Climate and Lacustrine Petroleum Source Prediction

Eric J. Barron
Earth System Science Center
Pennsylvania State University
University Park, Pennsylvania, U.S.A.

Lacustrine environments are a major contributor of petroleum source rocks. Lacustrine source rock prediction is, however, influenced by numerous, complex variables governing lake sedimentation. Current predictive capability can be improved by attempting to map essential climatic variables to limit in space and time the area of lacustrine source rock exploration. Climatic characteristics that govern lake occurrence and the potential for stratification have been investigated with a General Circulation Model of the atmosphere for the present and for the mid-Cretaceous. In this analysis, the distribution of areas with a positive water balance first is used as an indicator of the distribution of areas conducive to lake formation. Second, the distribution of areas that experience large annual climatic variations is used as an indicator of the distribution of lakes that are less likely to be stratified and, hence, less likely to be sites of high organic-carbon preservation. Four factors used to define large climatic variations include (1) seasonal temperature cycle in excess of 40°C; (2) seasonal temperature extreme of less than 4C°; (3) average seasonal differences in precipitation minus evaporation balance in excess of 5 mm/day; and (4) distribution of mid-latitude winter storms. Evidence is presented to support the capability of climate models that add insight into lacustrine source rock prediction by simulating geographic regions conducive to lake development and to stratification and organic-carbon preservation.

INTRODUCTION

Many factors, both climatic and tectonic, govern the distribution of lakes and influence lake productivity and preservation of organic matter. Lacustrine sedimentation may reflect a complex interplay of diverse morphologic and environmental factors. Consequently, efforts to investigate deposition of organic-rich sediment necessitates defining those factors (basin tectonics, drainage area, topography, rate of subsidence, nutrient level, light availability, turbidity, oxygen availability, depth, and sedimentation rate) that influence modern lakes or that appear to explain the known record of lacustrine source rocks (Katz, this volume). Although lacustrine source rock prediction is limited by the importance of so many variables, one can improve predictive capability by mapping a selected governing variable to limit the scope of exploration, either spatially or temporally. Therefore, understanding climate becomes important in assessing many aspects of the geologic record, including lacustrine sequences (Summerhayes, 1988).

Large-scale global climate models potentially can improve predictive capability in two ways. First, the occurrence of a lake implies a positive water balance, even if only for a relatively brief geologic time. Consequently, a positive regional precipitation-evaporation (P-E) balance can be a key (although not exclusive) predictive variable for lake occurrence. Second, climatic variability often governs the potential for lake stratification and oxygen availability and, hence, the preservation of organic matter.

General Circulation Models (GCMs) of the atmosphere are state-of-the-art tools that help define climatic water balance and climatic variability associated with diverse geographies and diverse global climates of the past. In demonstrating the potential of this approach, Kutzbach and Street-Perrot (1985) illustrated a remarkable correspondence of North African lake levels to GCM-simulated changes in moisture balance associated with evolution of the Earth's orbit during the last 18000 yr.

This study, intended for application over much longer time periods, is considerably less specific. The objective is to map "regimes" of lake occurrences and characteristics for different geographies, first by describing regions of positive moisture balance, and then by describing the subset of those regions with (a) high seasonal temperature variation (potential seasonal lake overturn through development and destruction of a seasonal thermocline); (b) high seasonal variation in P-E balance (potential for development and destruction of a seasonal pycno-

Memoir 50: Lacustrine Basin Exploration: Case Studies and Modern Analogs (1990)

cline); and (c) highly seasonal changes in surface energy (e.g., winter storms that influence lake mixing and oxygenation). Model-generated lake regimes first are predicted for the present as a guide to model capability. Then, regimes are predicted for the mid-Cretaceous as a guide to potential variations in lake character and distribution for different geographies and for comparison with the rock record.

MODEL CHARACTERISTICS

The two simulations described in this study are based on a version of the National Center for Atmospheric Research's (NCAR) Community Climate Model (CCM). The CCM, which has evolved from the spectral climate model of Bourke et al. (1977) and McAvaney et al. (1978), consists of nine levels and an associated grid of 40 latitudes (~4.4 resolution) and 48 longitudinal grid points (7.5 resolution).

The model includes atmospheric dynamics based on fluid-motion equations and includes radiative processes, convective processes, and evaporation and condensation as described by Ramanathan et al. (1983) and Pitcher et al. (1983). The radiation-cloudiness formulation introduced by Ramanathan et al. (1983) and the surface hydrology formulation introduced by Washington and Williamson (1977) are two major modifications from earlier versions.

This atmospheric GCM is coupled with an ocean formulation consisting of an energy-balance mixed layer that includes heat storage. Specifying a 50-m-thick mixed layer allows realistic simulation of the full annual cycle. Sea ice forms and grows when surface temperatures fall below -1.2°C. The present-day control simulation is that of Washington and Meehl (1984), who compared favorably the results of the present-day annual-cycle simulation with present-day observations.

The model's capability to simulate atmospheric moisture balance is the most essential factor to consider for this discussion. In their comparison of CCM simulations for January and July using specified sea-surface temperatures, Pitcher et al. (1983) successfully simulated many primary features, including the intense equatorial rainfall belt, the subtropical desert zone, and mid-latitude precipitation maxima. Figure 1 compares observed annual average continental precipitation (after Walter, 1973) with annual averages simulated by the version of the CCM used here. Although precipitation associated with storm tracks and with monsoonal circulations were well simulated, two problems are, however, evident. First, precipitation rates, particularly in the tropics, tend to be larger than observed in simulations with an energy-balance ocean. Second, precipitation characterized by high spatial and temporal variability (e.g., convective precipitation) is poorly simulated. In addition, the scheme for surface hydrology, dependent only on the P-E balance with a soil moisture capacity of 15 cm (excess after 15 cm is simulated as runoff), is overly simplistic.

This experiment then should be viewed as a sensitivity test, but even this preliminary assessment demonstrates the CCM's potential to provide useful information about lacustrine source rock deposition. This study therefore will provide a first-order view of climatic controls that influence lake distribution and character.

MODEL PREDICTIONS FOR THE PRESENT

Large-scale characteristics of precipitation and evaporation patterns generally are well simulated by the CCM (Figure 1, see also details in Pitcher et al., 1983; Washington and Meehl, 1984; Barron et al., 1989). Regions of seasonal high precipitation, illustrated in Figure 2, are defined by (1) the basic structure of the atmospheric general circulation (i.e., tropical low pressure and high precipitation and subtropical high pressure and low precipitation); and (2) the primary role of geography and land-sea thermal contrasts in disrupting zonal circulation. Therefore, development of monsoonal regimes (e.g., New Guinea, India-Indonesia, Somalia, and eastern Africa) and distribution of mid-latitude precipitation maxima associated with the position of the jet stream and winter storm track can be well simulated. However, model capability is decidedly poorer in regions where precipitation depends on atmospheric processes that operate at a resolution finer than the model's (e.g., summer convective precipitation in southeastern United States). The model is remarkably successful in simulating the large-scale structure of precipitation patterns, given its coarser resolution, but magnitudes are less well simulated. Evaporation rates (Figure 3) reflect temperature (latitude), nature of seasonal changes in the general circulation, and on continents, availability of moisture. Regions of high continental rainfall tend to be regions of high continental evaporation.

The difference between annual average precipitation and evaporation then should define a first-order prediction for the occurrence of lakes. Because regions whose balance approaches zero are not, however, predictable with confidence. Figure 4 illustrates only those regions whose moisture balance exceeds 0.5 mm/day. Under these conditions the model delineates desert regions, which are eliminated from the scope of lacustrine exploration. However, other regions characterized by a near-zero balance (e.g., the Great Lakes, which has a model-predicted winter excess but a summer deficit) or by convective precipitation (southeastern United States) also are eliminated. Removing such regions from the "predicted" distribution of lakes, as defined solely by annual average atmospheric moisture balance, obviously is incorrect. Although imperfect, particularly in regions of near-zero moisture balance, model-

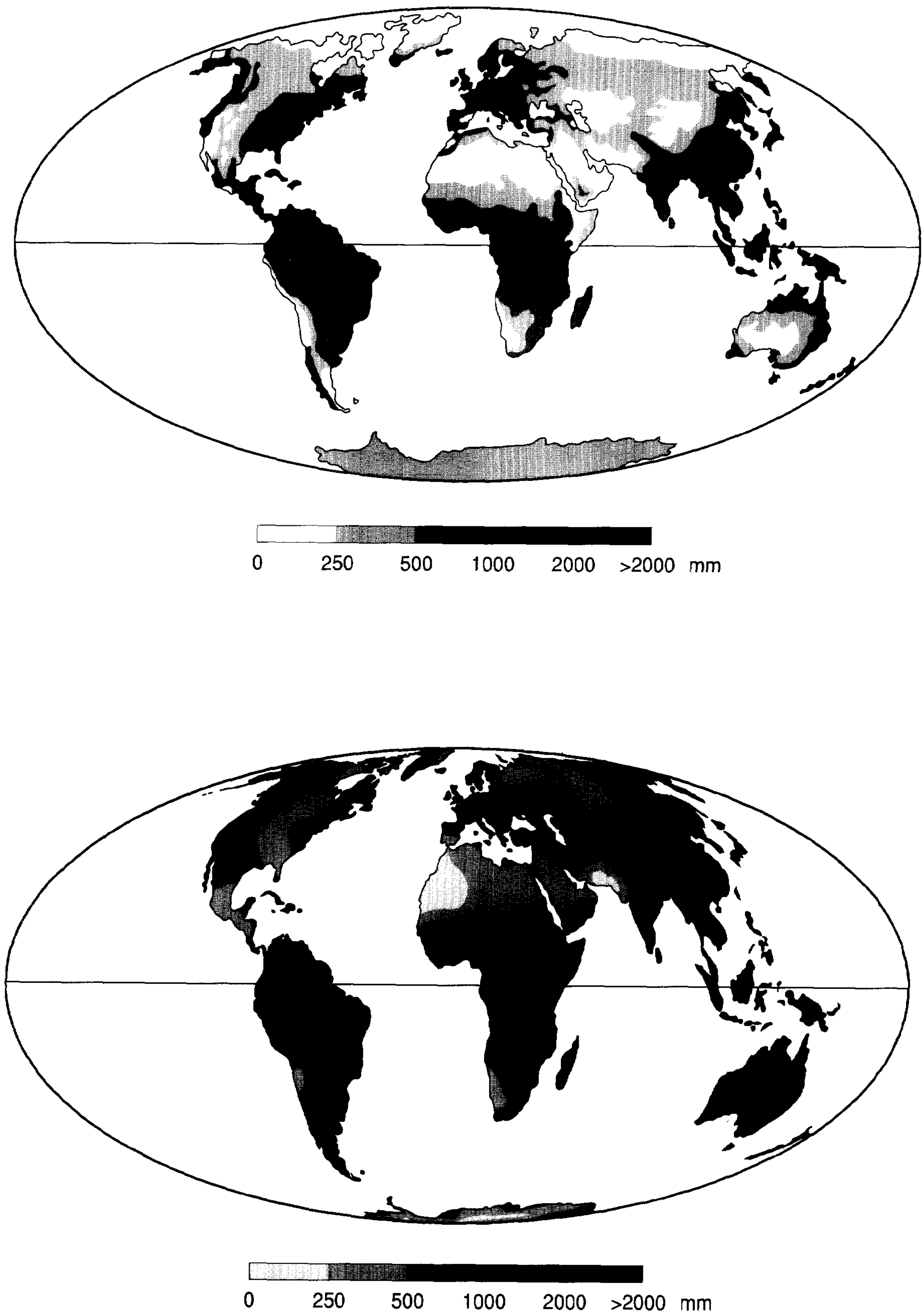

Figure 1. Comparison of (a) observed annual average precipitation (after Walter, 1973) and (b) CCM-predicted annual average precipitation (below).

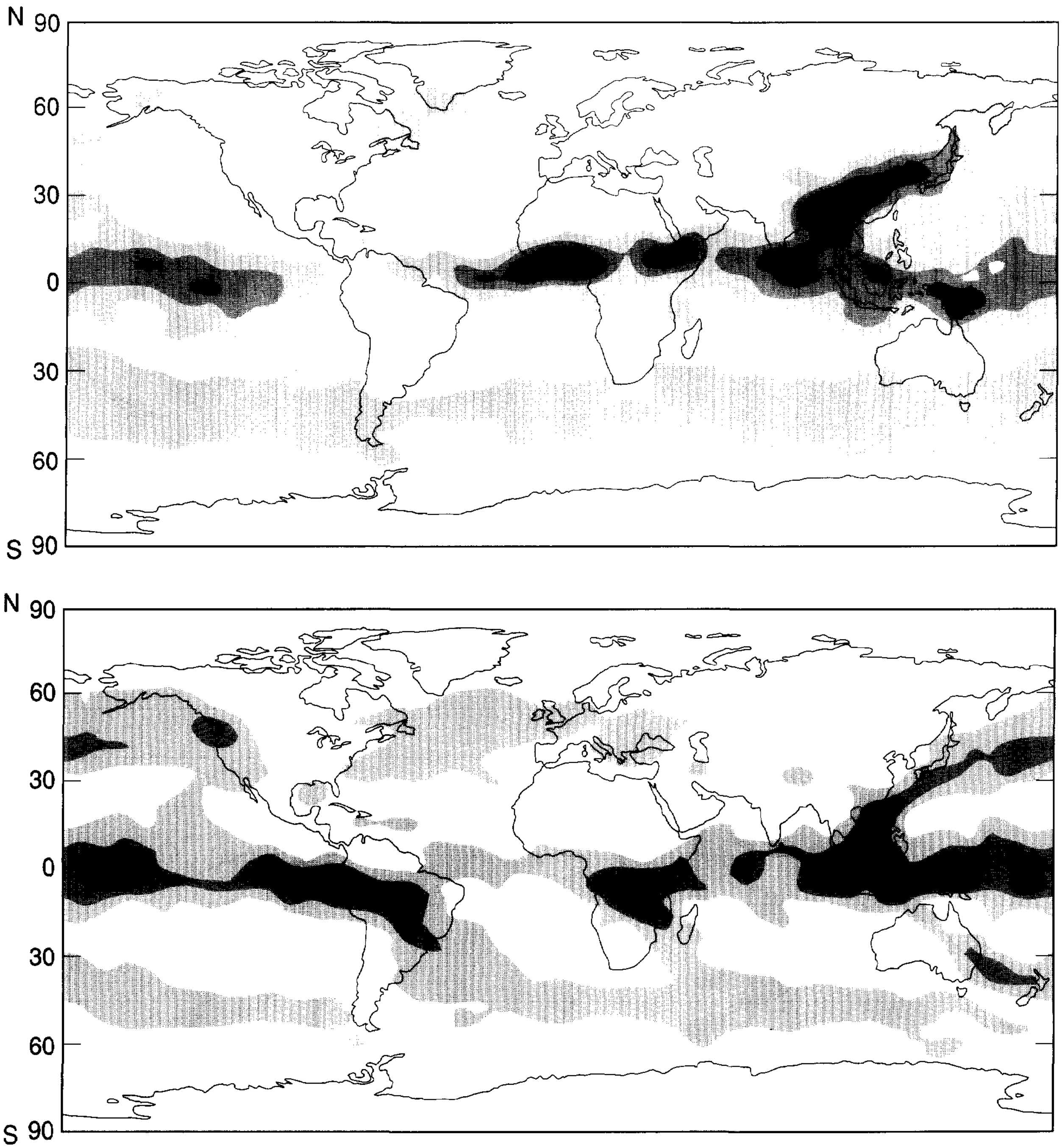

Figure 2. Present-day CCM-simulated precipitation (mm/day) for (a) average June, July, and August and (b) average December, January, and February (below). Shading indicates precipitation in excess of 3 mm/day (contour interval 3 mm/day).

predicted patterns of positive moisture balance generally are reasonable.

Predicted occurrence of lakes can be further analyzed by considering seasonal variability. Figure 5 illustrates seasonal characteristics of the P-E balance as the difference in the values from Figures 2 and 3. In particular, the overall pattern of meridional circulation, the importance of monsoons, and winter storm distribution become evident by defining regions of strong (>1.0 mm/day) moisture deficit and excess and regions of high seasonal variability. Strong seasonal variations in P-E (Figure 6) become evident where the differences between Figures 5a and 5b exceed 5 mm/day.

A second major source of variation, amplitude of the annual cycle of temperature based on the present-day simulation, is illustrated in Figure 7. In particular, continental interiors at high to middle

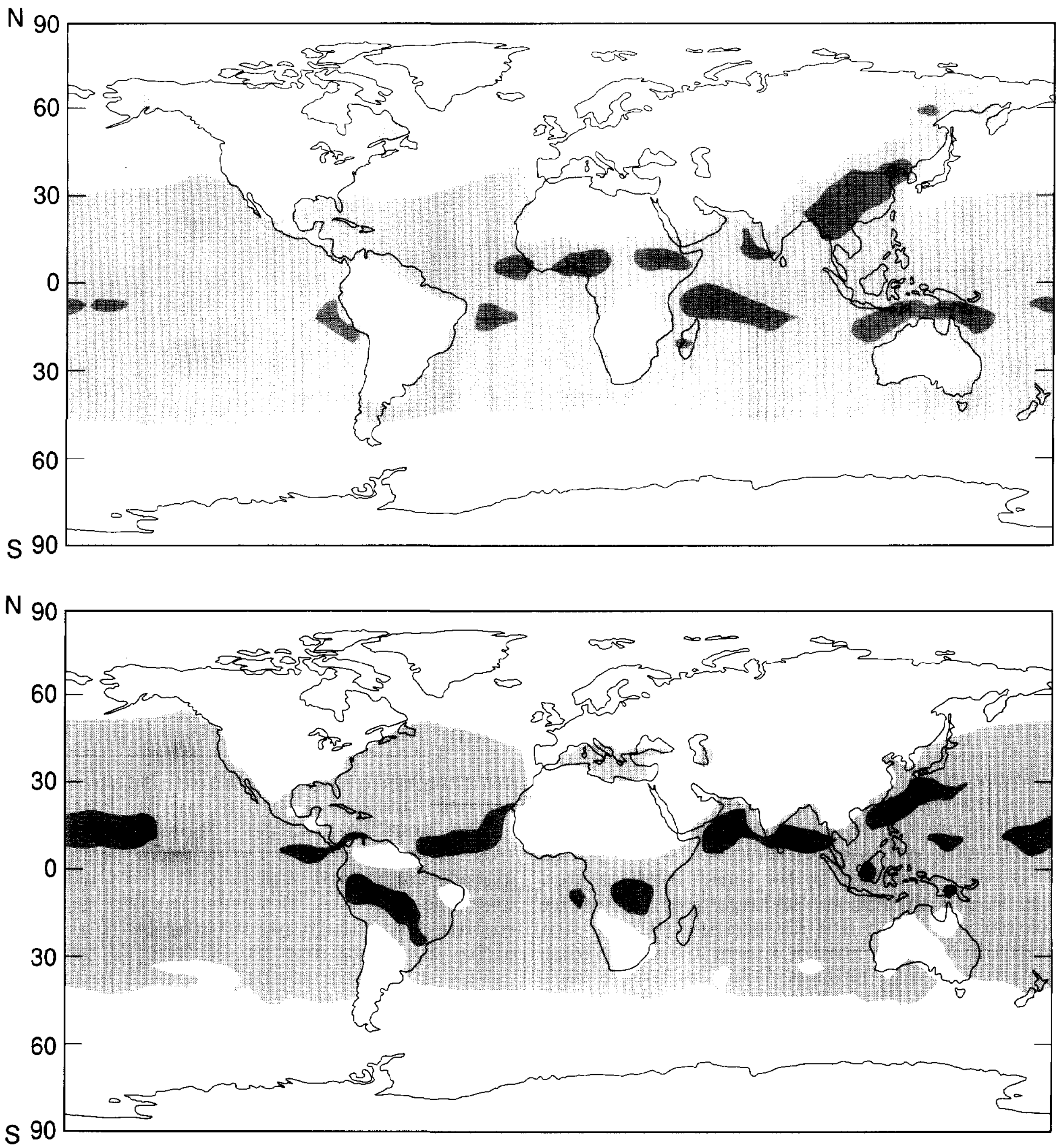

Figure 3. Present-day CCM-simulated evaporation (mm/day) for (a) average June, July, and August and (b) average December, January, and February. Shading indicates evaporation in excess of 3 mm/day (contour interval 3 mm/day).

latitudes experience considerable temperature variation due to the annual solar insolation cycle and the lack of thermal inertia of the continents. Continental size and latitude are the primary controls on amplitude of the annual temperature cycle.

Large seasonal variation in heating or moisture supply promotes seasonal overturn and likely poor organic carbon preservation. For example, Lake Baikal (southern Soviet Union) lies in a region of model-predicted moisture excess but would be eliminated from the scope of lacustrine source rock exploration on the basis of an annual temperature cycle greater than 40C°. Incidentally, if the Great Lakes had been simulated as a region of positive moisture balance, they also would have been characterized by large seasonality and therefore removed from exploration consideration. The distribution of winter air temperatures below 4°C,

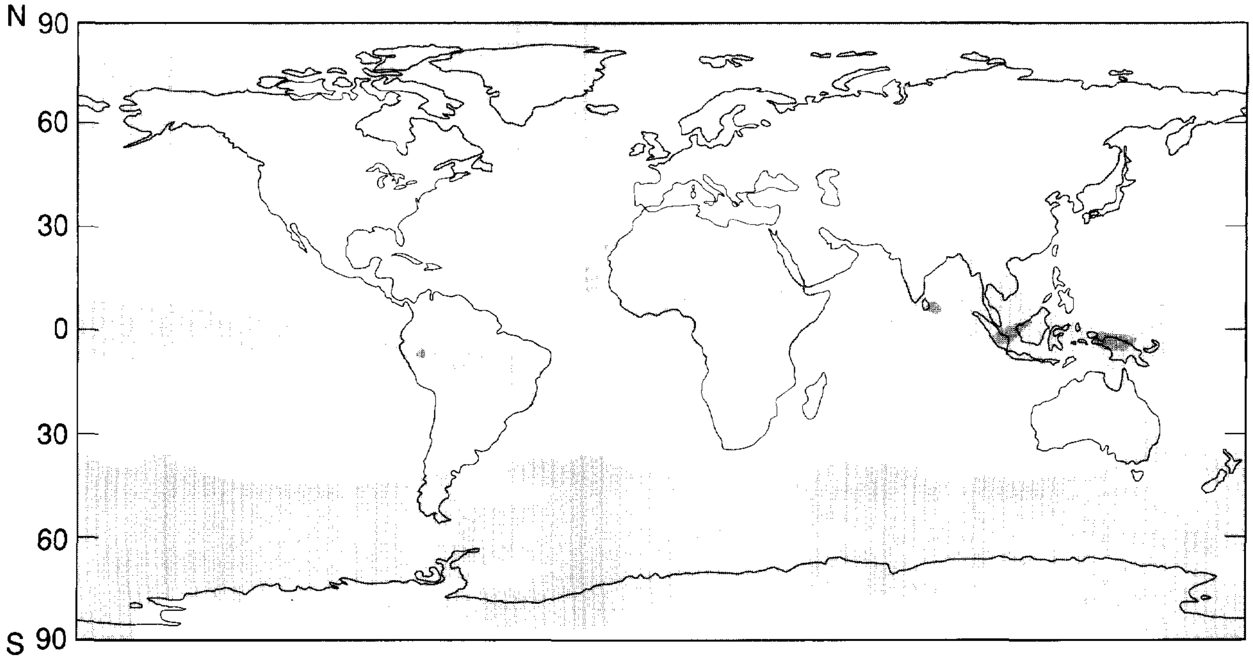

Figure 4. Present-day CCM-simulated precipitation minus evaporation (mm/day) for a given annual average. Light shading indicates positive balance in excess of 0.5 mm/day; dark shading indicates excess of 5.0 mm/day. Hatchuring indicates extreme deficit (<-5.0 mm/day).

because of the relationship between density and temperature in fresh water, becomes another temperature indicator of seasonal overturn.

The model-predicted distribution of winter storms (Figure 8), as defined by the time-filtered standard deviation of the geopotential height field—a measure of how often high- and low-pressure systems pass (Barron, 1989)—is another reason to discount some middle- to high-latitude lakes as source rock environments. The position of the storm track's main axis is closely tied to land-sea thermal contrasts and can be related to the annual cycle of temperature (Figure 7).

The large seasonal differences in P-E balance (Figure 6), regions of large temperature variation (Figure 7), and the position of the winter 4°C isotherm provide a basis for subdividing the model-predicted distribution of positive moisture balance illustrated in Figure 4. Lake distribution then can be defined as three "regimes" of positive annual moisture balance but with (1) large annual temperature variation, (2) large annual variation in P-E balance, or (3) no large annual variation (Figure 9). This third case represents model-predicted regions conducive to lake development with the potential for organic-rich sedimentary deposition, as defined solely by large-scale climatic criteria. Although such a prediction clearly is inaccurate because so many factors influence lake sedimentation, it reasonably serves to limit the spatial scope of investigation by eliminating desert regions and by characterizing regions of large seasonal variation.

The lacustrine "target" regime is primarily tropical or subtropical but includes some high-latitude continental regions subject to moderate maritime influence. However, the 4°C isotherm eliminates most high-latitude sites based on probability of seasonal overturn. Distribution of winter storms or seasonal sea-ice cover could be used to further characterize high-latitude lacustrine environments as suitable or unsuitable. Evidently the regions most conducive to source rock deposition in lacustrine environments occur within the low-latitude climatic regime, which includes Lake Tanganyika, often cited as a type example for high organic-carbon deposition (Degens and Stoffers, 1976).

As partial confirmation, six of ten modern lakes containing more than 1% organic carbon content (Bradley, 1966; Swain, 1970; Kelts, 1988; Talbot, 1988; and Binjie et al., 1988) lie within the target regime in Africa. A shallow Florida lake (Bradley, 1966), a lake in Nicaragua (Swain, 1970), and one African lake within the monsoonal belt (Talbot, 1988) all lie outside model-predicted regions of conducive environments. Substantially higher predictive capability could be gained by integrating the climatic information from Figure 9 with a knowledge of topography, drainage divides, interior drainage, and basin distribution.

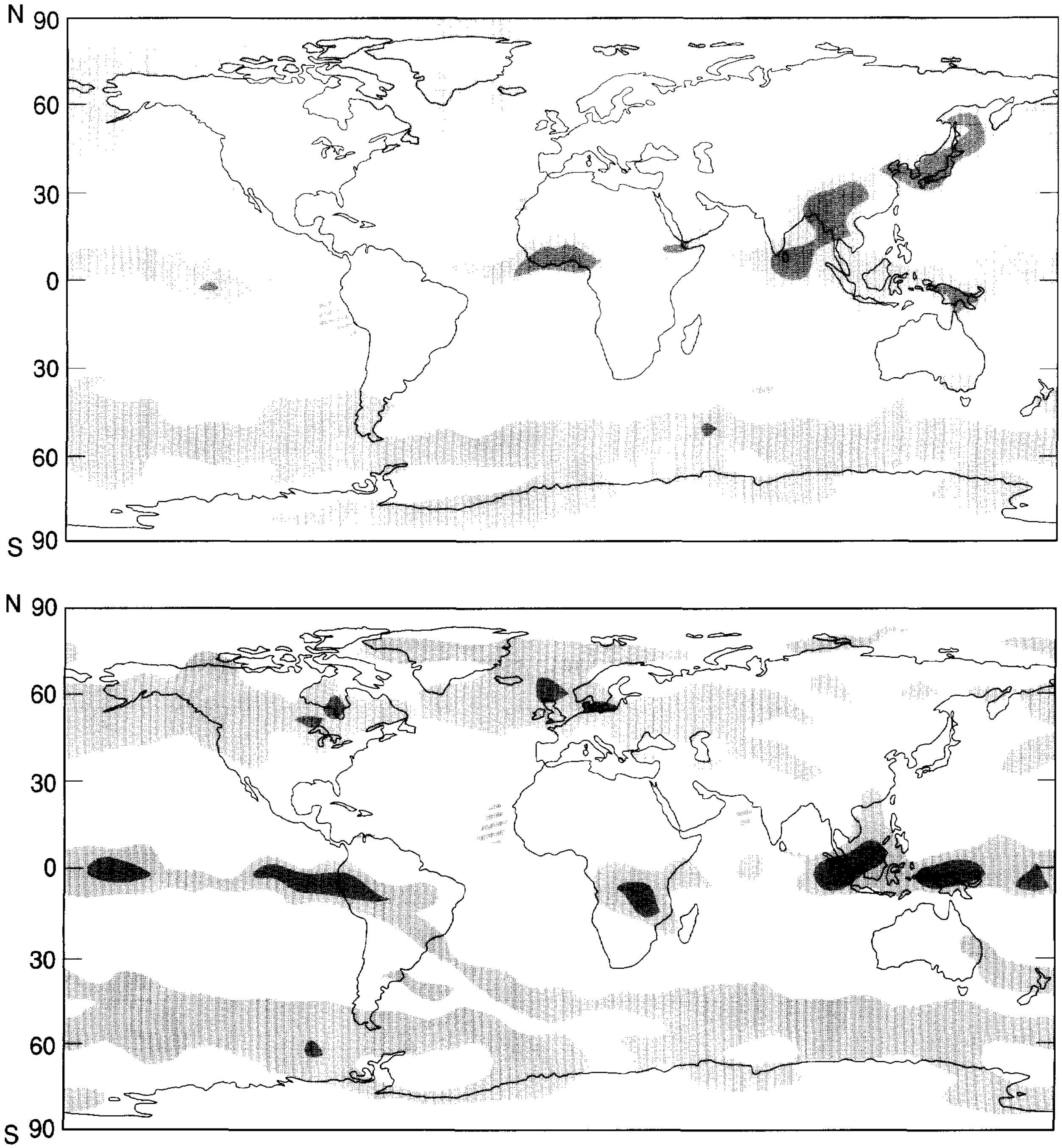

Figure 5. Present-day CCM-simulated precipitation minus evaporation (mm/day) for (a) average June, July, and August and (b) average December, January, and February. Light shading indicates positive balance in excess of 1.0 mm/day; dark shading indicates positive balance in excess of 5.0 mm/day. Hatchuring indicates extreme deficit (<-5.0 mm/day).

MODEL PREDICTIONS FOR THE MID-CRETACEOUS

The CCM next was applied to mid-Cretaceous geography described by Barron and Washington (1984). Although the general structure of Cretaceous precipitation maxima and minima (Figure 10) with respect to latitude is similar to present-day control (Figure 2), the simulations differ in several important respects. First, the mid-Cretaceous hydrologic cycle intensity was substantially greater, reflecting conditions for a warmer planet and large oceanic areas within the subtropical evaporation region (Barron et al., 1989). Second, the zonal nature of the

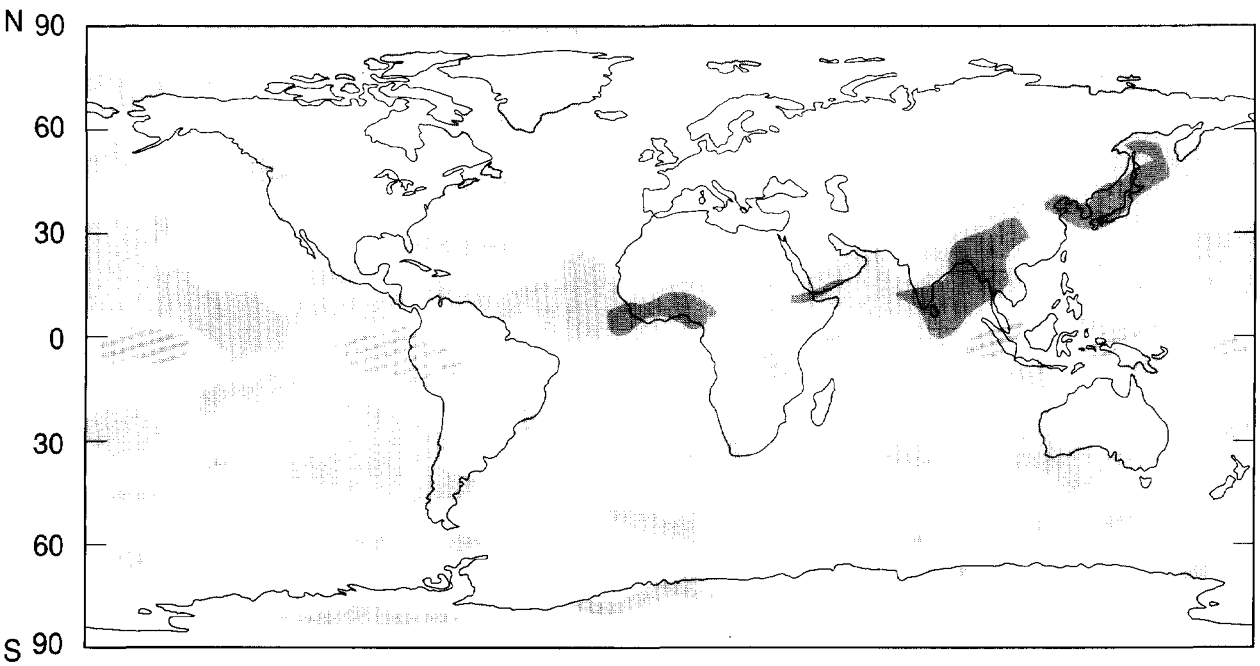

Figure 6. Present-day CCM-simulated differences in precipitation-minus-evaporation balance calculated by subtracting the December, January, and February P-E balance (Figure 5b) from the June, July, and August P-E balance (Figure 5a). Light shading indicates positive balance in excess of 1.0 mm/day; dark shading indicates positive balance in excess of 5.0 mm/day. Hatchuring indicates extreme deficit (<-5.0 mm/day).

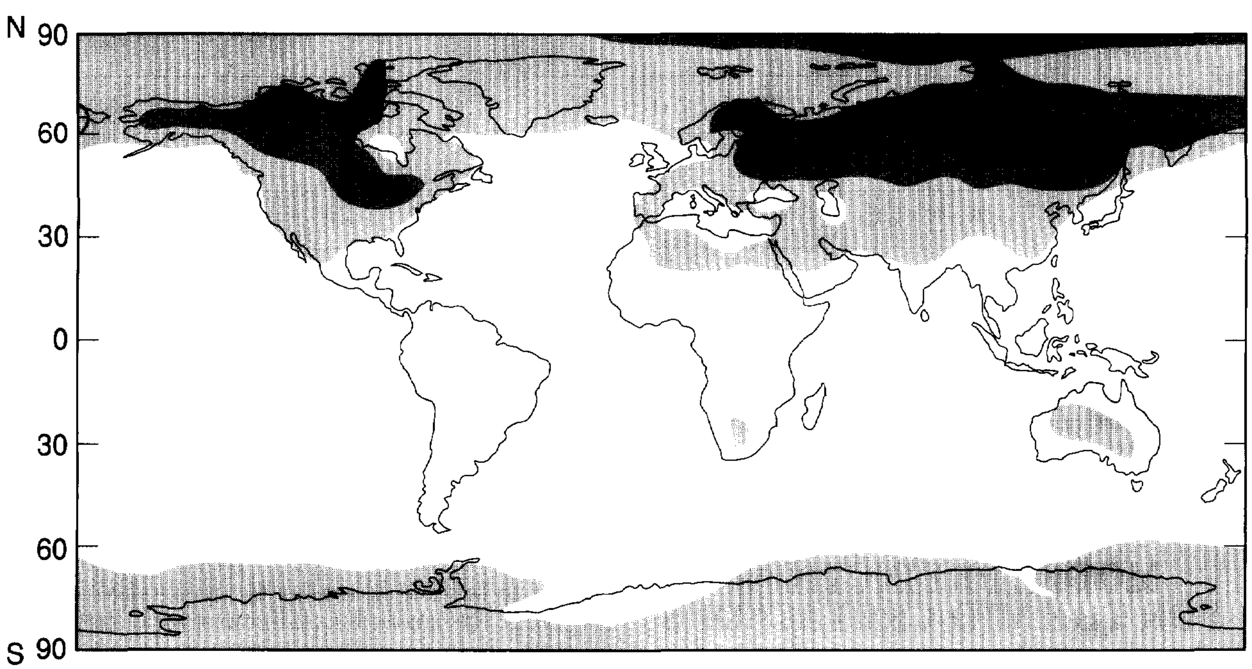

Figure 7. Present-day CCM-simulated temperature difference between June, July, and August and December, January, and February. Shading indicates annual temperature contrast in excess of 20C° (contour interval 20C°).

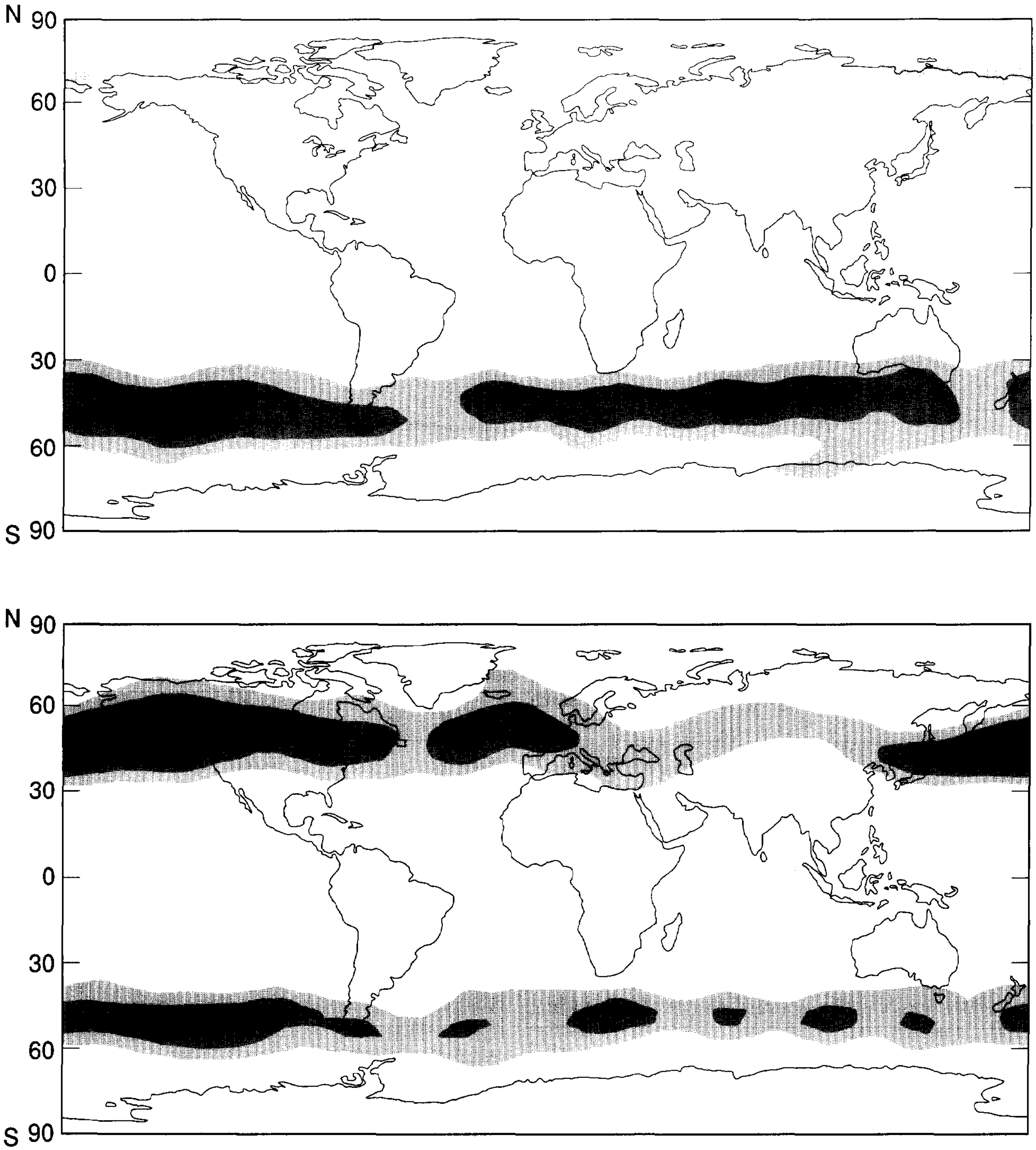

Figure 8. Present-day CCM-simulated storm tracks as represented by the standard deviation of the geopotential height field for (a) average June, July, and August and (b) average December, January, and February. Darkening of contoured areas indicates increasing standard deviation and more frequent, higher magnitude storms.

Tethys Ocean exerted strong control on distribution of high precipitation, which occurs on both the northern and southern continental boundaries of Tethys. Third, northern hemisphere mid-latitude winter precipitation maxima were poorly developed during the mid-Cretaceous, reflecting, in part, major differences in the characteristics of winter-storm distribution (Barron, 1989).

Simulated evaporation rates (Figure 11) reflect temperature (latitude), nature of seasonal changes in general circulation, and on continents, the availability of moisture.

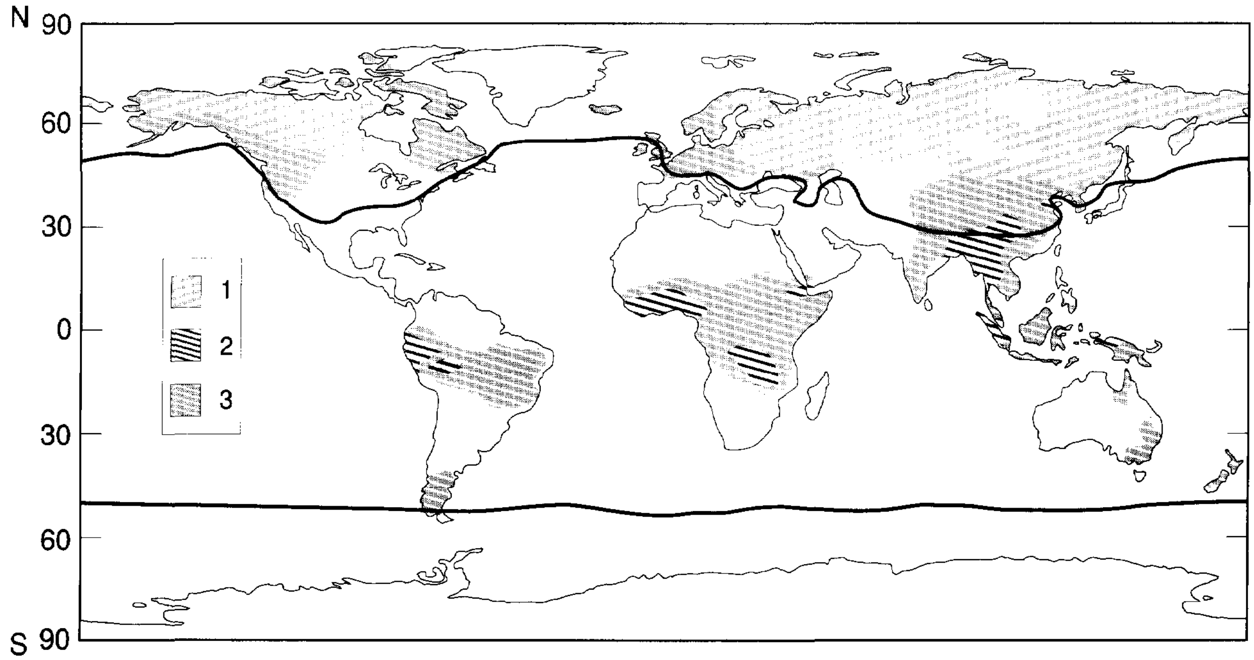

Figure 9. Present-day CCM-defined regimes of lacustrine conditions. Shaded regions are characterized by positive annual moisture balance in excess of 0.5 mm/day (after Figure 4). Within these regions, pattern 1 represents large annual temperature variations (>40C°, after Figure 7); pattern 2 represents large annual P-E variations (>5 mm/day seasonal average, after Figure 6); and pattern 3 represents regions with no substantial variation. Heavy lines indicate interseasonal average positions of the 4°C isotherm.

By the same procedure used to derive Figure 4, differences between annual average precipitation and evaporation were computed to define a first-order prediction of mid-Cretaceous lake occurrence, shown in Figure 12, which similarly illustrates only regions with a moisture balance greater than 0.5 mm/day.

Comparing the mid-Cretaceous and present-day control simulations (Figures 12 and 4) reveals several interesting differences. Most Cretaceous continental areas are characterized by positive moisture balance; smaller areas of evolving southern Africa, Argentina, and Tibet-western China are predicted as either primary deserts or areas of near-zero moisture balance. These results are entirely consistent with the Cretaceous record of continental humid and arid zones, distribution of which is defined by coals and evaporites, respectively. Those described by Hallam (1984) for Aptian to Cenomanian time are remarkably consistent with Figure 12.

By the procedure described earlier, mid-Cretaceous regions predicted to be conducive for lake formation are further subdivided by considering seasonal variability. In Figure 13—seasonal characteristics of P-E balance as a difference between values in Figures 10 and 11—the overall pattern of meridional circulation and the importance of monsoons are evident, although position of the Tethys Ocean clearly dominates distribution of regions of strong moisture excess and deficit. Figure 14, calculated as the difference in seasonal P-E (Figures 13a and 13b), identifies regions of strongest seasonal difference in moisture balance. Tethys Ocean and its margins again are the most apparent areas of seasonal contrast.

The second major source of variation, amplitude of the annual cycle of temperature, is illustrated in Figure 15 for the mid-Cretaceous simulation. Most importantly, Cretaceous geography also is characterized by high-latitude regions of substantial seasonal temperature variation (most significantly Greenland, Siberia, and Antarctica). A similar argument applies—the combination of seasonal variation in solar insolation and lack of thermal inertia of the continents results in a large annual cycle of temperature. This appears to be a robust aspect of model simulation (Crowley et al., 1986; Schneider et al., 1985; Sloan and Barron, 1990).

Model-predicted distribution of mid-Cretaceous winter storms (Figure 16), as defined by time-filtered standard deviation of the geopotential height field, provides additional information on annual variability. Northern hemisphere winter storms are shifted poleward compared with the present day and, because the North Atlantic is not well developed, the pattern is dominated by the North Pacific (Barron, 1989). Southern hemisphere winter storms are predicted to be weaker.

Large seasonal differences in P-E balance (Figure 14), regions of large seasonal temperature difference (Figure 15), and position of the winter 4°C isotherm

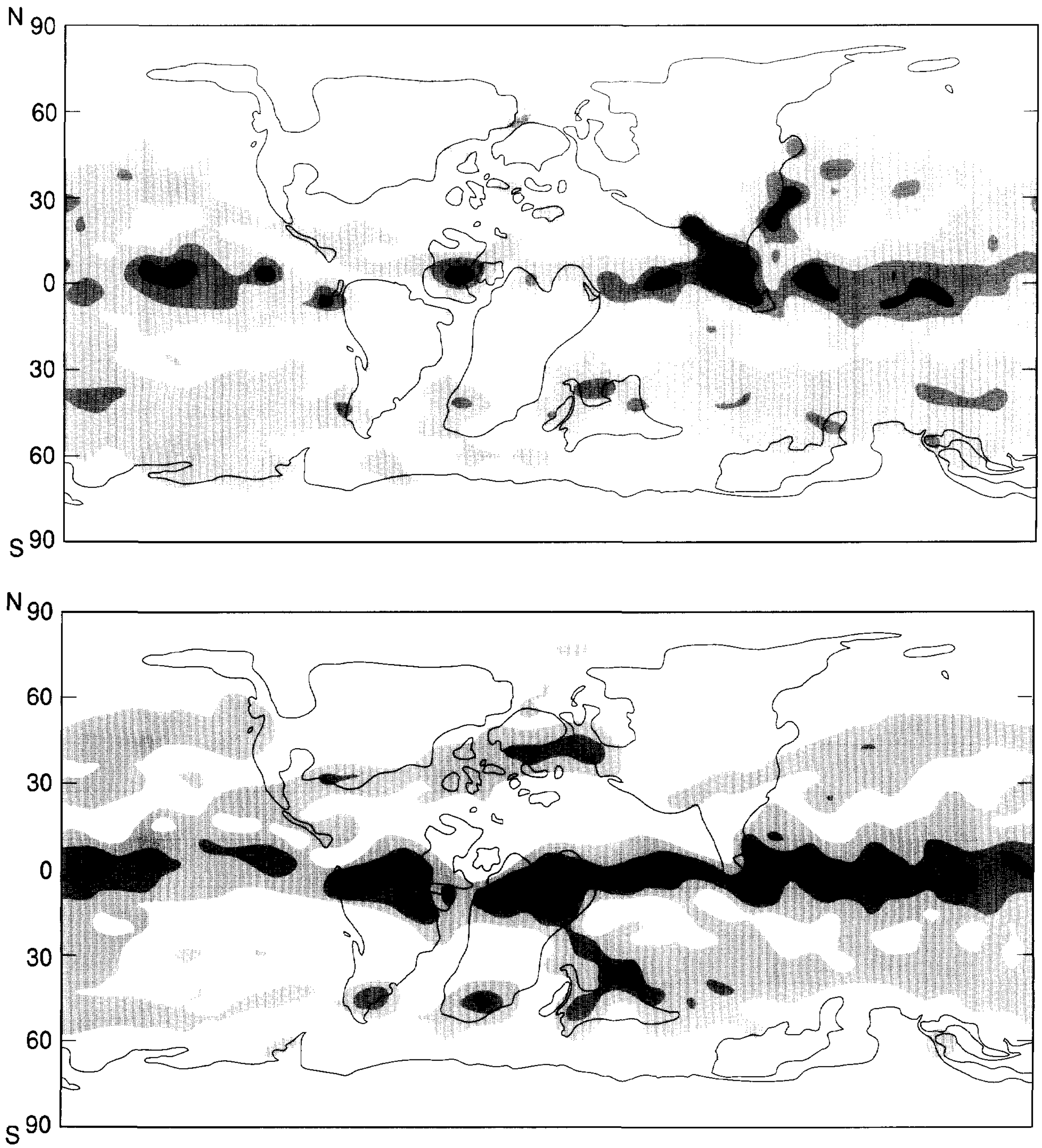

Figure 10. Mid-Cretaceous model-simulated precipitation (mm/day) for (a) average June, July, and August and (b) average December, January, and February. Shading indicates precipitation in excess of 3 mm/day (contour interval 3 mm/day).

provide the basis for subdividing the model-predicted distribution of positive moisture balance illustrated in Figure 12. Lake regimes in Figure 17 then can be defined as for the present day. Regions of positive annual moisture balance that lack large annual variation correspond to model-predicted regions conducive to lake development with potential for organic-rich sedimentary deposition, as defined solely by large-scale climate criteria.

The target regime again is primarily tropical or subtropical. Greater areas within the middle latitudes are characterized by relatively small seasonal climatic variations. This may reflect greater potential at middle and higher latitudes because of characteristics of mid-Cretaceous geography and greater winter warmth compared with the present. However, position of the winter 4°C isotherm may eliminate many mid-latitude regions from exploration

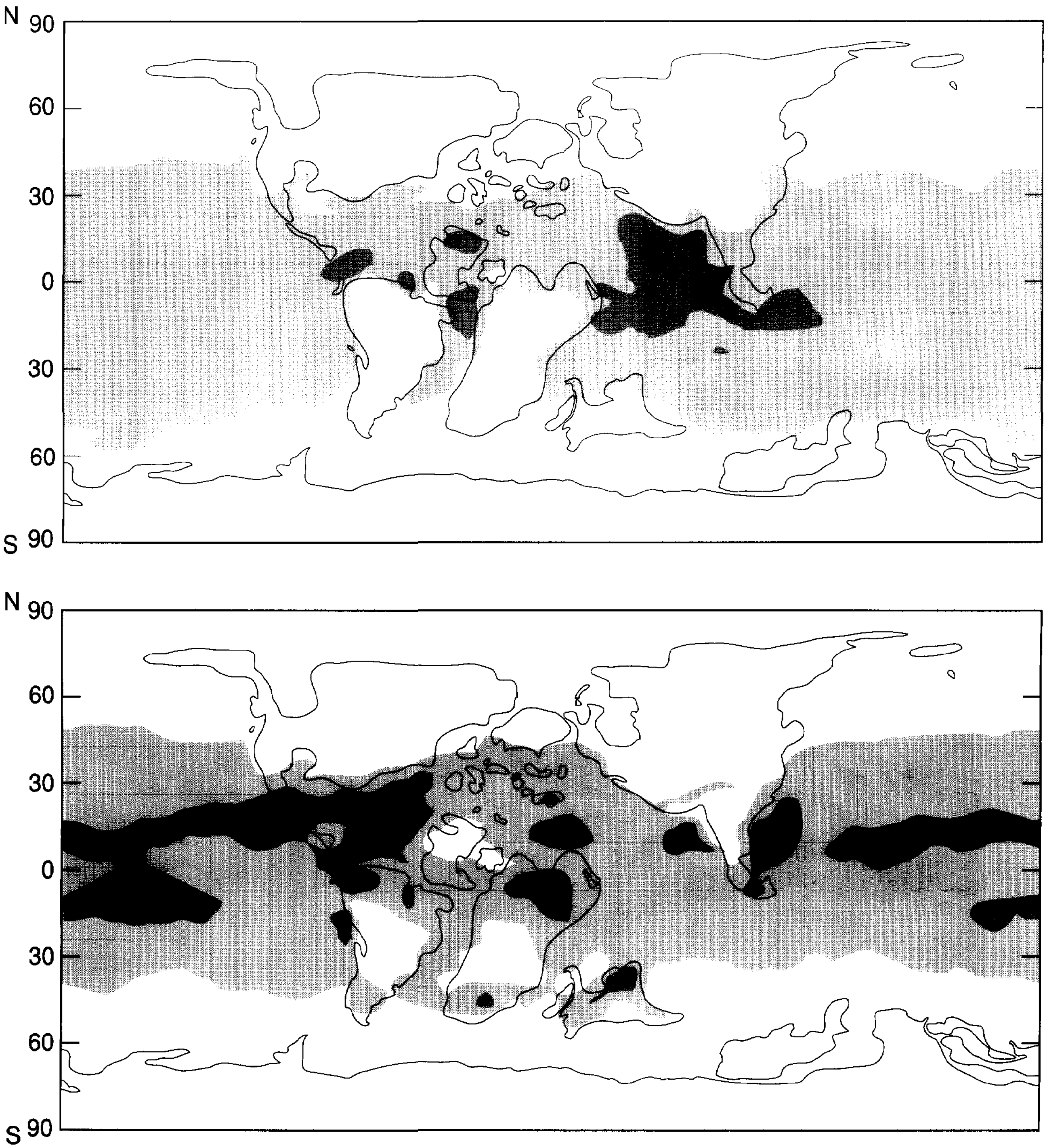

Figure 11. Mid-Cretaceous model-simulated evaporation (mm/day) for (a) average June, July, and August and (b) average December, January, and February. Shading indicates evaporation in excess of 3 mm/day (contour interval 3 mm/day).

unless they lie close to the continental margin. In terms of climate, the mid-Cretaceous is somewhat more conducive to development of lacustrine source rocks than is the present. Figure 17 includes an initial comparison with a data set of the distribution of Cretaceous lacustrine source rocks. Although not perfect or comprehensive, most Cretaceous lacustrine source rocks fall within predicted "conducive" environments. However, if the 4°C isotherm is a good criterion for lake turnover and oxygenation, then more than one-half of Cretaceous lacustrine source rocks are eliminated, but this may reflect the fact that Cretaceous climates were warmer than simulated by the model (see Barron and Washington, 1985). Conversely, if Cretaceous undifferentiated sites are eliminated, most remaining sites lie near coastlines and may experience strong maritime influences under conditions of warm ocean temper-

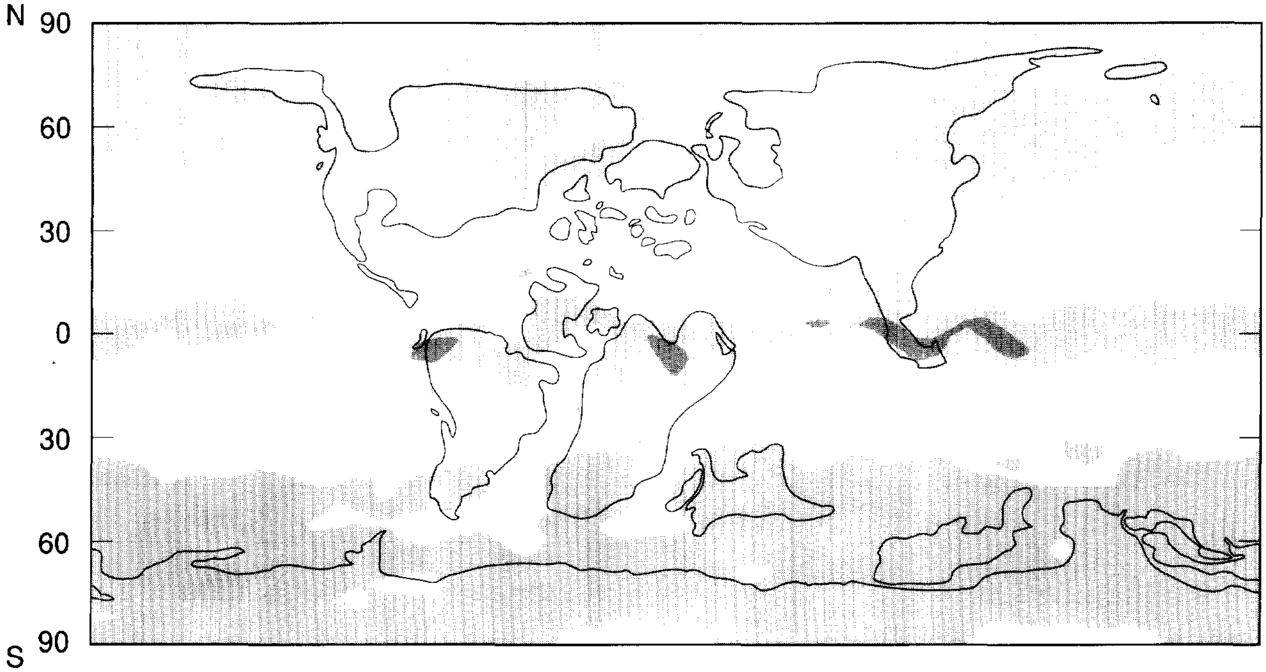

Figure 12. *Mid-Cretaceous model-simulated precipitation minus evaporation (mm/day) for a given annual average. Light shading indicates positive balance in excess of 0.5 mm/day; dark shading indicates excess of 5.0 mm/day. Hatchuring indicates extreme deficit (<-5.0 mm/day).*

atures. Further research will be needed to examine sequences case by case and to compare model results for higher atmospheric CO_2 concentrations (warmer Cretaceous simulation).

DISCUSSION AND CONCLUSIONS

Lakes are dynamic environments, and lake sedimentation represents the interaction of many complex physical, biological, and chemical variables. The complexity of this interaction limits predictability of lake distribution and lake characteristics. Consequently, the initial approach described here was an attempt to map key governing variables—in this case, climate—that then can be used to limit the scope of exploration either spatially or temporally. This investigation of climatic control on lake distribution and characteristics was highly simplified, based on a twofold assumption that positive moisture balance is a limiting factor in lake distribution and that large annual climatic contrasts are incompatible with stable stratification and the preservation of organic matter.

Applications of the Community Climate Model to the present day and to the mid-Cretaceous illustrate the first-order climate relationships that may aid in investigating lacustrine source rock distribution through geologic time. The simulations suggest substantial variations based on differences in geography and global climate. In addition, several general relationships are apparent.

First, the tropics are the primary region consistently predicted to be a conducive environment; however, this relationship may not apply throughout Earth history. For example, Kutzbach and Gallimore's (1989) simulations of Pangean megacontinents suggest extensive continental aridity even in tropical continental regions. Continental size apparently influences tropical moisture balance.

Second, the cores of middle- to high-latitude, and particularly large, continental regions are likely to experience substantial annual climatic variability and seasonal overturn and, therefore, are less likely to promote high organic-carbon deposition.

Third, environments conducive to lake formation and lake stratification may occur in the middle latitudes depending on the relationship to monsoonal circulations, position with respect to winter storm tracks and intensity of winter storms, and the extent to which climate is modulated by oceanic regions. These regions less easily follow simple rules that can be qualitatively applied to different paleogeographic reconstructions.

The importance of the model results is demonstrated by the CCM's capability to simulate modern climate and by the apparent match with mid-Cretaceous arid and humid climatic indicators. Evidently, the models provide a reasonable determination of arid and humid environments and, therefore, a reasonable estimation of potential lake distribution. In addition, they reasonably simulate

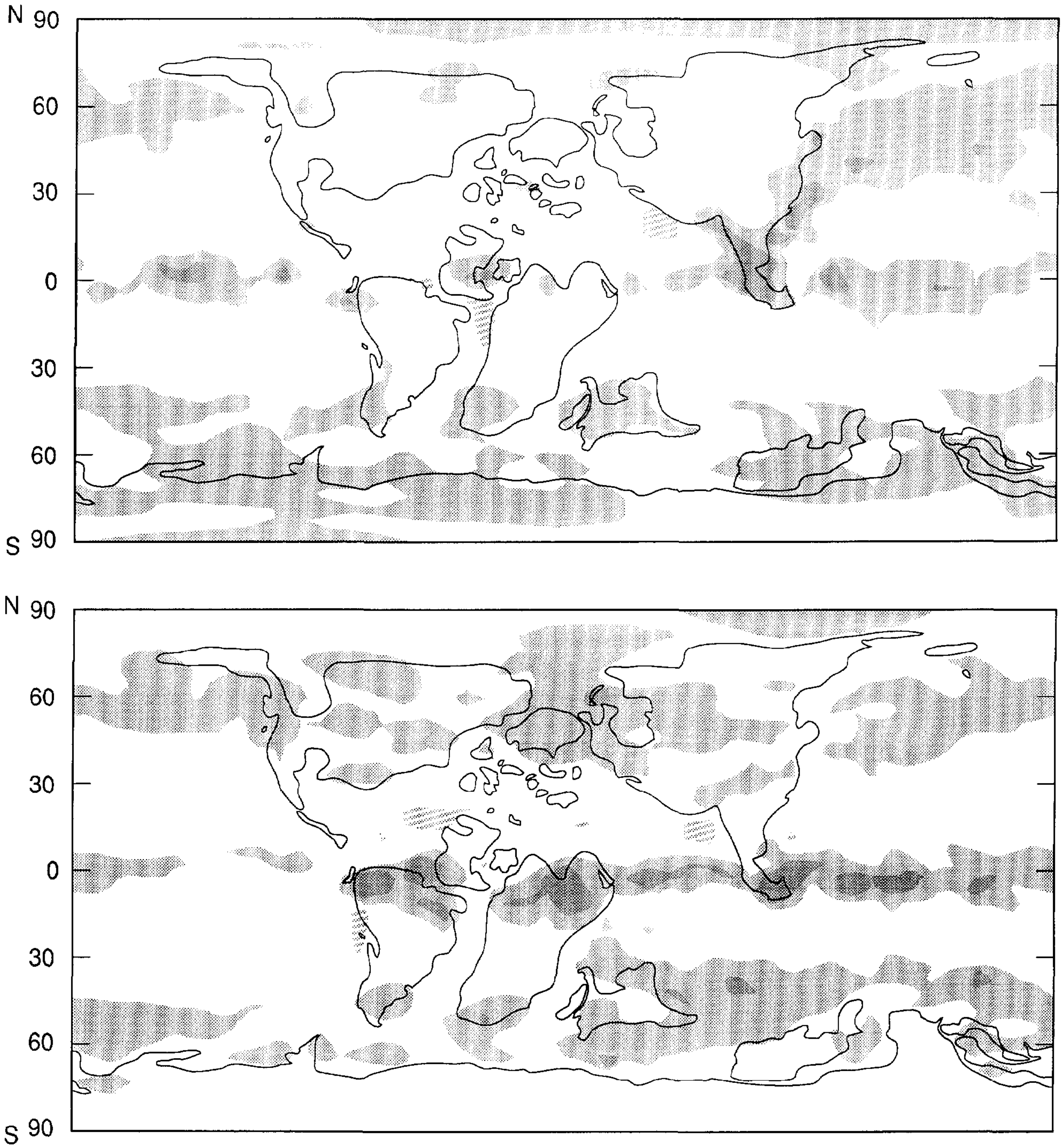

Figure 13. Mid-Cretaceous model-simulated precipitation minus evaporation (mm/day) for (a) average June, July, and August and (b) average December, January, and February. Light shading indicates positive balance in excess of 1.0 mm/day; dark shading indicates positive balance in excess of 5.0 mm/day. Hatchuring indicates extreme deficit (<-5.0 mm/day).

climate variation through the annual cycle. The most significant test of these predictions will be a comprehensive reconstruction of mid-Cretaceous lacustrine source rocks. The question here is the extent to which climatic variability explains source rock distributions. These ideas are largely untested for Earth history.

Coincidence of model predictions and actual lacustrine source rock distribution cannot be expected for three reasons. First, many aspects of the hydrologic cycle, particularly as they relate to model resolution, are not well simulated. Second, experiments are not comprehensive and therefore may not have addressed all the driving factors that

Figure 14. Mid-Cretaceous model-simulated differences in precipitation-minus-evaporation balance calculated from subtracting the December, January, and February P-E balance (Figure 13b) from the June, July, and August P-E balance (Figure 13a). Light shading indicates positive balance in excess of 1.0 mm/day; dark shading indicates positive balance in excess of 5.0 mm/day. Hatchuring indicates extreme deficit (<-5.0 mm/day).

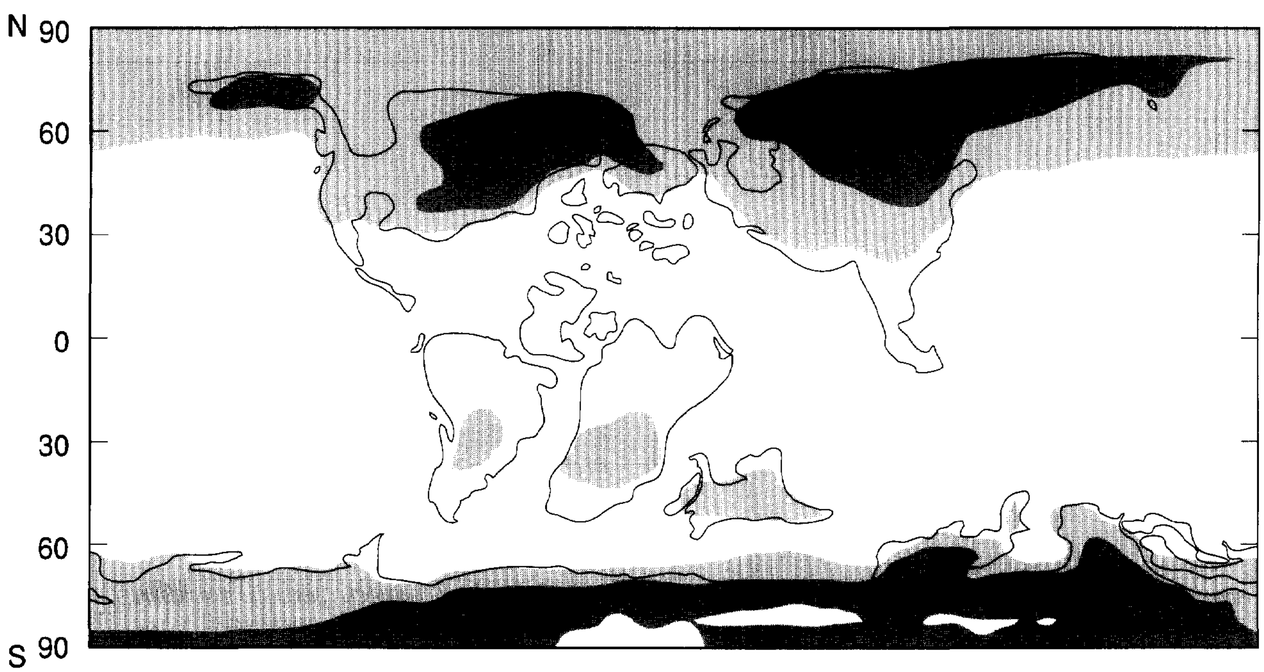

Figure 15. Mid-Cretaceous model-simulated temperature difference between June, July, and August, and December, January, and February. Shading indicates annual temperature contrast in excess of 20°C (contour interval 20°C).

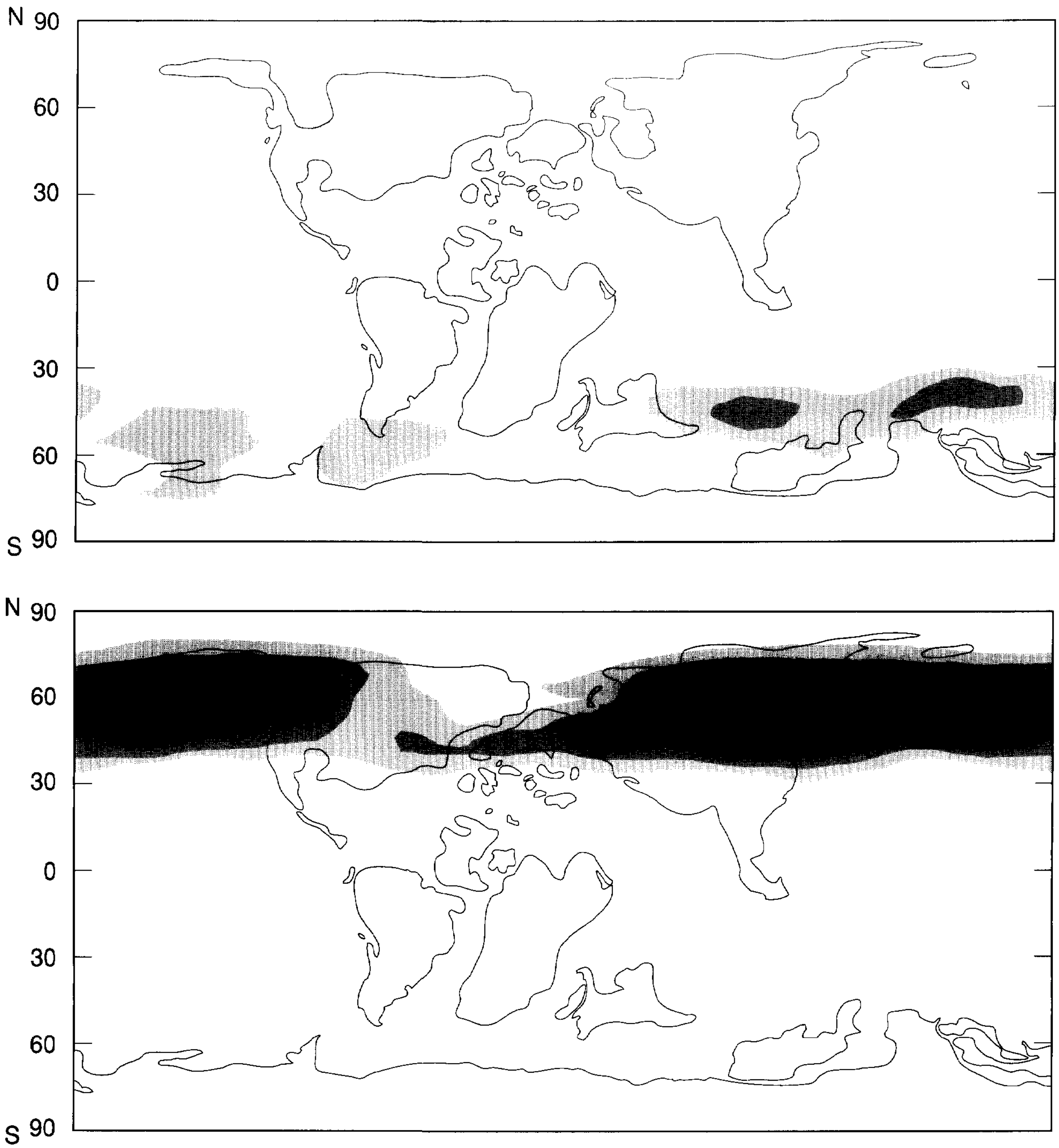

Figure 16. Mid-Cretaceous model-simulated storm tracks as represented by the standard deviation of the geopotential height field for (a) average June, July, and August and (b) average December, January, and February. Stippling indicates greater standard deviation and more frequent, higher magnitude storms.

may have influenced Cretaceous climate (e.g., CO_2 levels). Third, lake location, size, shape, productivity, and organic-matter preservation are governed by climate, tectonism, and various biological and chemical factors. For example, elevation may be a factor in lake overturn even in tropical regions (Håkanson and Jansson, 1983; Katz, this volume).

Rather than expect perfect correspondence, if climatic analysis can help successfully limit the scope of exploration, without inadvertent loss of potential source rocks from consideration, then GCM prediction provides a foundation for lacustrine source rock prediction. The next step should be to combine climatic data and knowledge of basin formation and

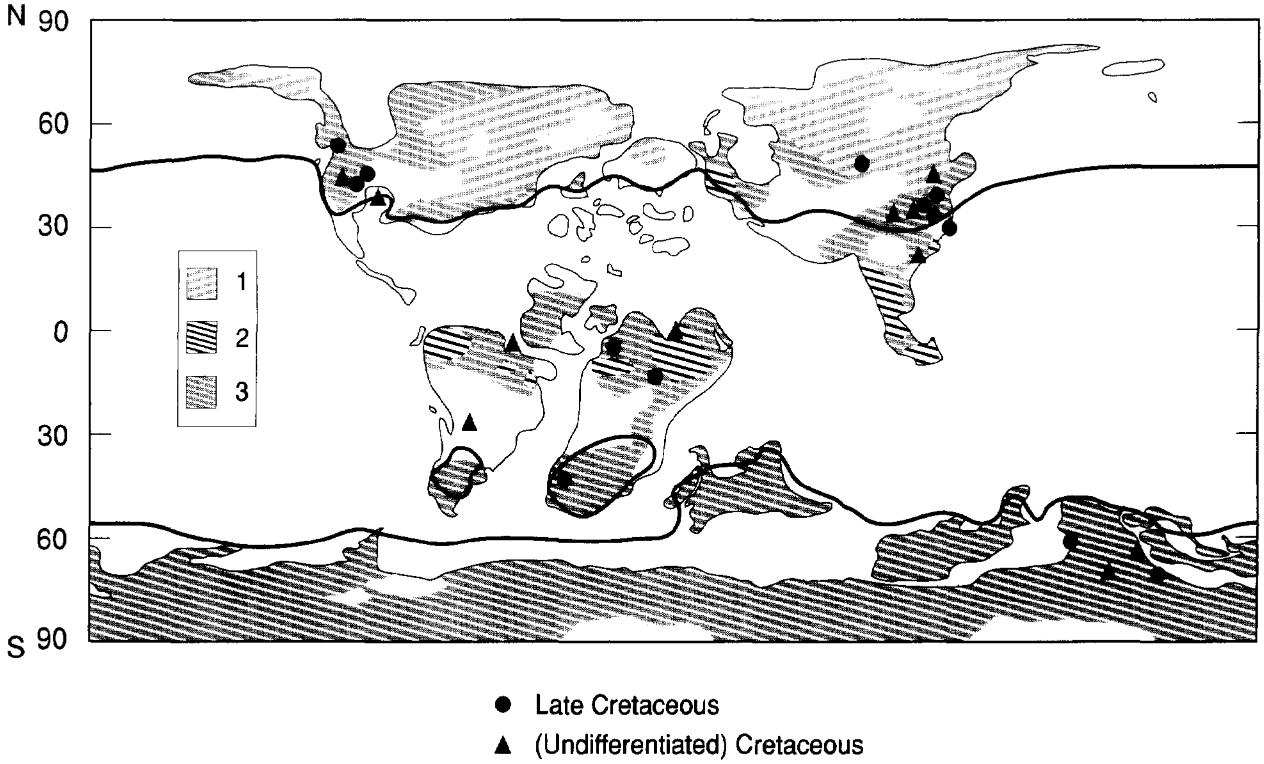

Figure 17. Mid-Cretaceous model-defined regimes of lacustrine conditions. All shaded regions are characterized by positive annual moisture balance in excess of 0.5 mm/day (after Figure 12). Of these regions, large annual temperature variations (>40°C after Figure 15) are indicated by pattern 1; large annual P-E variations (>5 mm/day seasonal average, after Figure 14) are indicated by pattern 2; and regions without substantial annual variation are indicated by pattern 3. Winter seasonal average position of the 4°C isotherm is indicated by heavy line. Locations of Cretaceous lacustrine source rocks after Smith (1990) are plotted. (Circle indicates Late Cretaceous; triangle indicates undifferentiated Cretaceous.)

distribution to identify specific regions of lake deposition under conducive environmental conditions.

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