic cycle.* We believe that both approaches must be car-

ried out in close cooperation to achieve the goals of the two programs.

2. Scientific goals

We have discussed the worth of computing the hydrologic and energy cycles in the earth system, but we have not addressed the existing estimates of these cycles or the value that further refinements of such calculations will have. In this section, we will give a rationale for a new calculation of the water and energy cycles.

The paradigms for our calculations of the water and energy cycles will be Peixoto and Oort (1983) and Oort and Vonder Haar (1976), respectively. In those two papers, estimates from the best data then available were published, giving the fresh-water transport in the oceans as a residual in the former, and the total heat flux through the earth's surface and the divergence of the oceanic heat transport as residuals in the latter. Peixoto and Oort (1983) had deduced that the major sources of moisture in the atmospheric branch of the hydrologic cycle are the oceans, and that this is also true for precipitation over the continents; i.e., the precipitation over land generally has moisture sources in the oceans. They also found that the meridional transport of water vapor in the atmosphere is carried out mainly in the planetary boundary layer. Oort and Vonder Haar (1976) tabulated results for both the atmospheric and terrestrial branches of the energy cycle for monthly means, noting that heat storage in the land and cryosphere is negligible and that there is a large amount of cross-equatorial heat transport by the world oceans. Of additional interest in the latter study, the authors produced estimates of the reliability of their calculations indicating that for some of the components the uncertainty could be as large as one-quarter of the signal (e.g., divergence of oceanic heat transport) and that for other components there was even some uncertainty in the sign (e.g., oceanic heat storage).

For some of the components of these calculations, the sources of data and their reliability have become much better relatively recently. For example, in the calculation of the radiative flux at the top of the atmosphere and the radiative flux divergence in the atmosphere, the Earth Radiation Budget Experiment (ERBE) has produced a much more comprehensive view than was available in 1976 (Harrison et al. 1988; Jacobowitz et al. 1984). Likewise, several efforts are underway to estimate radiative flux at the surface. As another example, recent advances in data-assimilation techniques (Bengtsson and Shukla 1988) have made atmospheric analyses, particularly over the

oceans and in the Southern Hemisphere, much more reliable than those which were available prior to 1983. These two examples illustrate that the improvements in observations and techniques of utilizing observational data provide incentives for revisiting the water and energy cycles.

These improvements in our ability to observe and analyze atmospheric and oceanic parameters, albeit substantial, have only been applied to the mean, macroscale variables whose values are relatively easy to verify. When we come to the question of measuring the details of the hydrologic and energy cycles, the improvements will be put to a more stringent test. For the water cycle, there are a number of terms for which we have neither a good climatology nor a reasonable means of getting statistics for station observations of these terms. For example, the nature of evaporative flux makes it technically difficult to measure: over the ocean there are the problems of sea spray and large, breaking waves, which make the distinction between sea and air inexact, and over the land surface there are physical problems associated with trying to measure fluxes at the top of forest canopies 40 m above the ground. The energy cycle has both the problem of quantities which must be measured (e.g., radiative flux at the surface), and the problem of accuracy requirements. Since the quantities involved in the computation of the energy cycle are typically quadratic or higher order in the measured atmospheric variables, the observational errors become compounded in the energy calculation. However, the conservative nature of energy can provide a bound on this error. Since the total energy is conserved and since certain components of the total energy are approximately conserved, it is possible to exploit these integral constraints in computing the terms in the energy equations.

The utilization of the existing datasets, data analysis procedures, and models of the earth climate system to provide guidance for the space-based observing systems scheduled for deployment in the 1990s should be a major goal in the community. This may be manifested in two ways. First, since the necessary calculations will have stringent accuracy and sampling requirements, these requirements will place limits on the accuracy and sampling characteristics of the sensors which are flown on the proposed platforms. Second, and perhaps more important, the calculations will provide an estimate of which parts of the water and energy cycles are the most critical and least understood components. By making such an identification, we will be able to make recommendations about which quantities must have highest priority for retrieval, and which areas of the globe should get the most attention.

A second major goal should be the development of a database and a data-analysis procedure for the establishment of ground-truth for the space-based observing systems. For the water cycle in particular, the quantities which are retrieved from the satellite measurements may not be readily verifiable from the surface. As a result, it will be necessary to have data and means of creating data which can be used as ground-truth to calibrate the satellite measurements when they are available. While very complex schemes for the retrieval of water fluxes or energy fluxes may be contrived, it will be necessary to perform the assimilation and carry out observing-system simulation experiments to determine whether or not the retrievals are producing measurements of the appropriate quantities which are of the required accuracy.

The intercomparison and evaluation of different methods for computing the water and energy cycles of the earth system should be a third objective. We envision four types of datasets which may be used in this regard. The first, and most obvious type, is the existing set of operational atmospheric analyses from the National Weather Service (NWS) (Dey and Morone 1985) and the European Centre for Medium-Range Weather Forecasts (ECMWF) as well as the experimental ocean analyses being produced by the Climate Analysis Center (CAC) of NWS. Based on results reported by Bengtsson and Shukla (1988), these analyses are now quite accurate and representative of the state of the atmosphere at a given moment, and Leetmaa (pers. com. 1988) has reported that the ocean analyses being produced at CAC are of high quality and fidelity. The second data type will be the output of the reanalysis feasibility studies such as those conducted by ECMWF, Geophysical Fluid Dynamics Laboratory (GFDL), and Kinter et al. (1989). For example, in the latter study, the investigators have been studying the possibility of performing research in data assimilation using operational data assimilation tools. They will produce new analyses of the atmosphere for the periods 20 November 1982–1 March 1983, and 20 May–1 September 1984, which use the same input data as were available for the original analyses but incorporate all the improvements in data-assimilation techniques and atmospheric modeling which have taken place in the intervening time. For the shorter periods in question, the reanalyzed data should represent a better source than the original analyses. The third type of data will be from a long integration of a GCM. This dataset will include the systematic errors and climatic drift inherent in the GCM and will, therefore, be a less suitable source for actual computations of the water and energy cycles. However, this dataset is interesting because it will allow estimates of uncertainty in water and energy cycles due

to changes in interpolation techniques. Finally, after the GEWEX period, the retrievals from the GEWEX (Schiffer 1987), TRMM (Simpson et al. 1988), and/or Eos (Butler 1988) platforms will be available to recompute the water and energy cycles already calculated from the other datasets. In this way, we will be able to provide ground-truth.

The fourth goal should be validation of the GCM. Since we believe that our understanding of the global-earth system will primarily improve through the use of GCMs as both diagnostic and predictive tools, we consider it crucial to seek ways to validate GCMs so that we can be confident of their climate predictions. This is especially vital in the problem of climate change where it will be necessary not only to estimate the ultimate climate we may expect under an enhanced concentration of trace gases, but also to estimate the rate at which the transition to such an altered climate will take place. If we cannot have confidence in the GCM's capability to simulate the seasonal cycles of water and energy transports or its ability to reproduce observed interannual fluctuations in these cycles, we cannot have much confidence in the predictions made by such a model about the coming climate change. By validating the sensitive and necessarily accurate calculations of the global water and energy cycles, we will impose stringent and relevant tests on the GCM.

3. Suggestions for pre-GEWEX study

a. *The hydrologic cycle*

In broad terms, the hydrologic cycle may be characterized as having eight branches connecting five reservoirs. The five reservoirs are the world oceans, the atmosphere, the land surface including lakes and streams, the biosphere, and the world's ice and snow or cryosphere. The eight branches are oceans-atmosphere, oceans-cryosphere, land surface-oceans, land surface-biosphere, land surface-atmosphere, land surface-cryosphere, biosphere-atmosphere, and cryosphere-atmosphere. The reservoir having the largest mass of water is the world oceans. Water from the world oceans changes phase to the vapor stage through evaporation from the surface and is then transferred to the atmospheric reservoir. The atmosphere transports water vapor from place to place until the vapor condenses to liquid phase (clouds) and is precipitated out either back into the world oceans or onto the land surface reservoir. In regions of the land surface which are vegetated, the biospheric reservoir plays a major role in the disposition

of water. The remainder of the water precipitating on the land surface runs off into the lakes and streams, eventually reaching the world oceans. The fifth major reservoir of water is the ice and snow which may increase its store of water through accumulation of falling snow (from the atmospheric reservoir) and may decrease its store of water either through melting and runoff or through direct sublimation to the vapor phase.

The terrestrial reservoir of water must be differentiated into ocean surface and land surface in terms of its interaction with the atmosphere. Over the ocean, the major processes influencing the surface-energy budget and the fresh-water flux in the ocean are evaporation and precipitation. Over land, there are several processes, including evaporation and evapotranspiration, which influence the surface-energy budget, the surface-radiation budget, and the evolution of land-surface characteristics on many time scales. From a disciplinary point of view, the branches of the hydrologic cycle connecting the atmosphere and the other two climate system components, as well as the transport of water within the atmosphere, have been the subject of scrutiny by meteorologists, while the flow of water from the land surface to the biosphere and into the world oceans has been the topic for hydrologists. Oceanographers have looked at the fresh-water flux, but it has only recently been a topic of concern to ocean modelers. Thus, in order to get a complete view of the entire hydrologic cycle, it must be examined in a multidisciplinary framework.

A more quantitative description of the hydrologic cycle may be given as follows. If we consider the reservoir of water in the atmosphere only, we may define a quantity $\{q\}$ which is the vertically integrated specific humidity in the entire atmospheric column, also called the precipitable water. Taking the conservation equation for specific humidity in the atmosphere and integrating it vertically gives

$$\frac{\partial\{q\}}{\partial t} = E - P - \nabla \cdot \{q \mathbf{V}\} \quad (1)$$

where E is the rate of evaporation from the surface below the column, P the precipitation rate and \mathbf{V} the horizontal velocity vector. The vertical transport of water vapor has been integrated out of this expression. Thus, precipitable water is increased by evaporation from the surface and by moisture-flux convergence into the column, and is decreased by precipitation.

The oceanic reservoir of water may be similarly characterized, except that we will write an equation for the rate of change of surface salinity which is, of course, related to the fresh-water content.

$$\frac{\partial S}{\partial t} = -\mathbf{V} \cdot \nabla S + K_h \nabla^2 S + \frac{\partial}{\partial z} \left[K_v \frac{\partial S}{\partial z} \right] + S_o - S_i \quad (2)$$

where S is the salinity, K_h and K_v are the horizontal and vertical eddy diffusivities, respectively, and where the sources (S_o) and sinks (S_i) are directly related to the evaporation and precipitation, respectively.

If we were to write an equation for the land-surface reservoir, it would be complicated by the presence of vegetation and ice or snow. However, from the point of view of the atmosphere, we can write such an equation which obviates these details:

$$\frac{\partial W}{\partial t} = -E + P - R \quad (3)$$

where W is the land-surface moisture content and R is the runoff.

b. The hydrologic cycle over land

As may be seen from (3), there are four components in the moisture balance at the land surface. These are the storage term, the evaporation, the precipitation, and the runoff. We have not made a distinction between liquid and solid precipitation, although they may give very different properties to the underlying surface. We must recognize the differences between the vegetated land and bare soil because the presence of vegetation will make a substantial difference in the evaporation rate.

How can these four components be measured or computed? For land areas, it is clear that the precipitation rate is the easiest to measure of the four quantities; surface stations at varying densities over the globe record the accumulated rainfall or snowfall on at least a daily basis. In data-dense regions, such as the United States, this can give us a well-established observational basis to relate to the other measurements and to use for further calculations.

It should be noted that, in the long-term time mean, the tendency terms in (1) and (3) are much smaller than the other terms in those equations and can therefore be neglected. Then, again for a long-term time mean, it can be seen that the $(E - P)$ term is common to both equations but of the opposite sign. Thus, we can say that the land-surface runoff term is approximately equal to the convergence of vertically integrated moisture-flux convergence in the atmosphere. Insofar as we have sufficient confidence in the atmospheric data to compute the divergence of moisture flux, we can obtain one estimate of the temporal average of the runoff. An independent measure of the runoff may be obtained on the catchment-basin scale from streamflow measurements taken on a monthly

basis. This is because (3) may be horizontally integrated over any area of interest, such as a watershed for a particular river, and the resulting integral of runoff should be well correlated with the streamflow statistics for that river.

The two remaining terms in equation (3), $\partial W/\partial t$ and E , are much harder to obtain individually, since the W term is an aggregate of water stored both in the vegetation as well as in the soil and since the evaporation is a flux quantity the measurement of which is painstaking and demanding. We suggest that in order to make accurate measurements of either the water-storage term or the evaporation rate over land, a suitable model of the land surface must be used. Given a physical model of the soil properties, the properties of the vegetation canopy, and the properties of snow and permanent land ice, it is possible to reconstruct the soil moisture and vegetation amounts as well as the evaporation rate for a given set of atmospheric forcings (e.g., Sellers et al. 1986). As a by-product, with a given input of atmospheric parameters including the rate of precipitation, it is possible to use such a model of the land surface to compute the runoff rate as well. The latter can be used to verify the runoff calculations made by the two other methods or to validate the land-surface model.

c. The hydrologic cycle over the oceans

While the atmospheric data used to compute the moisture-flux convergence over the oceans have not (in the past) been considered of the same quality as their counterparts over land, advances in modeling and data-assimilation techniques during the last decade indicate that we may have some confidence in more recent analyses (Bengtsson and Shukla 1988). Thus, we may assume that, given the datasets described in section 2, it should be possible to arrive at reasonable estimates of the seasonal and interannual variations of moisture flux convergence over the ocean as well as over the land. However, the other terms in (1) and (2) are not so easy to obtain.

Just as we have no direct measurements of evaporation and water storage over land (except in a small sample of field experiments), there are no reliable observations of the evaporation over the ocean. A number of atlases have been published which include maps of the latent and sensible heat fluxes over the oceans (e.g., Esbensen and Kushnir 1981), but these have relied upon bulk aerodynamic formulae for the fluxes which, in turn, have required the use of less than well-known surface winds and drag coefficients. Even less well measured is precipitation. We have a number of island stations' time series of rainfall and there have been atlases published (e.g., Jaeger 1976), but the spatial coverage is quite limited

and the maps appearing in the atlases are in many areas based on assumption rather than on actual measurements. Finally, the liquid-solid transitions of water in sea-ice zones are very poorly known. The latter may have a substantial effect on the overall balance of fresh water in the oceans, but we do not have enough measurements to even make useful estimates.

A number of these observational difficulties are expected to be addressed by the advent of satellite data either from the GEWEX and TRMM sensors or from the Eos mission or both. However, before these observations are available, it will be necessary to provide evaluation criteria and accuracy requirements within the framework which will be used to analyze the satellite data. This framework will have to be a combined retrieval and data-assimilation procedure; parts of this are currently available, but will require considerable refinement before the data may be fully utilized.

The existing analyses and reanalysis datasets described above should be used to compute the hydrologic cycle over the oceans as follows. First, the moisture-flux convergence in the atmosphere must be computed exactly as in the GCM involved in making a first guess or long integrations. Second, the evaporation can be computed using the most reliable bulk formula available to data (Scoggins and Mooers 1988) from the best estimates of surface winds made by the GCMs involved. Third, the precipitation may be computed as a residual using Eq. (1). This computed precipitation would then be verified against other proxies for the rainfall rate including the outgoing longwave radiation (Arkin 1979) and microwave radiation based estimates such as that available from SMMR (see section 3e).

In order to close the hydrologic cycle over the oceans, it is necessary to take into consideration the fresh-water flux, or alternatively, salinity flux, as shown in (2). From the calculation of the atmospheric branch of the cycle, it should be possible to infer water transport over the ocean; this will have to be balanced by a reverse transport in the oceans (Peixoto and Oort 1983). Given Eq. (2), it is possible to verify this inferred transport of fresh water if one either has good estimates of the eddy diffusivities where the diffusion terms are important or has good estimates of the advecting currents in regions where the dynamic terms are important. It may be possible to perform the former calculation in a box-model framework, but wherever the advective terms are important (such as in the tropics and near the western-boundary currents of the midlatitudes) it will be necessary to have a reliable model of the ocean basin capable of simulating the distribution and transports of momentum and heat in response to an imposed wind-stress forc-

ing. Such models have already been integrated with observed wind stresses and the resulting ocean currents are available for diagnostic study of the transport of fresh water.

d. The energy cycle

The annual cycle of the atmospheric general circulation represents the largest "climate change" recorded by modern observations. Although the annual cycle of solar insolation is nearly periodic, and although it produces nearly periodic changes in the earth's climate, the interplay of the various radiative and dynamic processes which produce the observed changes in atmospheric circulation and rainfall are not fully understood. Energy conversion and energy-transport terms are, by definition, quadratic or higher-order moments, and therefore require relatively more accurate observations than what would have been required for a calculation of the mean of circulation variables. It is hoped that one can make more reliable estimates of energy conversions and energy transports utilizing a more complete four-dimensional (4-D) description of the atmospheric circulation.

A detailed and accurate calculation of the observed energy cycle is also required for a validation of global GCMs. In order that the predictions made by the global models about the future climate change be considered reliable, it is not sufficient that these models simulate only the observed mean climate, but they also must simulate the mechanisms which maintain the observed climate. This means that the model-simulated energy generation and dissipation, as well as energy transports, must also be in agreement with the current observations. In the absence of such similarity between the model-generated and observed energy transports, it would be difficult to rely on the predicted climate change, including the predicted water and energy cycles. The most important energy exchanges at the top of the atmosphere are radiative and at the bottom of the atmosphere (at land and ocean interface) are radiative as well as through sensible heating and evaporation. For fields of radiative-energy exchanges at top and bottom, one can simply take the most comprehensive datasets available for radiation budgets. The global fields of sensible heat flux and evaporation may be produced as discussed in sections 2b and c.

The basic energy equations for the atmosphere can be written as (Lorenz 1967)

$$\begin{aligned}\frac{\partial}{\partial t}(\phi + I) &= Q - C \\ \frac{\partial K}{\partial t} &= C - D\end{aligned}$$

where ϕ , I , K , are the potential, internal, and kinetic

energies of the atmosphere respectively, Q is the total heating, D the total dissipation and C the rate of conversion of total potential energy into kinetic energy by reversible adiabatic processes. Lorenz introduced the concept of available potential energy (A) which is the excess of total potential energy over that of a reference atmospheric state for which the total potential energy is minimum. We can further resolve the energy components and their conversions and dissipations due to zonally averaged motions and departures from the zonal mean (eddies). The equations for the energy cycle then become

$$\begin{aligned}\frac{\partial \bar{A}}{\partial t} &= \bar{G} - C(\bar{A}, A') - C(\bar{A}, \bar{K}) \\ \frac{\partial A'}{\partial t} &= G' + C(\bar{A}, A') - C(A', K') \\ \frac{\partial \bar{K}}{\partial t} &= C(\bar{A}, \bar{K}) - C(\bar{K}, K') - \bar{D} \\ \frac{\partial K'}{\partial t} &= C(A', K') + C(\bar{K}, K') - D'\end{aligned}$$

where bars refer to the zonal mean and primes refer to departures from the zonal mean. Conversion terms are given in the form $C(X, Y)$, which represents conversion from X to Y . The zonal mean and eddy-generation terms (\bar{G} and G') require calculation of the covariance of heating and temperature for which we can use the heating terms produced by the GCM. The conversion terms require the knowledge of general-circulation variables only and their calculation is relatively straightforward. It would then be possible to compare the new and earlier estimates.

One can make a comprehensive calculation of all components of the energy cycle (Lorenz 1967) using three-dimensional gridded data available from the operational numerical weather-prediction centers. We believe that only now with sophisticated data-assimilation techniques, the 4-D structure of the atmosphere is known with sufficient accuracy to calculate all the terms of the energy cycle independently. In the past, it was necessary to calculate some of the terms as residuals. It should now be possible to calculate the individual contributions of radiation and convection towards generation of zonal and eddy available potential energies. We are not aware of any comprehensive estimates of the relative importance of radiation and condensation processes in atmospheric energetics. It is also expected that the new datasets will produce more realistic estimates of the mean meridional circulations and conversions between zonal mean-available potential energy and zonal mean-kinetic energy.

We recognize that a mere description of the water and energy cycle does not necessarily lead to an ex-

planation either for the maintenance of the mean climate or for the causes of climate change. However, accurate quantitative estimates of the various components of the energy cycle including energy conversions and energy transports are absolutely necessary to validate the global models and to advance possible theories for climate change.

First, the atmospheric energy cycle should be calculated using GCM datasets which are complete and internally consistent. All the "observations" are available at the vertical coordinate surfaces for the model and therefore all the calculations can be done exactly for the GCM fields. Then model fields can also be interpolated to pressure surfaces and the energy cycle calculations can be repeated. This will provide an estimate of the uncertainty in the present day estimates of energy conversions and energy generations.

e. Evaluation and validation

Once analyses of the global water and energy cycles have been produced, it will be necessary to verify that the results are accurate or at least in agreement with the corresponding independent observations. There are two procedures involved in the validation process. The first is to estimate the degree of uncertainty in the analyses based on either a priori estimates of the observational error or on comparisons with the available data. This is a fairly routine procedure which can be carried out to obtain gross estimates of the uncertainty.

The second procedure for validating the calculations of the water and energy cycles requires a broad range of comparisons involving as many datasets and independent measurements as possible. These comparisons can be made against four datasets. First, one can compare with station data at land points. For example, estimates of the precipitation at each analysis point can be interpolated to stations (under some constraints due to the short correlation length scale of precipitation) and verified against the station rainfall and snowfall records in the same way as analysis-error statistics are computed for data assimilation. These verifications can be repeated for spatial and temporal averages. This can also be done for the aerological data at upper-air stations to verify the atmospheric branch of the water and energy cycles. Second, one can compare with precipitation estimates over the oceans from outgoing longwave radiation (OLR) and Scanning Multichannel Microwave Radiometer (SMMR) data. It has been shown that precipitation anomalies are well correlated with the OLR anomalies over the tropical oceans on monthly-to-seasonal time scales (Arkin 1979). It has also been shown that SMMR data may be used to infer the rainfall rates over land (Spencer et al. 1983), in tropical cyclones (Olson 1987), and more generally over the

ocean (Wilheit et al. 1977). By these two techniques, —station data and satellite data verifications—one can independently check the estimates of precipitation produced both over the land and the oceans.

A third source of data for the verification of the global water and energy cycles is the Earth Radiation Budget Experiment (ERBE) estimates of the radiative flux at the top and bottom of the atmosphere (Jacobowitz et al. 1984). These data will not only provide the input for the solar radiative flux, which are needed to compute the energy cycle of the earth system, but can provide other verifying data for comparison with the computed energy cycle. For example, there are several estimates of the cloudiness and cloud-radiative effects available from the ERBE dataset which are potentially of use in evaluating the performance of the radiative transfer algorithms in the GCM. The fourth source of data will be the satellites which are launched in the 1990s associated with the GEWEX (Schiffer 1987), Eos (Butler 1988), and TRMM (Simpson et al. 1988) missions. Of course, the calculations described herein are intended to provide guidance for the design and deployment of those missions, but once they are flying, it will be possible to use the retrievals from those satellite sensors to validate and refine the estimates produced.

Finally, it can be noted that the conservative nature of the water and energy cycles is such that a number of integral constraints may be utilized in verifying parts of the results. For example, if (1) and (3) are averaged over the land surface of the earth and a time average of sufficient length is taken, the result is

$$\overline{\langle \nabla \cdot \{q \mathbf{V}\} \rangle} = \langle \bar{E} \rangle - \langle \bar{P} \rangle = - \langle \bar{R} \rangle$$

where the overbar represents the time average and the angle brackets represent the areal average. If the same operation is applied over the oceans, we obtain

$$\overline{\langle \nabla \cdot \{q \mathbf{V}\} \rangle} = \langle \bar{E} \rangle - \langle \bar{P} \rangle.$$

For global balance, the left-hand side (LHS) of the first equation must be equal and opposite to the LHS of the second. Thus, the $E - P$ deficit integrated over the oceans is equal and opposite to the same quantity over the land or, in other terms, to the integrated runoff. Since the calculation of this runoff may be done in several ways, as suggested above, there are many independent methods to evaluate the water cycle over the oceans.

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Report on the Second International Conference on School and Popular Meteorological and Oceanographic Education

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1. Introduction

The Second International Conference on School and Popular Meteorological and Oceanographic Education, organized and sponsored by the American Meteorological Society (AMS), was held 12–16 July 1989 at the Stouffer Concourse Hotel in Crystal City (Arlington), Virginia. The Royal Meteorological Society (RMS) and the World Meteorological Organization (WMO) were cosponsors. Organization of the conference was carried out by the AMS Board on School and Popular Meteorological and Oceanographic Education¹ (BSPMOE), working through the International Organizing Committee.²

The conference attracted a large number of general (nonspecialist) educators: of the 191 registered attendees, 112 were classroom teachers of grades K–12. Forty-six of those registered were AMS members.

The attendance of 99 precollege teachers was supported by the AMS using funds obtained from the Science and Engineering Education Directorate of the National Science Foundation (NSF). These teachers were drawn from 41 states, the Commonwealth of Puerto Rico, and American Samoa.

The conference focused on two themes: the role of the atmospheric and oceanic sciences in the formal science education of students, and the general education of the public in the use of the services and

products provided by national environmental services and the media. However, because of growing interest in the United States in improving education in general and science education in particular, the first theme was dominant. Perhaps 65 of the 76 presentations highlighted techniques for using topics in the atmospheric and oceanic sciences in the classroom.

2. Conference summary

The conference opened with an informal organizing session. Since it was anticipated that many attendees would not be members of the professional meteorological or oceanographic communities, a brief overview of each sponsoring agency was presented in this session. J. M. Walker (University of Wales, Cardiff, United Kingdom) described the RMS and some of its educational activities; G. V. Necco (WMO, Geneva, Switzerland) described the organization and role of the WMO; and R. E. Hallgren (AMS, Boston) sketched the organization and history of the AMS.

Following the organizational session, all classroom teachers attending the conference convened and were requested to complete a preconference survey. Developed by E. L. Kern (Southeast Missouri State University, Cape Girardeau, Missouri), this survey was designed to provide the AMS BSPMOE with a sampling of the current status of teaching of the atmospheric and oceanic sciences at the precollege level.

Participants were welcomed to the conference on behalf of the AMS by President J. Simpson at a formal opening session on Thursday morning, 12 July. President Simpson was followed by the keynote speaker for the conference, H. O. Anderson, president of the National Science Teachers Association (NSTA). Anderson outlined several NSTA initiatives intended to revitalize the teaching of science in the nation's schools by developing an integrated and comprehensive curriculum.

The formal program was subdivided into 12 sessions. Sessions 8 and 9 were unusual in that each

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¹ The 1989 AMS BSPMOE includes J. Borden, R. Breck, P. F. Giddings, L. M. Keller, S. J. Richards, B. W. Schwoegler, D. R. Smith, J. T. Snow (chair), S. D. Steinke, N. E. Surgi, and R. A. Yaros.

² The International Organizing Committee for the conference included: H. A. Friedman, E. L. Kern, H. M. Mogil, G. V. Necco (WMO), S. J. Richards, D. R. Smith, J. T. Snow (chair), O. E. Thompson (chair, Local Arrangements Committee), J. M. Walker (RMS), J. Williams, R. S. Weinbeck, and R. A. Yaros.