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DEPICTION OF MODERN AND PANGEAN DESERTS:

EVALUATION OF GCM HYDROLOGICAL DIAGNOSTICS FOR PALEOCLIMATE STUDIES

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ABSTRACT

Hydrologic patterns are imprinted in the geologic record and play a prominent role in the investigations of Pangean climate. However, the hydrologic aspects of climate are complex: 1) many variables are required to analyze hydrology, 2) hydrologic processes act on spatial scales that are smaller than GCM grid spacing, and 3) observational data bases for calibrating modern climate simulations are few. This study, which uses a GCM to depict arid climates of the past and present, is designed to evaluate a variety of simulated hydrologic variables which are becoming increasingly available for paleoclimate model/data comparison studies.

Simulations of the current climate show that there are quantifiable levels of precipitation (P), soil moisture, and surface runoff that delineate the locations of modern deserts. However, in a Pangean simulation, using the same model, the threshold values of these variables reveal disparate views of desert extent. Altered boundary conditions and atmospheric circulation can invalidate thresholds based on modern climatology. The credibility of these variables, thus, rests heavily on the accuracy of reconstructed boundary conditions. A more fundamental meteorological approach defines deserts as regions where the atmospheric demand for moisture (potential evapotranspiration, E_p) exceeds the supply (precipitation, P). GCM values of E_p are overestimated, thus simulated P-E_p fields are unusable. However, simulated E_p values can be derived independently using GCM-produced temperature values in empirically derived equations (E_{Tp}). Similar methods, using observed temperatures, are employed by atmospheric scientists to construct global and regional E_p data sets. The results of this study indicate

that $P\text{-}E_{Tp}$ is more accurate than other individual variables for calculating moisture balance and is more useful for paleoclimate model/data comparisons because of its fundamental meteorological basis and lack of dependence on prescribed vegetation and soil conditions. Ultimately, hydrological misinterpretations can be avoided by understanding the limitations of GCM parameterizations and by strictly cross-checking variables with each other and with available paleoclimate data.

INTRODUCTION

During the Triassic and Early Jurassic, Pangea was characterized by globally warmer temperatures and extreme hydrological conditions. Several paleoclimate modeling experiments have investigated the first phenomenon, past global warming, but only recently has an increasing accessibility to general circulation models (GCMs), which explicitly calculate the hydrological cycle, allowed modelers to present hydrological results. In part, the focus has been directed by an immediate need to understand the processes involved in global warming but, also, most climate models are particularly suited to temperature studies; GCMs can produce realistic likenesses of observed temperature fields but are inherently less accurate at simulating hydrological conditions. The reasons for this are numerous, among the most important being: 1) many variables are required to analyze hydrological conditions, 2) critical hydrological processes act on small spatial scales and give rise to fields with spatial variability that is not resolvable by GCM grid spacings, and 3) global hydrological data bases for the modern climate are sparse, making model calibration difficult. Ultimately, these complexities have forced most GCMs to use extremely simplified parameterizations for hydrological processes. Despite the model limitations, many paleoclimate studies are regularly presenting simulation results for variables such as precipitation, evaporation, soil moisture, and surface runoff. Moreover, model experiments are a necessary step in order to analyze the processes that connect cause (climate forcings) and effect (the geologic record).

In this paper I use a GCM to depict arid regions in the modern climate and to define the locations of Early Jurassic arid zones. While it is important to consider whether a GCM can help locate specific Pangean environments, the primary purpose of this study is to evaluate the simulated hydrologic fields, as these fields are becoming increasingly available for model/data comparisons. Arid climate depiction presents several advantages for discussing a variety of diagnostics. First, annually averaged results can be used to distinguish arid regions since true deserts are dry year round. Additionally, modern desert boundaries are easier to define than most other hydrological zones. Arid systems are also less affected by vegetation-atmosphere interactions, thus results presented here are less dependent on the GCM's vegetation scheme. This implies that the solutions may be comparable to observations, while conclusions might apply to a variety of GCMs.

GCM Description and Hydrological Parameterizatons

The model used for the simulations presented in this paper is the Goddard Institute for Space Studies (GISS) atmospheric general circulation model. This version of the GISS GCM has nine vertical layers in the atmosphere and an 8° x 10° horizontal resolution. It uses realistic topography and a fractional grid system, which allows coastal grid boxes to contain portions of both land and ocean. The GCM solves the conservation equations for mass, energy, momentum and moisture. Radiation equations account for aerosols and trace gases, as well as cloud cover. Clouds are predicted and include both convective and large-scale varieties. The annual results presented in this paper are averaged from full seasonal cycle simulations which included seasonal heat storage and diurnal temperature variations. Ground hydrology and surface albedo are functions of specified vegetation types, and are discussed in more detail below. Atmospheric CO_2 was fixed at 1958 levels (315 ppm) for both experiments and current orbital configurations were used. A complete model description and results from the modern climate control experiment are presented in Hansen and others (1983). Chandler and others (1992) present a detailed description of the Early Jurassic simulations.

Most GCMs employ simple ground hydrology and land surface schemes that promote moisture and heat feedbacks without necessarily recreating the true physical processes. Table 1 summarizes a few of the common parameterizations used in GCMs during the past decade. Vegetation distributions in these models are represented by variations in ground albedo, while groundwater and soil moisture are represented using constant-depth reservoirs or "buckets" to simulate the water holding capacity of upper ground layers. Groundwater reservoirs and subsurface flow are ignored. Surface runoff occurs when a grid cell's ground reservoir becomes saturated and precipitation exceeds evaporation over that cell. The GISS GCM has a slightly more complex parameterization, using two layers in the ground with water holding capacities that vary by vegetation type and season (Hansen and others, 1984; Hansen and others, 1983). Vegetation types may be specified from any of 8 categories (Table 2). Soil moisture in the GISS-GCM is defined as the time-averaged amount of water residing within the two ground hydrology layers. Moisture exchange from the upper layer takes place via precipitation, evaporation, and surface runoff and water is immediately available for evaporation from the upper layer during all seasons. In an attempt to mimic transpiration, the moisture of the lower layer is available in vegetated regions only, and only during the growing season (defined as year round, equatorward of 30°; May-August from 30°-90°N; November-February from 30°-90°S). At other times no water escapes the lower layer, although water may still diffuse in from the upper layer. Curiously (and probably incorrectly), the parameterization implies that in desert regions, which are assumed to have no growing season, water can never escape the second layer; a fact which creates a lower limit for desert dryness that is equal to the amount of water initialized in the second layer. Ground albedo is also a function of vegetation type (Table 2) and in winter vegetation partially masks the high albedo characteristics of snow. Surface runoff depends on precipitation rate, as well as absolute soil moisture, in an attempt to represent the lower infiltration rates that exist during downpours. Although more detailed, this scheme does not include realistic physical representations of ground-vegetation-atmosphere interactions.

Detailed hydrological schemes, which contain explicit representations of components such as vegetation canopies, rooting depths, soil infiltration, and plant physiology have been developed for use in several GCMs (Abramopoulos and others, 1988; Dickinson, 1984; Pollard and Thompson, 1993, Sellers and others, 1986). Such schemes should be incorporated as they become available because the added realism allows for process oriented studies. However, more realistic land surface schemes do not necessarily lead to improved climate simulations by themselves. The complex physical processes are not easily scaled to the coarse resolutions of a GCM (Rind and others, 1992) and, for most GCMs, the altered hydrology will require model "retuning" to achieve the best possible modern climatology. Further studies are required to evaluate whether or not these schemes will be useful for paleoclimate simulations. Many of the required input parameters are difficult, if not impossible, to estimate from the geologic record and the trade-off between increasing process reality and decreasing boundary condition reality has unknown ramifications. A likely benefit of the new schemes is that they should act to encourage detailed investigations of paleofloras and paleosols .

DESERTS: DEFINING ARID REGIONS

Modern Deserts and Their Causes

By most definitions, deserts make up approximately 20%-25% of the present day land surface (excluding Antarctica). Figure 1 shows the modern distribution of arid and semi-arid continental regions as compiled from meteorological data and proxy characteristics. Aridity in these regions results from several factors (see table 2). Most low latitude deserts are located between latitudes 10°N and 35°N and between 10°S and 35°S (e.g. Sahara and Kalahari Deserts, Africa). These deserts result from large-scale atmospheric subsidence associated with the poleward limb of the Hadley cell. This subsidence reduces relative humidity by heating the air adiabatically, suppressing cumulus convection and precipitation along with cloud cover. The lack of clouds allows the intense low latitude solar radiation to reach the surface, elevating ground temperatures and evaporation rates (Wallace and Hobbs, 1977, p.429-430). Once developed, positive feedbacks help to maintain desert conditions. Desert pavements, bare sand, and high albedo vegetation reflect up to 35% of the incoming solar radiation, reducing sensible heat flux and convection, and low ground moisture levels keep evaporation at a minimum, thus sustaining a dry atmosphere above the desert.

Arid regions may also exist outside of the subtropical latitudes (Fig. 1 and Table 2). For example, extensive deserts are located in the interiors of large continents where moisture sources are distant (e.g. Taklimakan and Gobi Deserts, Asia), in the rain shadows of mountain ranges (e.g. Patagonian and Monte regions, S. America), and adjacent to zones of ocean upwelling, where cool waters reduce evaporation and convection (e.g. Peruvian- Atacama Desert, S. America). The world's most arid conditions result from a combination of affects. The central Sahara, for example, is located beneath the descending limb of the northern hemisphere Hadley cell and is within the continental interior of north Africa. In southwestern Africa, the Namib desert lies beneath the descending limb of the southern hemisphere Hadley cell and is adjacent to a cool upwelling zone associated with the Benguela Current (Zinderen Bakker, 1975).

Any attempt to use computer models to predict the distribution of past or future deserts first requires an objective definition of an arid region. Furthermore, any diagnostics that are applied from

GCM simulations must, as an initial test, successfully reproduce the distribution of present day deserts. A good starting point, therefore, is to ask, what constitutes an arid region in the modern climate and to what extent can a GCM depict modern arid regions?

Defining Aridity

From a meteorological standpoint, arid zones are defined as regions in which the atmospheric demand for water exceeds the supply. Thus, direct measurements of hydrological parameters should provide the most definitive and quantitative estimates of aridity in the current climate. The balance of atmospheric moisture can be obtained by differencing the rate of precipitation (P) and the potential rate of evapotranspiration (E_p), with P representing the atmospheric supply of water and E_p being the theoretical atmospheric demand for moisture (Thornthwaite, 1948). Depiction of deserts, following this definition, requires detailed observations of precipitation as well as ground temperature, surface air temperature, wind velocity, and an estimate of the turbulent transfer coefficient, since these values are used in the calculation of potential evaporation (E_p):

$$E_p = C_Q V(q_g - q_s) \qquad (1)$$

where
C_Q turbulent transfer coefficient
V surface wind speed
q_g specific humidity at ground level
q_s specific humidity of the atmosphere at 30 meters height above ground.

These values are not monitored at most locations and, when vegetation interactions (particularly transpiration) are included "observed" values of E_p are virtually unobtainable. This fact has lead several researchers to derive empirical formulas for the calculation of potential evapotranspiration based on studies of bioclimatic interactions (see Holdridge, 1959; Köppen, 1936; Penman, 1948; Thornthwaite, 1948). In practice, arid regions generally are identified using more traditionally measured hydrological variables, such as precipitation, evaporation, soil moisture and runoff. Maps of these variables reveal a reasonable degree of correspondence with the location of modern deserts.

Arid Regions: GCM Results versus Modern Climatologies

The diagnostics that are most commonly used to assess continental moisture balance in GCM simulations are: precipitation (e.g. Manabe and al., 1965; Pitcher and others, 1983), the difference between precipitation (P) and evaporation or evapotranspiration (E) (e.g. Rind, 1984; Shukla and Mintz, 1982; Sud and Smith, 1985; Voice and Hunt, 1984), soil moisture (S_m) (e.g. Kellogg and Zhao, 1988; Milly, 1992; Rind, 1982; Zhao and Kellogg, 1988) and surface runoff (R_s) (e.g. Rind, 1984; Russell and Miller, 1990). More recently, several studies (Delworth and Manabe, 1988; Milly, 1992; Rind and others, 1990) have discussed the use of potential evapotranspiration as a diagnostic variable in GCM experiments, stressing the important distinction between the potential and actual rates of evapotranspiration for evaluating moisture balance. However, these studies also point out some severe problems with using GCM calculated E_p values, a matter discussed in detail below.

In the following sections global distributions of the above hydrologic fields are presented for a current climate GCM simulation. The accuracy of simulations is commonly assessed by comparing simulated results with global observational data bases.

Unfortunately, excepting precipitation, global data bases for hydrological variables do not exist. Instead, global data for evapotranspiration, soil moisture and surface runoff are calculated from a combination of analytical and empirical techniques (e.g. Korzun, 1978; Thornthwaite, 1948; Willmott and others, 1985), which use observed temperature and precipitation to estimate water balances. The global data bases, which represent long-term temporal averages, are referred to as climatologies in the following sections. Readers should be aware that the difference between hydrological climatologies and true measurements may, at some locations, exceed the difference between climatologies and GCM results, however, there is no way to accurately evaluate the magnitude of the errors. The lamentable state of current global monitoring projects suggests that this will be a problem for many years to come.

Precipitation

Precipitation is the most reliable of the hydrological global climatologies and the quality of other hydrologic fields relies heavily on the precipitation climatology. The Legates and Willmott (1990) data base, used here, consists of measurements made at 26, 858 stations, 91 percent of which are land-based. Figure 2a shows the global mean annual precipitation based on this data. The standard deviation of the annual precipitation is commonly 25% of the absolute measurements and exceeds 50% in some tropical locations (compare Figs. 3 and 4 in Legates and Willmott, 1990).

Comparing the observed precipitation rates in figure 2a with the GISS GCM simulated modern precipitation (Fig. 2b) shows that the 8° X 10° version of the GISS GCM generally reproduces the Earth's major precipitation zones. In particular, the precipitation values over the major deserts are similar to observations, although, the difference map (Fig. 2c) shows that most arid and semi-arid regions are slightly wetter than observations indicate. Comparing the precipitation results to the distribution of modern world deserts (Fig. 1), using a limit of 25 cm of rain per year (0.7 mm/day) to define arid climates (Glennie, 1987), shows that the GCM simulates aridity in the Sahara, as well as in deserts such as the Peru-Atacama and the Namib, which are downwind of cool ocean currents. The deserts of central Asia, southwest North America and Australia are dry relative to surrounding regions, yet they receive more than 0.7 mm/day of rain and are wetter than observed. Excess rainfall in Australia is likely a response to the altered position of the intertropical convergence zone (ITCZ) which, in the simulation, is displaced too far north in the Pacific and Indian Oceans. This decreases the amount of atmospheric subsidence occurring over Australia (as compensation to convection in the ITCZ) and reduces drying that, in the real world, occurs as a result of that subsidence. Central Asia and the southwestern U.S. are drier in finer resolution (4° X 5° and 2° X 2.5°) versions of the GISS GCM, suggesting that the lack of simulated aridity in those regions is caused by the inability of the coarser grid to resolve the Himalayan and coastal Californian ranges, thus reducing their rainshadow effect.

The precipitation diagnostic apparently yields a reasonable first-order estimate of the distribution of arid regions. However, pitfalls certainly exist when using precipitation patterns alone. Precipitation represents only the supply portion of the moisture balance calculation (Glennie, 1987; Rind and others, 1990) and, in

GCMs, the moisture supply is typically dependent on parameterizations of convection and cloud formation, which are heavily tuned to the present day climate. In addition to the moisture supply, most climatologists prefer to consider moisture losses (i.e. evaporation, transpiration) when interpreting hydrological patterns from climate change simulations.

Precipitation Minus Evaporation

The evaporation field calculated by the GISS GCM differs from the evapotranspiration climatology of Willmott and others (1985) by approximately the same order of magnitude as did simulated precipitation values (Fig. 3a). The tendency, in arid regions, particularly, is for the evaporation to balance the overestimated precipitation. Many paleoclimate studies have used the difference between precipitation and evaporation rates (P-E) as a diagnostic for determining patterns of aridity from GCM simulations (Barron and others, 1990; Chandler and others, 1992; Kutzbach and Gallimore, 1989; Voice and Hunt, 1984). As figures 3b and 3c show, negative P-E values are located, primarily, in subtropical regions and they identify those deserts that lie beneath the large-scale atmospheric subsidence associated the poleward limbs of the Hadley cells. Nevertheless, difficulties arise when interpreting the GCM P-E fields.

Over continents, GCM evaporation rates (E) are calculated as,

$$E = \beta E_p \quad (2)$$

where

β ground wetness factor (1 for saturated soils, 0 for dry soils)

E_p potential evaporation

The factor ß is limited by the moisture supply (Hansen and others, 1983), which includes precipitation, soil moisture, and the influx of runoff from regions up slope. If no soil moisture is available, as in deserts, the evaporation is limited to precipitation plus runoff. In current GCMs, runoff is calculated for diagnostic purposes but is not included in moisture supply calculations because GCM Cartesian grid arrangements do not resolve drainage basin patterns or hydrology. Thus, for a simulation that has reached equilibrium, continental deserts are not identifiable using this method because, without soil moisture or runoff, evaporation is limited by precipitation and, by definition, P-E cannot be negative. An analysis method, sometimes employed with GCM paleoclimate simulations, involves initializing all soils with a large supply of moisture then comparing the precipitation and evaporation rates as the simulation approaches an equilibrium state (but before soil moisture has been depleted in any location). Of course, since results may be affected by initial conditions (e.g. Shukla and Mintz, 1982) the method is of questionable use for paleoclimate experiments, where soil boundary conditions are poorly known.

Soil Moisture

The soil moisture (S_m) climatology shown in figure 4a was calculated using water balance equations that rely on observed precipitation and surface air temperature values (Willmott and others, 1985). Error estimates for the data are unavailable due to the lack of true measurement control, thus quantitative evaluation of the GCM's performance versus reality is not possible. Adding to the complexity, values used to represent "soil moisture" in a GCM are not necessarily directly comparable to the S_m climatology. Still, a qualitative comparison between the GISS GCM soil moisture values (Fig. 4b) and the S_m climatology is possible. GCM values of S_m are relatively dry over observed arid regions, implying that the soil moisture parameterization does respond to both atmospheric supply and demand; absorbing precipitated water and releasing it again through evapotranspiration. GCM values are wetter (10 to 30 mm) in most desert regions than the climatological data, which lie between 5 and 10 mm. This is consistent with the GCM's overestimated precipitation. Not surprisingly, regions that should reside in rainshadows (southwest U.S., central Asia, southern Patagonia) are the most poorly resolved by the GCM, again because the poorly resolved topographic barriers do not sufficiently intercept water vapor transports.

Qualitative comparability between simulated S_m values and modern desert locations does not necessarily make this a useful paleoclimate diagnostic. Simulated soil moistures can be sensitive to the model's specified water field capacities, a fact that Kellogg and Zhao (1988) and Zhao and Kellogg (1988) showed. In their studies, the GISS GCM, with variable field capacities from 2 to 65 cm, gave consistently higher soil moisture values than NCAR, UKMO, and GFDL GCMs, which have 15 cm field capacities. One might suspect that the GISS GCM, with variable capacities based on vegetation type, might give a better quantitative representation of S_m, but that is difficult to conclude based on available experiments. The concern remains, however, that positive feedbacks such as high albedo and low water field capacities, which tend to keep deserts arid, could bias model results if ground conditions are assigned incorrectly. The desert ground hydrology in the GISS GCM has a low soil moisture capacity compared with the other categories in the model (Table 2) and is generally initialized with lower amounts of ground water. For current climate experiments such specifications are justified, since they approximate known ground conditions. However, for paleoclimate simulations, where initial ground conditions are largely unknown, specified conditions, whether uniform or variable, may force the result unrealistically. Regardless, many paleoclimate experiments have, and will continue, to report soil moisture values, because they offer a single value that represents the GCM's regional supply and demand for water (e.g. Moore and others, 1992; Valdes and Sellwood, 1992).

Surface Runoff

Surface runoff (R_S) values, like soil moisture, can be qualitatively correlated with moisture availability; the lowest values do approximate desert locations in the current climate. A global, surface runoff climatology, produced by Korzun (1978) for use with the NCAR 4.5° x 7.5° GCM (Fig. 5a), was calculated using river discharge records modified by a "runoff coefficient"; a factor based on observed P-E values. Although not strictly observational, Korzun's data set provides one comparison for GCM runoff results (Fig. 5b). Compared to Korzun's climatology, the GISS GCM simulates R_S values that are higher across North America, and lower in Amazonia. However, basic patterns of wet and dry, are similar in both results and the absolute range of values are very close.

Like soil moisture, the GCM runoff diagnostic is not necessarily defined in a comparable manner to the Korzun climatology. Field measurements of R_S include data for stream and river outflow rates and are averages over individual drainage basins. Currently, GCM ground hydrology schemes do not distinguish the hydrological aspects of drainage divides, therefore, simulated R_S values are contoured from the model's grid system without regard to directional flow. The surface runoff calculated by most GCMs is a function of precipitation and evaporation rates as well as the saturation of the ground layer(s). In the GISS GCM runoff is parameterized as,

$$R_S = \tfrac{1}{2} W_1 P \qquad (3)$$

where W_1 is the water field capacity of ground layer 1 and P is the precipitation rate. Such simple parameterizations, obviously, do not capture the complexity of ground hydrological processes, but they were originally incorporated into GCMs as a means of supplying a reasonable moisture feedback to the atmosphere.

A more appropriate surface runoff diagnostic can be computed based on the aerial extent of drainage basins. Russell and Miller (1990) grouped the grid boxes in the GISS GCM by their locations with respect to drainage basin geography. They then compared the GCM results with the outflow from 33 of the world's largest rivers. Their comparison shows that, for some basins, the model yields reasonable results; however, R_S from the arid climate drainage basins are conspicuously overestimated (Fig. 6). The combination of too much precipitation in desert regions, the small water holding capacities of the desert ground hydrology layers, and the fact that surface runoff is not allowed to evaporate while in transit to the oceans, are likely causes for this overestimation. It is not known how the GISS GCM compares to other GCMs in this respect since similar experiments are not available for comparison. Unfortunately, the extent of ancient drainage basins are difficult to predict and the effective overall outflow of past river systems is even more difficult to estimate. Thus, even if the simulated R_s values can be improved to the point where they match modern values, it will be difficult to validate paleoclimate counterparts. In some experimental situations, Rs values may have an additional analytic importance, a factor I will discuss for the Early Jurassic experiments.

Drought Indices and the Significance of Potential Evapotranspiration

Drought indices (Palmer, 1965; Rind and others, 1990) are commonly used to analyze the intensity of atmospheric moisture deficits over land. They act as indicators of relative moisture availability since they have climatological means that equal zero for the current climate. Such indices calculate moisture balance using the *potential* rate of evapotranspiration (E_p) rather than the *actual* rate of evapotranspiration (E_a). Thornthwaite (1948) showed that when moisture is deficient, E_a is limited, because plants close their stomatal openings in order to conserve water. This limits E_a to some value beneath the true atmospheric demand for moisture. E_a is only equivalent to E_p (the true atmospheric demand for moisture) over free water surfaces or when water is plentiful in the ground because then evaporation and transpiration are not restricted. The dependence of E_a on available moisture suggests, therefore, that the true moisture balance of a region is obtained by comparing E_p (demand) with the rate of precipitation (supply).

Since a climate is arid when moisture demand exceeds supply ($P-E_p < 0$) over long periods of time, it would seem simple to compare the GCM simulated P and E_p values to define regions of aridity, either in current or paleoclimate settings. Unfortunately, this is not the case. Model calculated values of E_p, over continental regions, tend to be much larger than estimated values (Delworth and Manabe, 1988) for reasons which are only recently being addressed (see Rind and others, 1990; Milly, 1992). Figure 7a shows the simulated precipitation minus potential evapotranspiration ($P-E_p$) from the GISS GCM current climate control run. The resulting $P-E_p$ field indicates that all continental regions should be interpreted as arid. The problem arises because the GCM calculates high gradients between the ground temperature (T_g) and the surface air temperature (T_s), which leads to an increase in the specific humidity gradient (q_g-q_s), resulting in elevated values of E_p (see equation 3). As Rind and others (1990) have shown, the real world, unlike the simulated world of the GCM, contains a vegetated surface, or "canopy". The canopy is cooled by the process of transpiration, therefore, T_g does not get large. This keeps the ground to surface temperature gradient small, which, in turn, keeps the value of (q_g-q_s) low, reducing values of E_p. Future versions of most GCMs will include a simulated vegetation canopy in order to combat this problem. Developmental versions of such routines tested in the GISS GCM show that they improve the potential evaporation estimates but do not completely solve the problem.

Precipitation Minus Thornthwaite's Potential Evapotranspiration

Although E_p values generated by the GCM are not directly useful, potential rates of evapotranspiration can be calculated using the GCM's simulated surface temperature results together with empirical bioclimatic formulas, such as those of Thornthwaite (1948) or Penman (1948). Willmott and others (1985) employed such a technique, using observed temperature and precipitation fields, to derive their soil moisture estimates, discussed above. In their work they used a modified version of Thornthwaite's (1948) equation:

$$E_{Tp}(M) = 1.6(10T(M))/I)^m \,x\,(dayl/12)\,x\,(daym/30) \quad (4)$$

where

T(M)	long-term mean monthly temperature (°C)
I	annual heat index, $\sum_{12}^{1}(T(M))/5)^{1.514}$
m	$(6.75x10^{-7})I^3 - (7.71x10^{-5})I^2 + (1.79x10^{-2})I + 0.492$
$dayl$	daylength (hours)
$daym$	number of days in month

which yields monthly average potential evapotranspiration ($E_{Tp}(M)$) values. An important advantage of using the empirical equation is that E_{Tp} can be derived using only the simulated surface air temperatures as input. This is especially useful since surface air temperatures are considered to be a robust diagnostic field in GCMs. Differences between the E_{Tp} values and the GCM precipitation field are shown in figure 7b, giving a new estimate of the distribution of arid regions. P-E_{Tp} produces a reasonably good estimate of the distribution of aridity, showing dry conditions in all of the major deserts worldwide. The index slightly overestimates the dryness of southern Amazonia and underestimates the aridity of eastern Africa, both of which are caused by inaccuracies in the simulated precipitation rates over those regions. The P-E_{Tp} field also predicts drier than observed conditions in the southeastern United States and in the Congo.

Although this technique is widely used for hydrological studies of the modern climate, rarely is it used in paleoclimate experiments.

Advantages of the technique for paleoclimate model/data comparisons include an ability to successfully depict modern arid regions, a basis on fundamental meteorological principles, and the chance to calculate GCM moisture balance while largely circumventing the dependence on simplistic ground hydrology parameterizations.

ARID REGIONS: GCM RESULTS FOR THE EARLY JURASSIC

The expansion of desert regions into tropical and mid-latitude zones during the early Mesozoic is a climatically dramatic event. Of course, regions of aridity have changed, both in their expanse and in their distribution, throughout geologic time and even within human history. Modern deserts are subject to large-scale moisture fluctuations over periods of only a few thousands of years (Glennie, 1987; Lézine and others, 1990) and, on slightly longer time scales, lake levels, dune development, and fossil pollen reveal that rainfall amounts oscillate significantly in association with orbital variations (Nicholson and Flohn, 1980; Street-Perrott and Harrison, 1984; Kutzbach and Street-Perrott, 1985). However, during the past 200 million years, the geologic record indicates no desert expansion has been as extensive as that which occurred in the Triassic and Jurassic. A supercontinental configuration increases the distance to moisture sources and enhances aridity, but, as Hallam (1984) points out, the greatest latitudinal expanse of evaporites occurred well after Pangean break-up had begun. Rind and others (1990) suggest that the expansion may be related to the warmer air temperatures, which would have enhanced potential evaporation. If so, then regions that are today characterized by humid rainforests and rain-fed agricultural belts might face severe moisture deficits should global warming predictions come to pass.

Determining the causes of past, large-scale hydrologic changes is difficult because precipitation, potential evapotranspiration, soil moisture, and runoff cannot be measured directly. Proxy data, such as evaporites, eolian deposits and xeromorphic vegetation characteristics, are used to recognize the distribution of past arid zones, but they are qualitative to semi-quantitative representations of climate, offering few options for analyzing causal mechanisms. And yet, the proxy data do provide a means of validating numerical climate simulations thus they are indispensable for studying changes in the Earth's hydrological system.

A summary map of paleoclimatically significant, Early Jurassic sediments are shown in figure 8. The first-order hydrologic framework of Pangea is apparent; wet climates in eastern Pangea are attested to by extensive peat deposition (Parrish and others, 1982), and arid environments in western Pangea are delineated by evaporite (Gordon, 1975) and eolian deposits (Hallam, 1975; 1985; Kocurek, 1988). Several GCM simulations have shown that the basic hydrological structure reflected by the geologic data can be reproduced by numerical models (Chandler and others, 1992; Kutzbach and Gallimore, 1989; Moore and others, 1992; Valdes and Sellwood, 1992). It can also be shown, however, that discerning even first-order hydrological regimes depends greatly upon the definitions applied. The following section reviews the hydrologic results from an Early Jurassic simulation conducted using the GISS GCM. The primary boundary conditions used in the experiment are presented in figure 9, detailed descriptions are available in Chandler and others (1992). Figures 10-12 show the distribution of hydrological characteristics for the Early Jurassic simulation, similar to those discussed previously for the modern climate. It should be apparent from the following section that developing the capability to distinguish regional hydrological characteristics from paleoclimate simulations will require a selective and informed approach to analyzing GCM results.

EARLY JURASSIC GCM SIMULATIONS: HYDROLOGICAL RESULTS

The most striking aspect of the precipitation field from the Early Jurassic simulation (Fig. 10a) is the low rate of precipitation that exists over western Pangea in low and middle latitudes. Because evaporites and eolian dune deposits (Fig. 8) attest to the desert conditions that must have existed in those regions during the Early Jurassic the simulated precipitation field qualitatively identifies a first-order hydrologic characteristic of the climate of that period. Applying the conventional definition modern desert precipitation rates (<25 cm/yr; 0.7 mm/day) reveals that the precipitation field underestimates aridity in western Pangea and overestimates drying in northcentral Pangea. Additionally, the coastal zone of the southwestern Tethys Ocean is simulated as having had annually averaged precipitation rates of >4 mm/day; difficult to imagine for a region which supported major evaporite deposition. Minor peat deposits on the equatorial west coast of Pangea are also poorly corroborated by the Early Jurassic simulation, although minor peats could easily be related to orographic, fluvial, or convective phenomena that are below GCM resolution (Chandler and others, 1992). Differencing the precipitation and evaporation fields yields a very poor representation of the sedimentary deposits, underestimating the extent of continental desert. As explained for the modern climates, the GCM formulation for evaporation does not allow evaporation to exceed precipitation in the absence of soil moisture, thus negative values of P-E are impossible over the continents for a model in equilibrium. Only coastal grid cells, which in the GISS GCM are defined to contain a fractional amount of ocean, have unlimited moisture availability for evaporation and can, therefore, have negative P-E values (Fig. 10b).

Soil moisture contours from 10 to 50 mm and surface runoff contours between 0.1 and 0.5 mm/day, which correctly define modern desert distributions, compare qualitatively to Early Jurassic aridity indicators in low latitude western Pangea (Fig. 11a and 11b). Again, the central interior of northern Pangea is probably drier than indicated considering the peat deposits found in that zone, mirroring a problem found with most of the hydrological variables over this region. Simulated Early Jurassic soil moisture and surface runoff values are, however, strongly controlled by the specified boundary conditions. Altering Pangea's vegetation characteristics, from those used in the original Jurassic experiment (see Fig. 9d) to a uniform grassland vegetation type, changes the specified water field capacity of the ground (Table 2) and leads to a marked shift in the simulated soil moisture contours (Fig. 11c). Consequently, the usefulness of soil moisture and surface runoff in paleoclimate experiments is limited by the accuracy of the specified ground hydrology/land surface boundary conditions. The Pangean P-E_p results are no more useful than they were for the present day; the entire supercontinent appearing arid by this definition (Fig. 12a). Finally, Early Jurassic P-E_{Tp} values (Fig.12b) define the low latitude and mid-latitude aridity in western Pangea, yet, as with other variables, northcentral Pangea is simulated as semi-arid, in defiance of the sedimentary record.

DISCUSSION

Ultimately, knowing which method to use in the depiction of hydrological regimes from simulated variables is difficult. Specific values, that approximately delineate desert boundaries, exist for precipitation, soil moisture, and surface runoff. Although variation from one desert to another exists, and individuals could select from a range of possible quantities, reasonable values are: P = 0.7 mm/day, S_m = 10 - 50 mm, and R_s = 0.3 mm/day. In addition, meteorological moisture balance diagnostics, such as P-E, P-Ep, or P-E_{Tp} imply an absolute value of zero should distinguish desert boundaries, although the modern simulations show inherent problems with using these differences. Without being aware of these difficulties , or of the complications associated with boundary condition dependence many disparate views past desert extent are possible: each supported, in some way, by GCM results. Figure 13 shows how, using the standard definitions for desert climatology given above, one might draw very different conclusions about the possible locations of Pangean deserts. While a reasonable amount of understanding about the models helps avoid blatant misinterpretations, regional desert extent would be nearly impossible to interpret based the GCM results alone. Clearly, model/data comparisons are required, at this stage, to validate model representations of hydrological patterns.

The Missing Moisture of Northcentral Pangea.

The arid to semi-arid depiction that the Early Jurassic simulation shows for the northcentral region of Pangea is particularly troubling since,. generally, most of the hydrological variables agree on the lack of moisture in that region. Yet, the existence of extensive peat and coal deposits in that region attests to the humid conditions that must have existed their during the Early Jurassic. Sensitivity experiments using altered topography, altered vegetation characteristics, and various sea surface temperature gradients each fail to create moist conditions in the Pangean interior (Chandler, 1992 unpublished results). Increased levels of CO_2 might alter the moisture levels in this region, however, increased CO_2 poses additional difficulties for maintaining arid climates and realistic temperatures over low latitude Pangea. Crowley (personal communication) has suggested the possibility that the geologic record in the northcentral interior is biased towards particular orbital configurations and the correlation between monsoon intensity and precessional cycles identified by Kutzbach and Otto-Bliesner (1982) may support this idea. However, their is another possible cause of the erroneous arid climate depiction which is related to the GCM hydrological parameterization.

The GCM assumes that all surface runoff returns to the ocean (an infinite source and sink for water in the model). This parameterization is reasonable only for rivers that do not exchange significant amounts of water with aquifers or with the atmosphere prior to reaching the ocean. In some systems that is clearly not the case; for example, the White Nile loses approximately 60% of its water through evaporation in swamplands upstream from the city of Khartoum (Chan and Eagleson, 1980) and continental interior basins lose water solely through evaporative processes. If not included in the moisture balance for "downstream" grid boxes an important aspect of regional water supplies may go unaccounted for. To test the importance of this distinction the moisture balance for the interior of northern Pangea was reexamined (Fig. 9). Perhaps not coincidentally, this region is the only area in the reconstruction of Pangean continental topography surrounded entirely by grid cells containing higher elevations. In the GCM such a location is the equivalent of an interior drainage basin.

An estimate of the water that would collect in such a basin can be made by summing the surface runoff over all grid boxes of the interior drainage basin, R_{Sdb}, then dividing by the area of water accumulation, A_{ib},

$$\left(\sum R_{Sdb}\right)/A_{ib} \qquad (5)$$

In this case the region of water accumulation is defined as those grid boxes containing major peat deposits. Defined thus, the area of accumulating water is enormous (A_{ib} = 3.33 x 10^{12} m^2, or roughly 75% the size of the U.S.). Since it is assumed that the water covers that entire region uniformly the value obtained should represent a minimum depth. Subgrid-scale topographic highs and lows would allow ponding in some localities but, in order to explain the peat accumulations, it will be enough to determine whether or not northcentral Pangea could have sustained swampy conditions. Thus, the above equation provides a minimum estimate of the total amount of water that would be available, per day, to the peat depositional environments of northcentral Pangea.

Figure 14 shows, schematically, the interior drainage basin of northern Pangea, and includes values for the topography, land coverage, grid box areas (corrected for spherical geometry), and surface runoff amounts. Applying the above equation indicates that the moisture balance over the peat deposits within the interior of northern Pangea should include an additional 2.61 mm/day that is not accounted for by the model's current runoff parameterization. To put this into perspective, the total outflow from this drainage basin is approximately one-half that of the modern Amazon River Basin or six times the size of the Mississippi (Fig. 15a). Even if the values are normalized to account for the large land area being drained (compared to the smaller, present day continental drainage basins), the northern Pangean river outflow would still be comparable in magnitude to the outflow from major basins of the present (Fig. 15b). Assuming the runoff would drain towards the lowest points of the basin, it seems likely that some regions in northcentral Pangea could have accumulated more than enough standing water to have maintained large lakes or swamps; a scenario more in agreement with the Early Jurassic coal deposits found in that region.

If ground hydrology models were capable of accounting for horizontal transport of runoff and subsequent ponding in low regions, then accumulations of standing water or increased ground moisture could generate feedbacks that might alter the simulated climate over northern Pangea. For example, studies indicate that climate feedbacks resulting from deforestation in the Amazon basin could increase surface temperature by up to 3°C and decrease precipitation by over 25%. Although this is not a one-to-one analogy, it serves to emphasize the potential importance of modeling ground hydrology appropriately and specifying correctly the boundary conditions.

Summary and Conclusions

Unlike temperature fields, several diagnostics are required in order to describe the hydrological state of the continents. The diagnostic fields most commonly used include precipitation, precipitation minus evaporation, soil moisture, surface runoff, and precipitation minus potential evapotranspiration. In this paper I also present a method used commonly for modern hydrological analyses, but, unfortunately, rarely applied to paleoclimate experiments. This technique uses an empirical equation for calculating potential evapotranspiration from the GCM's simulated surface air temperatures. Differencing this potential evaporation with the simulated precipitation field ($P\text{-}E_{Tp}$) yields a physically realistic diagnostic for analyzing model-derived moisture balances.

Each of the above hydrologic diagnostics supplies information about arid climate distribution, yet, some of the diagnostics could are misleading, particularly in paleoclimate simulations. Some inaccuracies may arise due to our incomplete knowledge of the past surface and subsurface conditions, which must be specified in order to initialize a GCM experiment. For example, soil moistures simulated by the model are not independent of the specified water field capacities of ground layers. Such difficulties could increase as more physically realistic ground hydrology schemes, which require detailed specifications of soil and vegetation characteristics, become standard in GCMs. Other model-data mismatches are likely related to the GCM's imperfectly parameterized or absent physical processes. The lack of a realistic treatment for surface runoff, for example, in the northern Pangean interior basin seems to have caused the GISS GCM to overestimate the aridity of that region while overestimated potential evaporation values cause P-Ep results to give grossly inaccurate estimates of arid region extent.

To the first-order, it is apparent that precipitation alone provides a minimum estimate of continental aridity while P-Ep yields the extreme overestimate. The P-E field appears to be accurate over the oceans, but underestimates continental aridity. Soil moisture and surface runoff pinpoint deserts more accurately, but they are simplistically parameterized in models, reflecting a lack of observational data. $P\text{-}E_{Tp}$ provides a reasonable option for distinguishing modern arid regions and it is a good candidate for use in paleoclimate experiments because of its close relation to physically based moisture balance calculations. $P\text{-}E_{Tp}$ is also desirable because it depends only upon simulated precipitation and surface air temperatures fields. While precipitation fields are not as accurate as temperature fields, the current climate precipitation tendencies of most GCMs are well documented.

Above all, when examining simulation results, modelers and non-modelers alike should remember that GCM diagnostics, like properties in the real climate, are potentially ambiguous, and no individual hydrological variable can be used to describe all climates, at all times. Paleoclimate model-data comparisons are likely to increase in the future, and it will be important to be selective, as well as inventive, in our analyses of simulated hydrological characteristics. In addition, the need for quantitative paleohydrological data must be stressed if we hope to advance our understanding of past climate processes to new levels of detail.

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TABLE CAPTIONS

Table 1.

Soil moisture parameterizations for some of the more commonly cited general circulation models which have been in use during the past decade (modified from Kellogg and Zhao,1988).

Table 2.

Vegetation types used in the GISS GCM. The GISS GCM uses vegetation to define certain ground characteristics such as soil water holding capacity and surface albedo (from Hansen and others, 1983 and Matthews, 1984).

Table 3.

Primary causes of aridity over continental regions with some examples from the current climate. A GCM simulates each of these processes by including a three-dimensional representation of land-water distribution and topography, by specifying or calculating sea surface temperature fields, and by calculating air mass movements.

FIGURE CAPTIONS

Figure 1.

Present day distribution of world deserts showing arid and semi-arid regions. Based on a combination of climate data and proxy information. (after Glennie, 1987; Rasool, 1984; and Greeley and Iversen, 1985).

Figure 2.

a) Observed precipitation from the global climatology of Legates and Willmott (1990). b) Simulated precipitation from a modern climate control experiment using the GISS GCM. c) The difference between simulated and observed precipitation. [results shown are global annually averaged fields]

Figure 3.

a) The difference between GCM evaporation rates and evaporation rates calculated from observed temperature and precipitation fields (Willmott and others, 1985). b) Precipitation minus evaporation from the global data base of Willmott and others. c) Precipitation minus evaporation from the GISS GCM modern climate simulation. [results shown are global annually averaged fields]

Figure 4.

a) Soil moisture climatology based on the water budget analyses of Willmott and others (1985). b) Soil moisture results from the GISS GCM modern climate experiment. Simulated soil moisture is the total water stored in the two ground layers of the GCM.

Figure 5.

a) Surface runoff data from Korzun (1978) as estimated from observed stream discharge, precipitation, and evaporation values. b) Surface runoff results from the GISS GCM modern climate experiment.

Figure 6.

Simulated versus observed annually averaged runoff from four of the Earth's major, arid climate rivers (after Russell and Miller, 1990). The GCM's calculated river runoff is higher than observed values because, in the model, precipitation rates over arid regions are overestimated, runoff is not allowed to re evaporate, and because runoff is not allowed to recharge downslope ground hydrology layers.

Figure 7.

a) Simulated precipitation minus the GCM's calculated potential evaporation. b) Simulated precipitation minus potential evapotranspiration (Ep), where Ep is calculated from simulated surface air temperatures using the method of Thornthwaite (see text).

Figure 8.

Distribution of aridity and humidity indicators from the Early Jurassic paleoclimate record. [evaporites (e), eolian "dune" sandstones (D), peats or coals (p), ironstones (i), phosphates (Ph), Novosibirskiye paleoflora (N), Graham Land paleoflora (G). Novosibirskiye and Graham Land are the highest known latitudinal positions of Early Jurassic paleofloras.]

Figure 9.

Specified boundary conditions used in GISS GCM for the Early Jurassic simulation. a) Earl Jurassic (Pliensbachian) paleocontinental reconstruction. Shading indicates position of paleoshoreline (Ziegler and others, 1983; Rowley and others, unpublished data). b) Continental elevations. c) Sea surface temperatures. d) Terrestrial vegetation. The vegetation categories include; desert (DS), savanna-type vegetation (G), savanna with scattered shrubs (GS), savanna with scattered trees (GT), mixed deciduous-evergreen forest (DEF), rainforest (RF).

Figure 10.

a) Simulated precipitation field for the Early Jurassic. b) Precipitation minus evaporation from the Early Jurassic simulation.

Figure 11.

a) Simulated Early Jurassic soil moisture field. b) Simulated surface runoff field. c) The soil moisture change between the Early Jurassic simulation with "realistic" vegetation and an Early Jurassic simulation having uniform grassland-type (see Table 2) vegetation cover.

Figure 12.

a) Simulated precipitation minus the GCM's calculated potential evaporation from the Early Jurassic experiment. b) Simulated precipitation minus Thornthwaite potential evapotranspiration (E_{Tp}). E_{Tp} is calculated from simulated surface air temperatures using the method of Thornthwaite (see text).

Figure 13.

Hydrological variables that can be used to locate deserts in the modern climate or in modern climate simulations are not easy to interpret for paleoclimate scenarios. This figure shows how six diagnostic techniques yield drastically different views of Jurassic desert extent. Precipitation (0.7 mm/day), soil moisture (10 and 50 mm), and surface runoff (0.3 mm/day) values were chosen to coincide with values that gave reasonable depictions of desert extent in a modern climate simulation. Precipitation minus evaporation, precipitation - GCM potential evaporation, and precipitation minus Thornthwaite potential evapotranspiration are moisture balance diagnostics which should, theoretically, be less than zero for arid climate locations. For several reasons this is not always the case (see text).

Figure 14.

Diagram showing the values, by grid box, of boundary conditions and hydrologic variables that form the interior basin of northern Pangea (inset map shows location of grid boxes). Tabulated values are, from top to bottom: topography, percent of grid box within the drainage basin, percent land coverage in each grid box, aerial extent of each grid box (corrected for spherical geometry of the Earth), aerial extent of each grid box that drains towards the interior, surface runoff rate calculated by GCM for each grid box, and amount of surface runoff that drains towards interior. Surface runoff values from grid boxes that form the border of the basin are weighted to reflect the percentage of runoff flowing towards the interior. For example, a grid box with three out of four sides adjacent to other interiorly draining grid boxes would be multiplied by 0.75 before being added to the total amount of interiorly draining runoff.

Figure 15.

a) A comparison of total river runoff for major rivers of the present day continents with a hypothetical Pangaean river draining the northcentral interior basin. Both simulated and observed values are shown for current rivers (values for current rivers from Russell and Miller, 1990), b) as above, except runoff values are normalized by the size of each river's drainage basin. The large area drained by the Pangaean river reduces its runoff/area but the river is still comparable to other major rivers of the present day. Considering that this runoff would have all gone into an interior basin it seems likely that the northcentral interior of Pangaea must have contained numerous swamps and/or lakes.