The Annual Course of Precipitation Over Much of the United States: Observed versus GCM Simulation

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ABSTRACT: General Circulation Models (GCMs) may be useful in estimating the ecological impacts of global climatic change. We analyzed seasonal weather patterns over the conterminous United States and determined that regional patterns of rainfall seasonality appear to control the distributions of the Nation's major biomes. These regional patterns were compared to the output from three GCMs for validation. The models appear to simulate the appropriate seasonal climates in the northern tier of states. However, the spatial extent of these regions is distorted. None of the models accurately portrayed rainfall seasonalities in the southern tier of states, where biomes are primarily influenced by the Bermuda High.

INTRODUCTION

The likelihood of global climatic change is receiving much attention from the scientific and lay communities (CES, 1989). Global increases in atmospheric concentrations of CO_2, CH_4, N_2O, and CFCs are now well documented (Wuebbles and Edmonds, 1988). General Circulation Models (GCM) are important in projecting the global climate impacts of these trace gas increases. These models are now expected to provide greater regional detail for the purpose of projecting ecological responses to climatic change (Environmental Protection Agency, 1989). Although the models reproduce zonal average temperature and rainfall patterns from the tropics to the poles reasonably well, their representation of regional patterns is more problematical (Grotch, 1988).

Additional difficulty arises in that ecologists still do not understand how the large-scale features of atmospheric circulation cause the geographic arrangement of different biotic regions such as grasslands, forests, and deserts. The objective of a related paper was to build mechanistic hypotheses causally relating regional climate, hydrology, and the distribution of major biomes in North America (King et al., in review). Having determined the apparent climatic drivers of biome distribution, we ask in this paper if the GCMs reproduce these drivers. This can be viewed as a component of validation for the use of these GCMs in projecting ecological consequences of climatic change.

METHODS

Precipitation data were obtained from U.S. Historical Climatology Network (HCN) Serial Temperature and Precipitation Data (Quinlan et al., 1987). Mean total monthly precipitation for selected stations was calculated for the 1941-1970 interval. HCN stations were selected along several east-west and north-south transects gridding the conterminous United States. Two east-west transects traversing the United States at latitudes of roughly 43° and 33°N (Figure 1) portray most of the climatic regionalization observed over the grid. Three-dimensional graphs were generated to portray spatial and seasonal gradients in observed precipitation along these transects (Neilson and Wullstein, 1983).

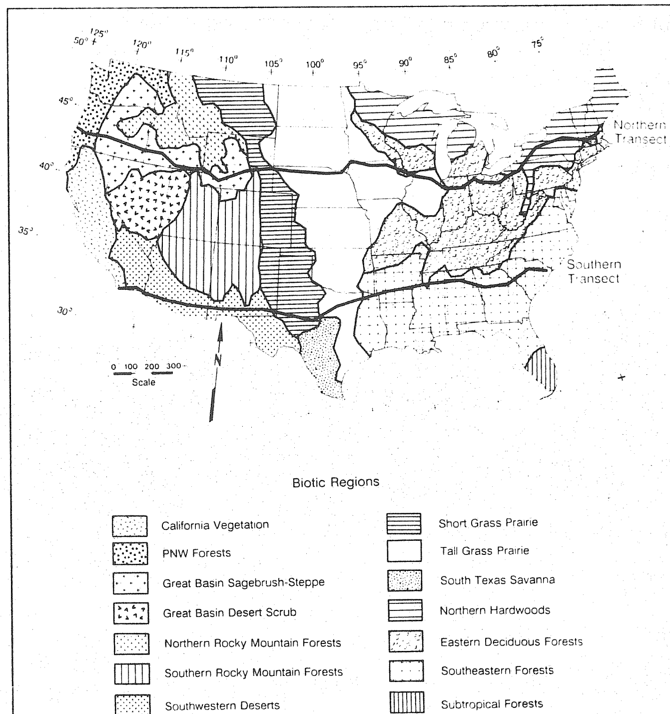

Figure 1. Biotic regions of the United States *(modified from Dice, 1943)*.

Station selection is stratified by elevation to suppress orographic complications. Stations were selected for the lower elevations within a region. When a mountain range was encountered, stations were selected from valleys on both sides of the mountain. The hypothesis is

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that presence of the mountain range does not influence the general patterns of rainfall seasonality, only the amplitude. In some cases we find that the mountain influences the regional patterns and controls regional climatic boundaries. The coastal mountains and Rocky Mountains influence the seasonality of rainfall patterns over large regions (Bryson and Hare, 1974). The smaller mountains between these cordilleras have primarily local, orographic influences (Bryson and Hare, 1974). The Appalachians also produce a local influence on rainfall, but do not appear to control regional patterns of seasonality. The sampling approach described here allowed isolation of the specific mountain ranges that demarcate adjacent climatic regions.

The sampling design was intended to examine only horizontal climate patterns, rather than vertical zonation in mountains. Therefore, transects through the western United States pertain to the biomes that occupy the broad basins and were not intended to explain the forested zones at higher elevations within mountains.

U.S. Geological Survey (USGS) daily streamflow records (U.S. West, 1988) formed the basis for runoff data. Stream gages were selected to coincide with the two rainfall transects and were selected for watersheds between 100 and 200 km^2. Values for the selected gage stations were normalized by basin size and then converted to mean total monthly equivalent depths for comparison with the observed rainfall depths.

Simulated precipitation and runoff data were generated by three general circulation models:

- Goddard Institute for Space Studies (GISS) model (Hansen et al., 1988),
- Geophysical Fluid Dynamics Laboratory (GFDL) model (Wetherald and Manabe, 1988), and
- Oregon State University (OSU) model (Schlesinger and Zhao, 1988).

Model output was analyzed as total monthly precipitation and runoff depth. GCM output was compared to the real data along the two east-west transects.

In comparing the real and synthetic climates along the two transects, a word about resolution is appropriate. The selected weather stations are spaced about 2° of latitude, while the grid resolution of the GCMs is either 4°x5° or 8°x10°. Comparisons between models and the real values should be made at the same resolution, an exercise we have not included in this analysis. An equally important issue is that of translating coarse-grid information to a finer scale. Such scaling is required for the application of GCMs to ecological models. In this sense we feel it is instructional to compare the models to the real events in spite of the different resolution. This is useful in determining what needs to be done to rescale the GCMs to real situations.

RESULTS

The two east-west transects of climatic patterns display large regional climatologies associated with the major boundaries between the biomes in the conterminous United States (Figures 2 and 3). These boundaries are primarily a result of changes in the seasonality of rainfall (King et al., in review). Specific mechanisms have been proposed that causally related these changes in rainfall seasonality to distributions of the biomes (King et al., in review). Temperature patterns will not be discussed.

The key features to be examined along each transect are the geographic sequence of precipitation seasonality and the locations of transitions from one pattern of seasonality to another. Thus, the northeast forested region receives high rainfall with virtually no seasonal pattern (Figure 2). The mid-continent grasslands along the northern transect are characterized by a strongly seasonal rainfall pattern with a mid-summer peak and a mid-winter minimum. The Great Basin receives low rainfall all year, with a significant winter precipitation peak. The west coast is dry in summer and very wet in winter. The transitions between biomes occur at ca. 87°, 103°, 107°, and 122° and are consistent with the regional transitions in rainfall seasonality (Figure 2b).

Comparison of the rainfall and runoff plots (Figures 2 and 3) suggests that streams in the northeast are drawn to low levels in summer, even though summer rainfall is quite high in both the grassland and forested regions. The persistence of runoff in summer in the forested region appears to result from the presence of high winter precipitation. This should recharge the deep soil layers during late winter and early spring snowmelt and runoff. Thus, a deep soil reservoir is apparently provided and allows tree transpiration, since summer rainfall apparently is not sufficient to balance the transpirational demand. The lack of sufficient winter rainfall in the grassland region apparently disallows the accumulation of a deep soil reservoir sufficient to maintain the water balance of trees on a regional scale. Note the lack of summer runoff in the grassland (Figure 3b). The sharpness of the spatial gradient in hydrology at the prairie-forest boundary, between 85° and 90° longitude (Figure 3b), is even more well defined than that in the rainfall gradient (Figure 2b).

The southern transect also displays large-scale regional rainfall patterns (Figure 4) that are similar to, but yet distinct from, those along the northern transect. The southeast forested region, like the northeast, receives high rainfall throughout the year. However, unlike the northeast, there are strong seasonal patterns of rainfall with winter and summer maxima. At the prairie-forest border (ca. 96°W, Figure 4b) the winter maximum has become a spring peak of rainfall, supplying necessary spring rains to the grasslands (Neilson, 1987; King et al., in review). Mid-summer rains in the southeast forested region become quite diminished at the border with the grasslands, leaving the prairie dry in mid-summer. The plains also receive a fall precipitation peak. The spring rainfall peak over the plains ceases at the Rocky Mountain/Sierra Madre Oriental axis (extending into Mexico)and becomes a spring drought in the southwest deserts (ca. 103°W). Southwest deserts are dominated by mid-summer rains, with spring and fall droughts and a mid-winter peak. The transition between the prairie

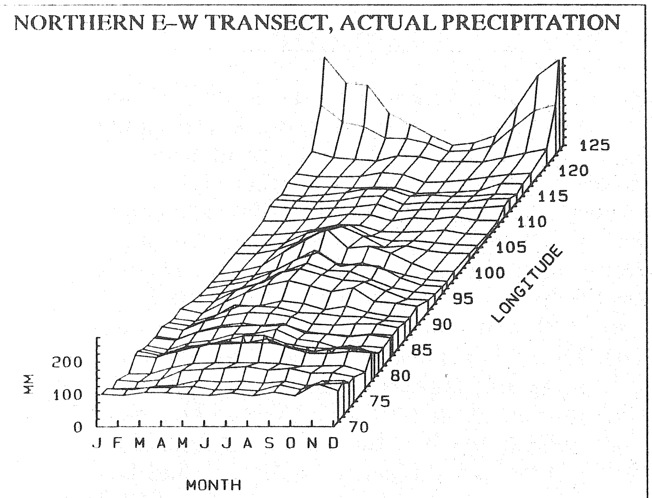

Figure 2a. Seasonality of precipitation across the northern transect. Locations of weather stations used to construct the graph are indicated by lines parallel to x-axis.

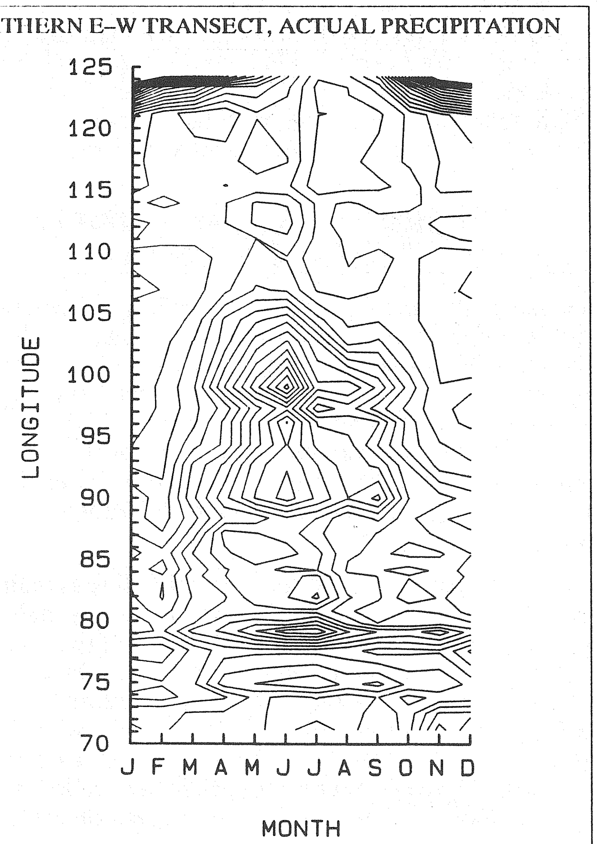

Figure 2b. Contour map of the surface in 2a. A particular contour represents seasonal distribution of a particular amount of precipitation. Contour interval is 10 mm, starting at 10 mm.

and desert climates is one of the few instances where a single mountain range controls a transition from one seasonal rainfall pattern to another (Bryson and Hare, 1974). The far-west coast is characterized by winter rains and mid-summer drought.

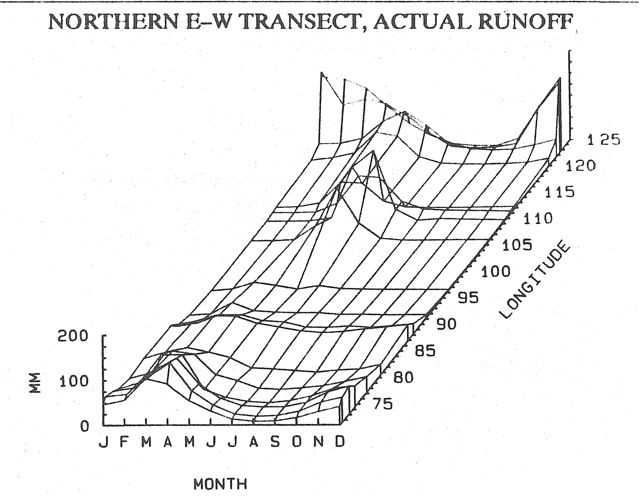

Figure 3a. Seasonality of runoff across the northern transect.

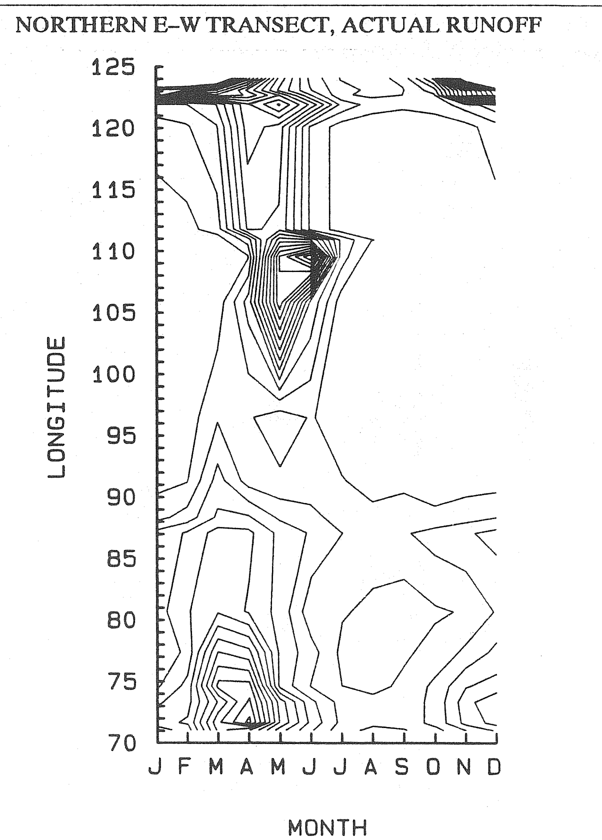

Figure 3b. Contour map of the surface in 3a. Contours as in 2b.

Seasonal runoff patterns along the southern transect (not shown) show similar patterns of regionalization. Again, the prairie-forest border is quite striking, with runoff all year in the forested region but only in spring in the grassland region. The hypotheses for explaining the seasonal runoff patterns and biome distributions are the same as for the northern transect.

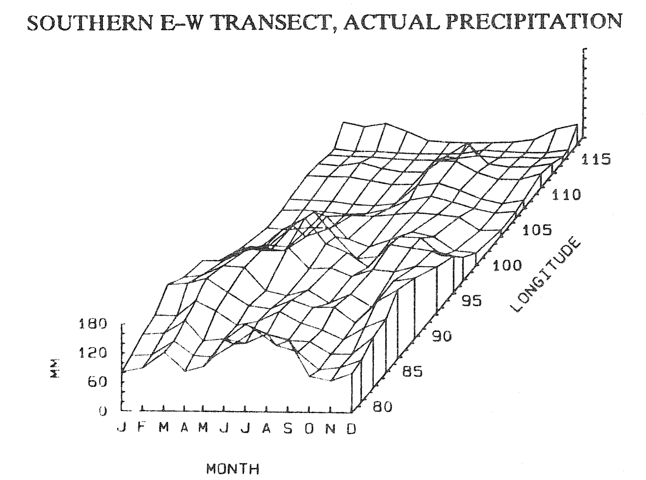

Figure 4a. Seasonality of precipitation across the southern transect.

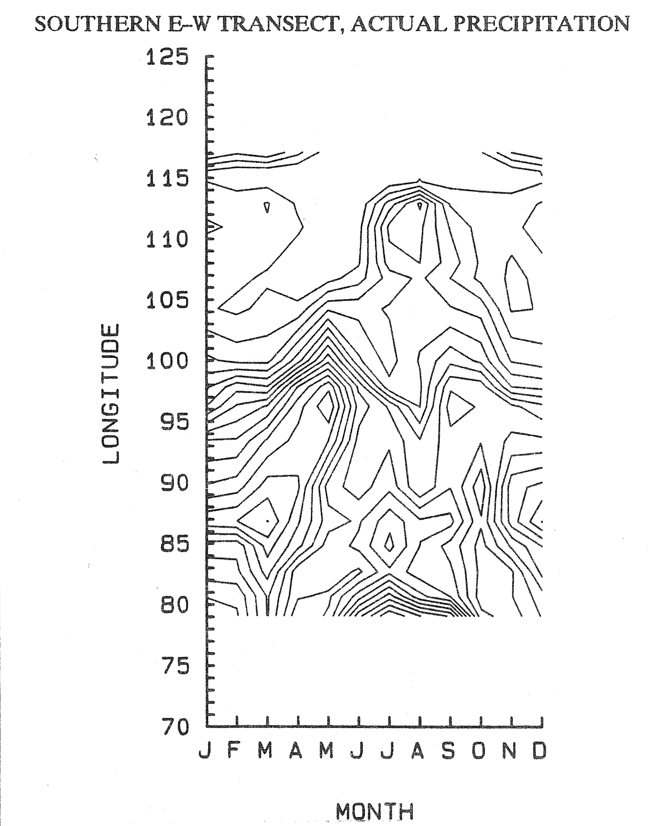

Figure 4b. Contour map of the surface in 4a. Contours as in 2b.

DISCUSSION

Regional rainfall patterns over the conterminous United States are produced by the large-scale, atmospheric circulation features such as the polar front, subtropical jetstreams, and associated storm tracks (Barry and Chorley, 1982; Bryson and Hare, 1974; Tang and Reiter, 1984). The flow of the atmosphere over and around the major mountain ranges drives most of the regional patterns observed along the northern transect (Barry and Chorley, 1982; Bryson and Hare, 1974; Tang and Reiter, 1984). Except for the winter rainfall pattern on the west coast, the entire southern transect is dominated by seasonal behavior of the Bermuda High and its associated storm tracks to produce the distinct regions of seasonal weather (Bryson and Hare, 1974; Bryson and Lowry, 1955; Carleton, 1986; Coleman, 1988; Cry, 1967; Hales, 1974; King et al., in review; O'Connor, 1961; Rasmusson, 1967; Reyes and Cadet, 1988; Wendland and Bryson 1981). These relationships will not be pursued here. However, we find it intriguing that distributions of three very different biomes (forest, grassland, and desert) appear to be a function of one large-scale feature of the atmosphere, the Bermuda High, and its seasonal dynamics. A reasonable question, then, might be: Under global warming, what will happen to the large-scale circulation features and their seasonal patterns?

HISTORICAL DATA AND MODEL INTERCOMPARISONS

The use of GCMs for predicting local impacts has been criticized because the local climate is at a sub-gridscale resolution. The patterns we have described as controlling biotic distributions are, however, large-scale features of the climate and should be present in the GCMs. The model runs we examined were used by the EPA in predicting potential ecological effects of climate change in a report for Congress (Environmental Protection Agency, 1989).

Recall the geographic sequence of rainfall seasonality along the northern transect (Figure 2a): aseasonal in the eastern deciduous forest, a sine-wave in the mid-continent peaking in mid-summer, low amplitude seasonality in the Great Basin, and a sine-wave on the west coast peaking in winter. Examination of plots for the three models suggests that all these features are present to varying degrees (Figures 5a-c, N.B. the models and real data have not been rescaled to a common grid).

The GFDL model is perhaps the best (Figure 5a). However, the Great Basin climate is quite protracted in space, while the mid-continent peak is positioned too far to the west. The same is true for the OSU model, with the additional observation that seasonal amplitude shifts are not strong enough (Figure 5b). The GISS model is most distorted and is also on the coarsest grid. The Great Basin climate is virtually absent, while the mid-continent rains appear to extend all the way to the west coast (Figure 5c). The west coast seasonal rainfall occurs in a grid-cell over the Pacific Ocean.

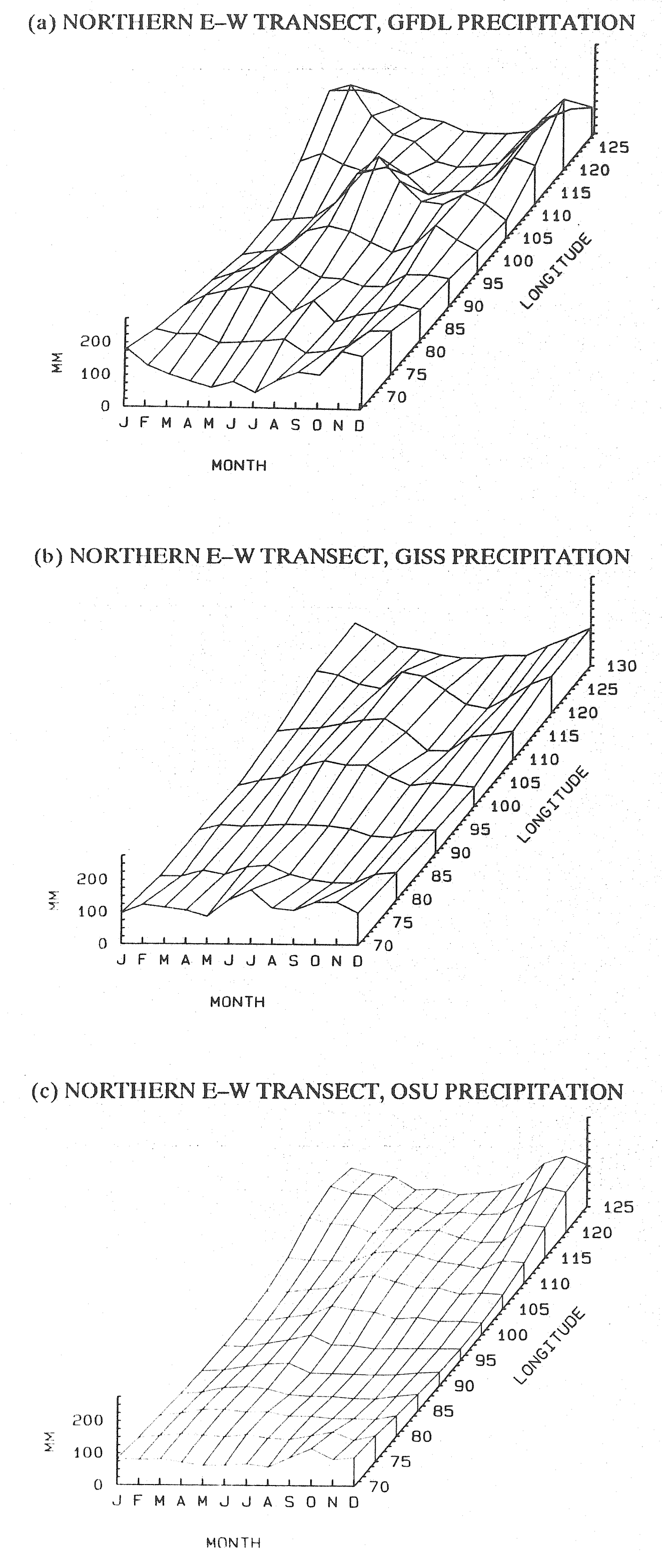

Figure 5. Seasonality of rainfall along the northern transect as produced by three General Circulation Models: a. GFDL b. GISS, c. OSU

We suggest that all these models have a reasonably correct spatial sequence of the seasonality of rainfall. However, the output appears to be spatially distorted. We hypothesize that this occurs in part because of the coarse representation of topography, being in part a function of the size of the grid-cells. For example, at an 8°x10° resolution, as in the GISS model, the coastal and Rocky mountains cannot be well resolved, likely producing the absence of the Great Basin climate. These spatial distortions appear to be artifacts of the topographic parameterization and should be stable within a model and between different model CO_2 runs, but different between models. Examination of 2x CO_2 runs from the models (not shown) suggests that the spatial distortions are stable. The altered climate in the doubled CO_2 runs is apparent in the 3-dimensional plots as amplitude variation in the peaks and troughs. We propose that this stable distortion is one of the reasons the GCMs do not agree well in the regional rainfall patterns. However, the disagreement may not be as serious as previously thought. These distortions could be corrected in the calibration of the GCM output to the real data, but they never have been (Grotch, 1988).

Although we suggest that the distortions in the models could be corrected, we recognize that this may not be consistent with the current representation of physics in the models. Variables such as winds, radiation, and clouds should also be analyzed in this way for consistency. Ground-surface interactions in the models may also be inconsistent with the suggested corrections. These are research questions.

The models also produce estimates of seasonal runoff. Comparison of Figure 3a with Figures 6a-c reveals considerable variation in fidelity of the models to the real data. The GFDL model comes the closest, followed by OSU and GISS.

Turning attention to the southern transect, comparison of Figures 7a-c with Figure 4a reveals that there is no similarity between the modeled and real data in the spatial sequencing of seasonal rainfall patterns. This is a critical observation, given that the seasonality of rainfall along this transect appears to control the biotic distributions. Apparently the GCMs examined do not contain the large-scale features of the Bermuda High. Instead, they contain a circumglobal, subtropical high pressure belt, rather than three high pressure cells (Barry and Chorley, 1982). This would explain the lack of the appropriate storm tracks.

Runoff has been examined along the southern transect. However, since the rainfall seasonality bears little resemblance to the real data, the runoff plots are essentially meaningless and are not shown.

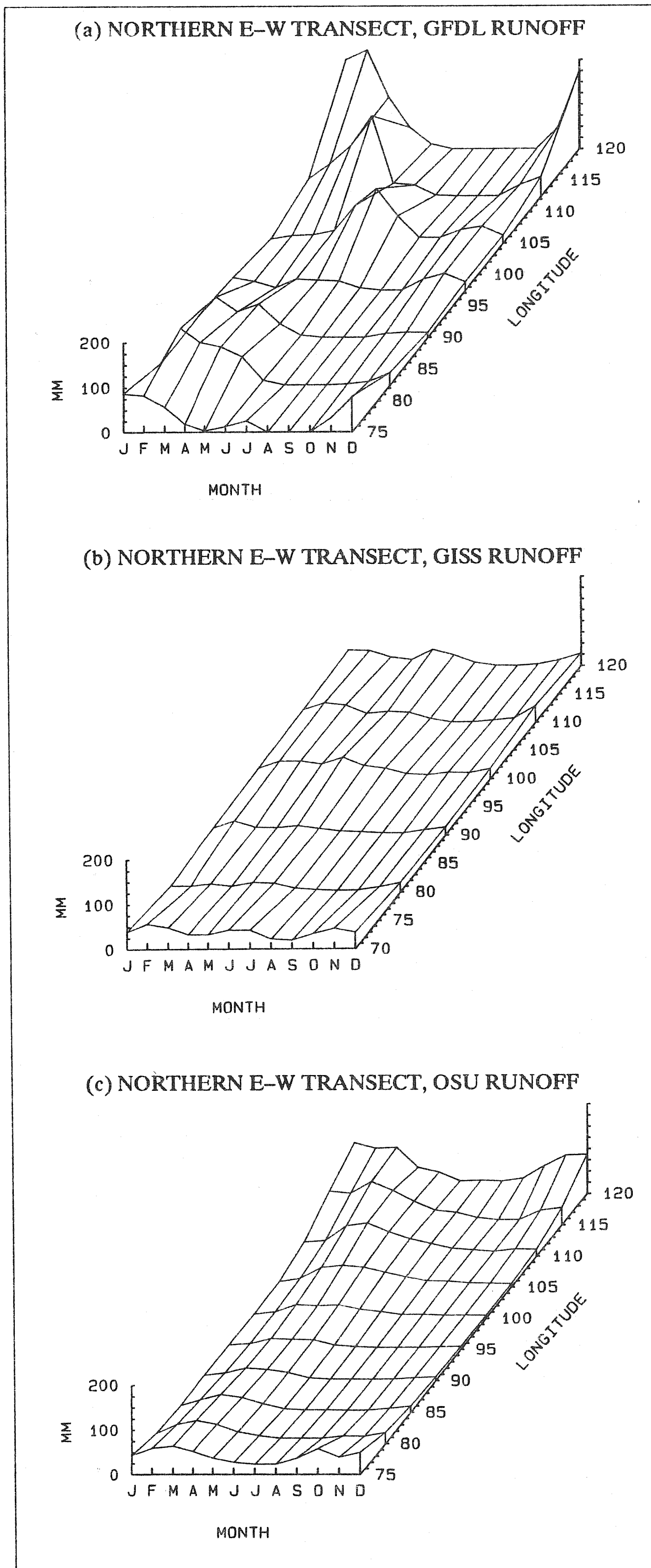

Figure 6. Seasonality of runoff along the northern transect as produced by three General Circulation Models: a. GFDL b. GISS c. OSU

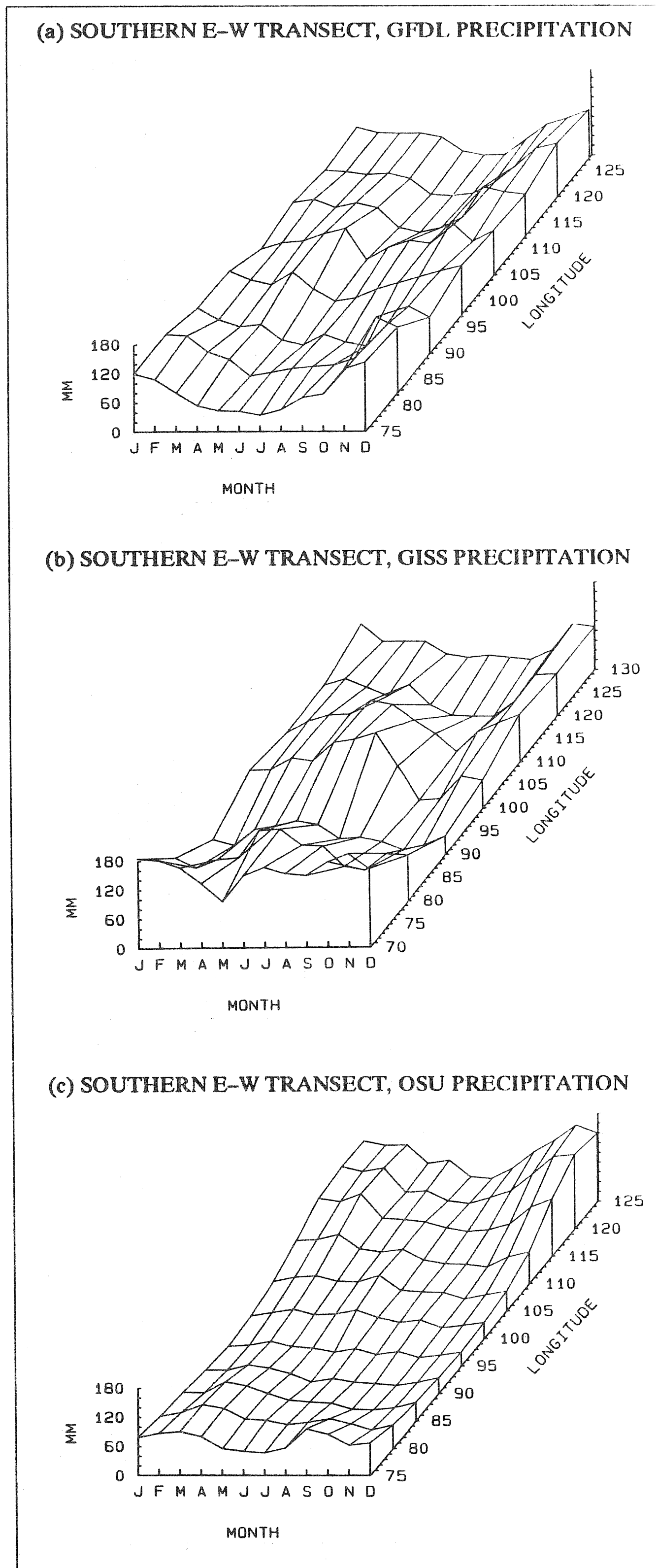

Figure 7. Seasonality of rainfall along the southern transect as produced by three General Circulation Models: a. GFDL b. GISS c. OSU

CONCLUSIONS

Analyses of weather patterns over the conterminous United States reveal relatively homogeneous climatic regions, defined from the rainfall seasonality. These regions coincide with the major biotic regions of the country and appear causative of the biome distributional patterns (Bryson and Hare, 1974; King et al., in review).

These analyses suggest that there are large zonal bands where the models are valid in reproducing seasonal rainfall patterns and large zonal bands where they are not valid in this sense. Where the models do appear valid, comparisons suggest that the regional rainfall patterns are spatially distorted compared to the actual regional patterns. This implies that rules could be developed for calibrating model output to the actual spatial sequence of climates. This may have the effect of reducing discrepancies between models of regional rainfall patterns. Having made these corrections, the CO_2 driven anomalies should be examined for consistency between models.

The subtropical rainfall patterns do not appear to be valid in these models, suggesting the need for further model development. Potential areas of research are well recognized and consist of both sub-grid and large-scale processes, such as cloud parameterizations and feedbacks and ocean-atmosphere interactions.

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