Zbl. Geol. Paläont. Teil I	1992	H. 11/12	1253-1265	Stuttgart, Mai 1994

Results of a climate model for Triassic Pangaea

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With 5 figures in the text

HAY, W. W., THOMPSON, S., POLLARD, D., WILSON, K. M. & WOLD, C. N. (1994): Results of a climate model for Triassic Pangaea. - Zbl. Geol. Paläont. Teil I, **1992** (11/12): 1253-1265; Stuttgart.

Abstract: We have used a new General Circulation Model, GENESIS version 1.02, derived from the U. S. National Center for Atmospheric Research Community Climate Model I (NCAR-CCM I) to simulate the climate of an Earth with realistic Pangaean geography. The climate model was run assuming that the ocean heat flux was similar to that of today, atmospheric CO_2 content was four times that of today, the solar constant was 2 % less than today, and the Earth's orbit was circular, with mean obliquity 23.4°. Models were run for paleogeographies at 245 Ma (Scythian) and 225 Ma (Carnian).

The results indicate that no ice cap would develop over the land, and there is no permanent sea ice. The seasonal temperature variation in the interior of the continent is in the order of 50 °C. The continental areas are very dry except for a few coastal areas and along uplifts. The models both suggest an extreme seasonal monsoonal circulation, with strong westerly winds parallel to the entire coast of Gondwana and the east coast of Laurasia during the northern hemisphere summer. In both hemispheres, the effect is to cause coastal upwelling. The model also predicts permafrost in the deeper soil layers poleward of 50° N and S. The effects of topographic uplifts on the atmospheric circulation are pervasive. Topography strongly affects the monsoonal circulation causing major deviations of the wind systems suggested in model runs with idealized geographies. Topography also plays a crucial role in concentrating rainfall in a few small areas.

It is evident that in order to have a realistic simulation of paleoclimate, an accurate representation of the paleotopography is essential. It is also evident that the paleoclimate models may be useful in suggesting geological criteria that can confirm or reject the predicted paleoclimatic conditions.

0340-5109/93/1994-1253 $ 2.50

Zusammenfassung: Mit Hilfe eines neuen General Circulation Model, GENESIS-Version 1.02, wird das Klima der Erde mit einer realistischen Pangäa-Geographie für 245 Ma (Skyth) und 225 Ma (Karn) simuliert. Das Klimamodell unterstellt, daß der ozeanische Wärmefluß ähnlich ist wie der heutige, der CO_2-Gehalt der Atmosphäre vierfach so hoch, die Solarkonstante 2 % geringer als heute und die Erdachse eine Neigung von 23,4° hat.

Die Ergebnisse zeigen, daß sich auf den Festländern keine Eiskappen entwickeln konnten und daß es kein permanentes Meereseis gab. Die jahreszeitliche Temperaturschwankung im Innern des Kontinentes hat eine Größenordnung von 50 °C. Die Kontinente sind, abgesehen von einigen wenigen Küstenregionen und Hochgebieten, sehr trocken. Beide Modelle lassen eine extreme jahreszeitliche Monsun-Zirkulation vermuten, mit heftigen westlichen Winden parallel zur ganzen Küste von Gondwana und der Ostküste von Laurasia während des Nordsommers. In beiden Hemisphären bewirkt das ein Upwelling an den Küsten. Das Modell sagt ebenso Dauerfrost voraus in tieferen Bodenhorizonten polwärts von 50° N bzw. S. Die Topographie beeinflußt die atmosphärische Zirkulation, vor allem die Monsun-Zirkulation, stark: Die Modelle zeigen bedeutende Abweichungen der Windsysteme gegenüber solchen, die mit einer idealisierten Geographie arbeiten. Die Topographie bewirkt ebenfalls die Konzentration der Niederschläge auf einige wenige kleine Gebiete.

Eine genaue Wiedergabe der Paläotopographie ist unabdingbar für eine realistische Simulation des Paläoklimas. Es ist evident, daß Paläoklimamodelle nützlich sind, um geologische Kriterien zu beurteilen, die nämlich die vorhergesagten paläoklimatischen Bedingungen bestätigen oder nicht bestätigen.

Introduction

During the last decade a number of simulations using atmospheric general circulation models (AGCMs) have been applied to studies of Pre-Quaternary paleoclimatology (BARRON & WASHINGTON 1982a, 1982b, 1984, 1985, BARRON 1983, 1984, 1985, BARRON et al. 1985, 1989, SCHNEIDER et al. 1985, KUTZBACH & GALLIMORE 1989, HAY et al. 1990a, 1990b, MOORE et al. 1992a, 1992b, CHANDLER et al. 1992, ROSS et al. 1992). Technical descriptions of the most widely used models, the U. S. National Center for Atmospheric Research (NCAR) Community Climate Model 1 (CCM 1) and the U. S. NASA Goddard Institute of Space Science (GISS) Model II have been published by WILLIAMSON et al. (1987) and HANSEN et al. (1983), respectively.

A new AGCM, GENESIS version 1.02, has been expressly designed to more realistically simulate ancient climates. It has been developed from CCM 1 by STARLEY THOMPSON and DAVID POLLARD of NCAR with input from K. M. WILSON and W. W. HAY. GENESIS differs from CCM 1 in several important respects: The atmospheric part of the model is a heavily modified version of CCM 1. It uses semi-Lagrangian transport for water vapor, rather than advecting it in spectral transform space as in CCM 1. At each step the semi-Lagrangian method interpolates the water vapor field back to the departure points of the model grid, which preserves sharp gradients better and avoids problems with calculation of negative water vapor inherent in the earlier spectral method (WILLIAMSON & RASCH 1989, WILLIAMSON 1990). GENESIS has an explicit plume model for atmospheric convection and the planetary boundary layer which produces more realistic vertical penetration than the earlier bulk convective adjustment scheme in CCM1. It has the THOMPSON et al. (1987) solar radiation scheme for aerosols, uses a more sophisticated cloud parameterization following SLINGO & SLINGO (1991), allowing for stratus, anvil cirrus and convective clouds. GENESIS is coupled to a slab ocean and includes more realistic treatment of vegetation, soil, snow and sea ice. The ocean is represented by a thermodynamic slab 50 m thick that crudely approximates the seasonal heat capacity of the real ocean mixed layer. Ocean heat transport is prescribed as a function symmetric about the equator, based on present-day observations (COVEY & THOMPSON 1989). Up to two vegetation layers ("trees" and "grass") can be specified at each grid point. The radiative and turbulent fluxes through these layers to the ground surface are calculated. Precipitation can be intercepted by the vegetation to subsequently drip to the ground and evaporate. The soil is up to six layers, extending to 4.25 m depth. Each layer can have different porosity and permeability, and infiltration is governed by non-linear equations. Soil moisture and ice are computed as proportions of the pore space in each layer. Finally, GENESIS has independent AGCM and surface grids, transferring values between the fields by interpolation or averaging. Both the surface and atmospheric grids have a diurnal cycle, with solar radiation calculations performed every 1.5 hours. Full AGCM calculations are performed every 0.5 hours except for absorptivities and emmissivities of H_2O, CO_2, and O_3, which are calculated once every 24 hours.

A more extensive discussion of the results of the Triassic simulations for both the Scythian (245 Ma) and Carnian (225 Ma) is presented in WILSON et al. (1993).

Triassic paleogeography

HAY, WILSON and WOLD developed a new plate tectonic reconstruction of Pangaea that serves as the paleogeographic base for the Triassic simulations. The new reconstruction uses 15 large blocks and 240 terranes. The continental margins have been restored to their configuration prior to the stretching that occurred during rifting. The larger subsequent internal deformations have been removed from all of the continents except Asia. The assembly of the major blocks for 225 Ma (Carnian) is shown in Fig. 1. For the final reconstructions, terranes were added along the western margin of North America and in the Tethys region. The paleolatitude reference frame is that of HARRISON & LINDH (1982) for North America; all other blocks are located with reference to North America.

The ages for the simulations are Scythian (245 Ma) and Carnian (225 Ma), chosen to represent the driest and wettest times during the Triassic. The Triassic paleogeography was plotted on the new reconstruction. The shorelines for the two reconstructions were taken from the Early and Late Triassic maps of RONOV et al. (1989). The paleotopography was estimated using the method described by HAY et al. (1987); it was assumed that major elevations are a result of 1) subduction of

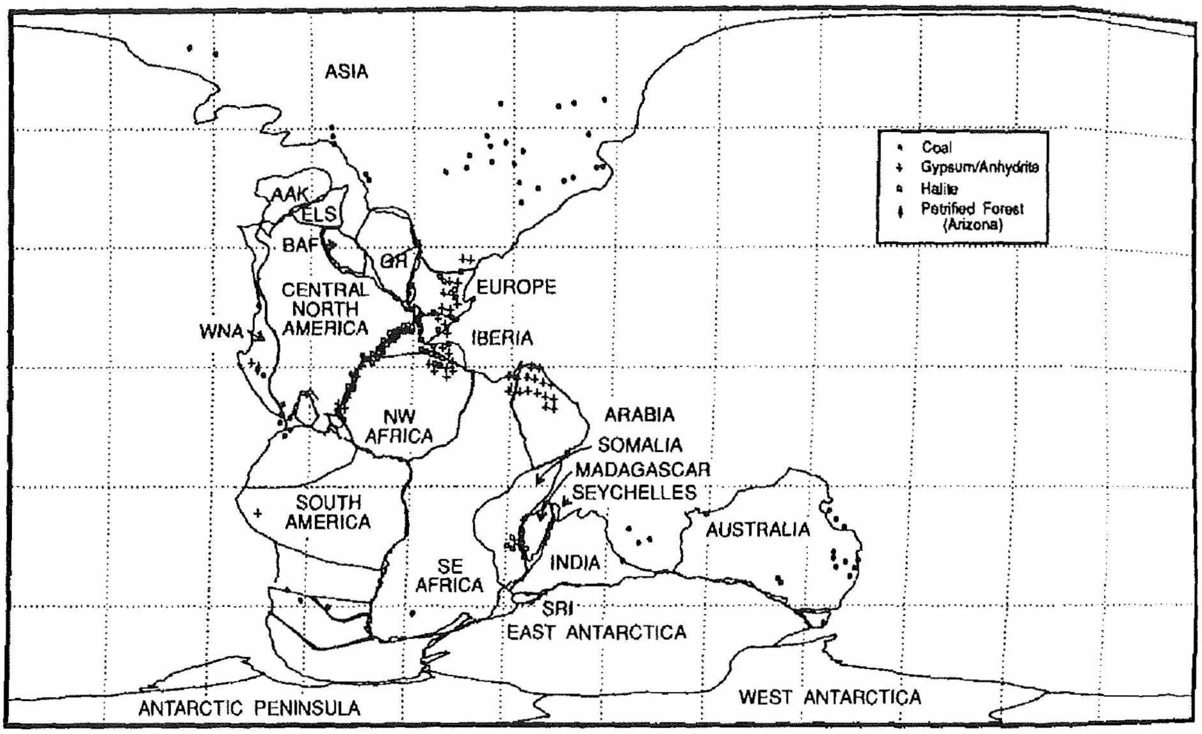

Fig. 1. Assembly of major blocks during the Carnian (225 Ma). Paleolatitude reference frame is from the paleolatitude for North America of HARRISON & LINDH (1982), with other blocks plotted relative to North America. The distribution of three climate-sensitive lithologies, coal, gypsum/anhydrite, and halite, are shown. The location of the Petrified Forest of Arizona, USA, is also shown; it lies directly on the paleoequator near the western margin of the supercontinent.

young ocean lithosphere; 2) collisions of continental fragments or oceanic plateaus with continental blocks; and 3) thermal uplift prior to and during continental rifting. Following the argument of SOUTHAM & HAY (1981) that the average elevation of Pangaea was in the order of 1.5 km, an increment was added to the topographic variations to produce average elevations for the Scythian (245 Ma) and Carnian (225 Ma) of 1374 m and 1260 m, respectively. The elevations were estimated in terms of 1 km steps.

In describing the paleogeography for the paleoclimate model, the geography must be reduced to a common level of resolution; for the simulations described here, the resolution of the surface is 2° by 2°. Some important features, such as the rift separating North America and Africa, cannot be resolved at the 2° by 2° resolution and disappear. The paleogeography used for the simulations is shown in Fig. 2.

Fig. 1 also shows the distribution of several climate indicator sediments, coal and evaporites. The deposition of gypsum/anhydrite and salt in the rift between North America and Africa and in a rift between Somalia and Madagascar are important features of the geologic record of climate, but the environments in which they were deposited are too small to be resolved at the 2 x 2° resolution used to define boundary conditions for the models.

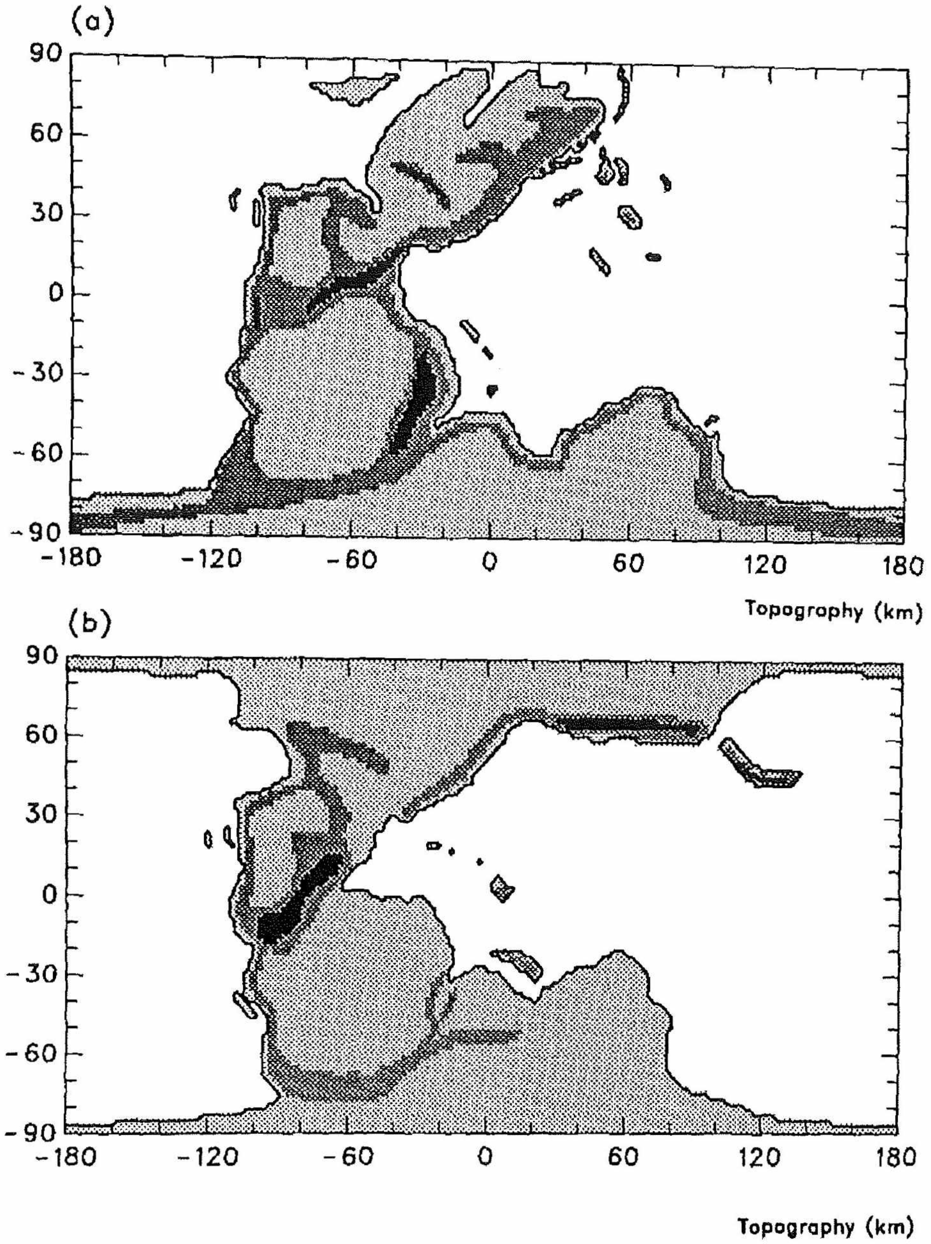

Fig. 2. Paleogeography for (a) Scythian (245 Ma), and (b) Carnian (225 Ma). Three elevation steps are shown: light shading = 1 km, medium shading = 2 km, dark shading = 3 km.

Boundary conditions

The model simulations reported here used 2 x 2° horizontal resolution for surficial processes and 4.5 x 7.5° resolution for atmospheric processes.

Except for paleogeography and vegetation, boundary conditions for both of the simulations were assumed to be the same. The solar constant was assumed to be 1342 W m^{-2}, 98 % of its present value, following CROWLEY & BAUM (1991). The orbit was assumed to be a "mean" Milankovitch configuration, with an eccentricity of 0, and an obliquity of 23.4°. The assumption of a circular orbit eliminates eccentricity and precession variations. The atmospheric CO_2 concentration was assumed to be 4 times that of today, 1360 ppm. The soil was assumed to be everywhere a light sandy loam to a depth of 4.25 m. Ocean heat flux was assumed to be symmetric about the equator, and to have convergence values of -30 w m^{-2} at the equator, increasing to 30 W m^{-2} at 50° and decreasing to 16 W m^{-2} poleward of 60°.

There being no descriptions of Triassic plant communities, it was assumed that the vegetation at each of the elevation steps was globally uniform. The vegetation at 1 km was assumed to be analogous to that of the present Sonoran desert, that at 2 km assumed to be an evergreen forest, and that at 3 km to be analogous to modern tundra. Attributes of these vegetation types are given in DORMAN & SELLERS (1989); our three vegetation types correspond to their biomes 8, 4, and 10, respectively.

Results

Given the paleogeography and boundary conditions described above the simulations portray the conditions that should have existed on the Triassic earth. The model results are very sensitive to the assumptions about paleotopography, and errors in the formulation of atmospheric and surficial processes or in the boundary conditions would affect the results. The simulations, although representing the current state of the art in understanding of the way the atmosphere behaves, must be regarded as a preliminary quantitative assessment of what conditions in the Triassic may have been like.

The spin-up period for the GENESIS v1.02 simulations presented here was ten model years. The results are averages over monthly or annual periods over model years eleven through fifteen.

The results of the Triassic simulations are discussed at greater length in WILSON et al. (1993). The results indicate that no ice cap would develop over the land, and there is no permanent sea ice. The continental areas are very dry except for a few coastal areas and along uplifts. Both simulations suggest extreme seasonal monsoonal circulation, with strong westerly winds parallel to the entire coast of Gondwana and the east coast of Laurasia during the northern hemisphere summer. In both hemispheres, the effect is to cause coastal upwelling. The model also predicts permafrost in the deeper soil layers poleward of 50° N and S. The effects of topographic uplifts on the atmospheric circulation are pervasive. Topography strongly affects the monsoonal circulation causing major deviations of the winds systems suggested in model runs with idealized geographies. Topography also plays a crucial role in concentrating rainfall in a few small areas. We report here on a some aspects of the simulations that relate to the Triassic in Germany and are particularly thought provoking. During the Scythian, Germany lay at about 10°-15° N and by the Carnian it had migrated to about 15°-20° N.

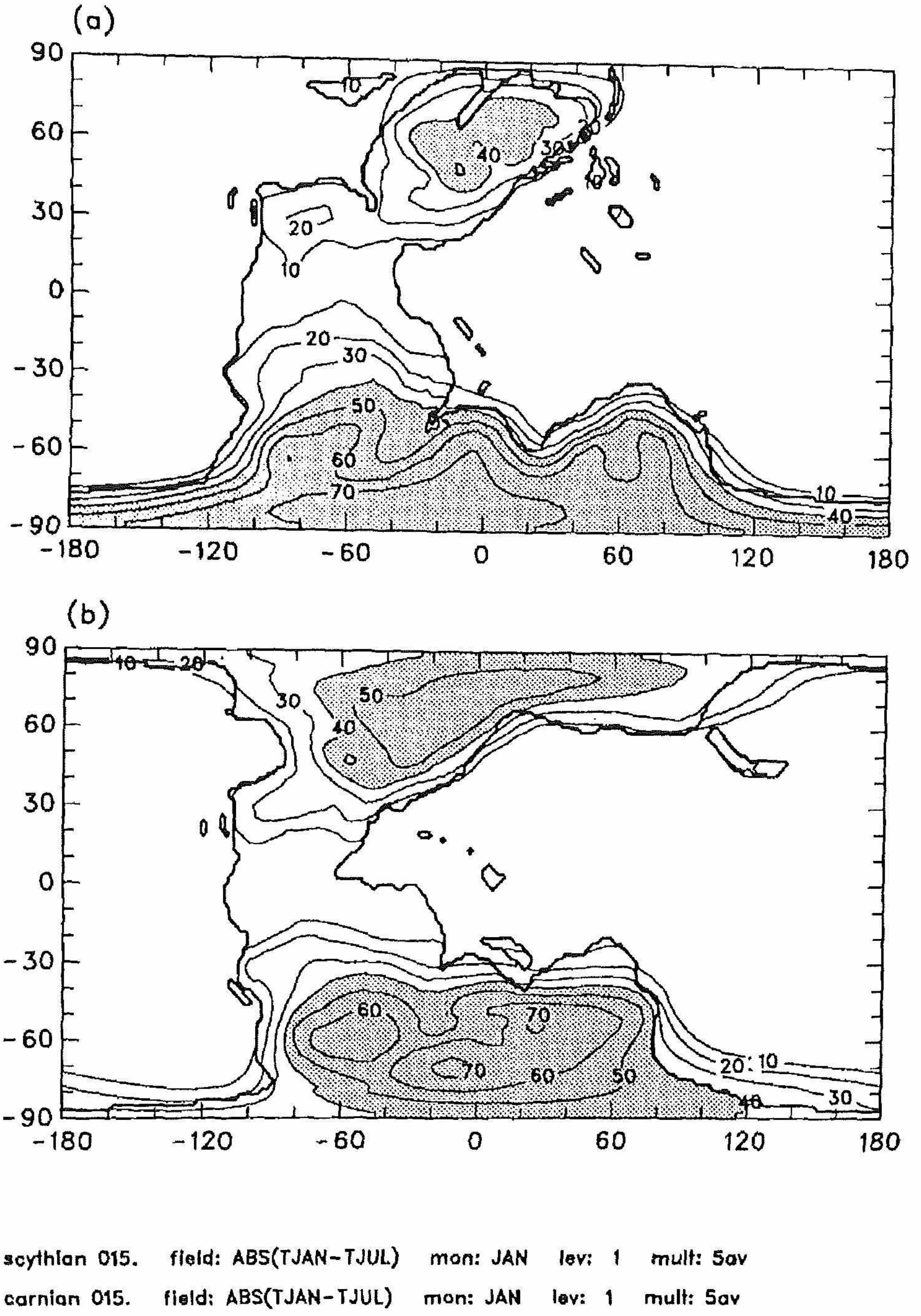

Fig. 3. Seasonal (summer - winter) difference in temperature of the air 2 m above the surface for (a) Scythian (245 Ma) and (b) Carnian (225 Ma). Areas with a seasonal difference >40 °C are shaded.

The simulations suggest that extensive areas in the interior of the continents have very hot summers and cold winters. The seasonal variation is shown in Fig. 3. Gondwana has more extreme conditions than Laurasia, with seasonal tempeature variations of over 70 °C. According to the simulations, the seasonal temperature variation in Germany was only about 30 °C, because of its proximity to the Tethys. The seasonal variations in temperature are large only over land, most of the ocean remains thermally stable and experiences large variations only in the regions off the high-latitude coasts of Gondwana and Laurasia.

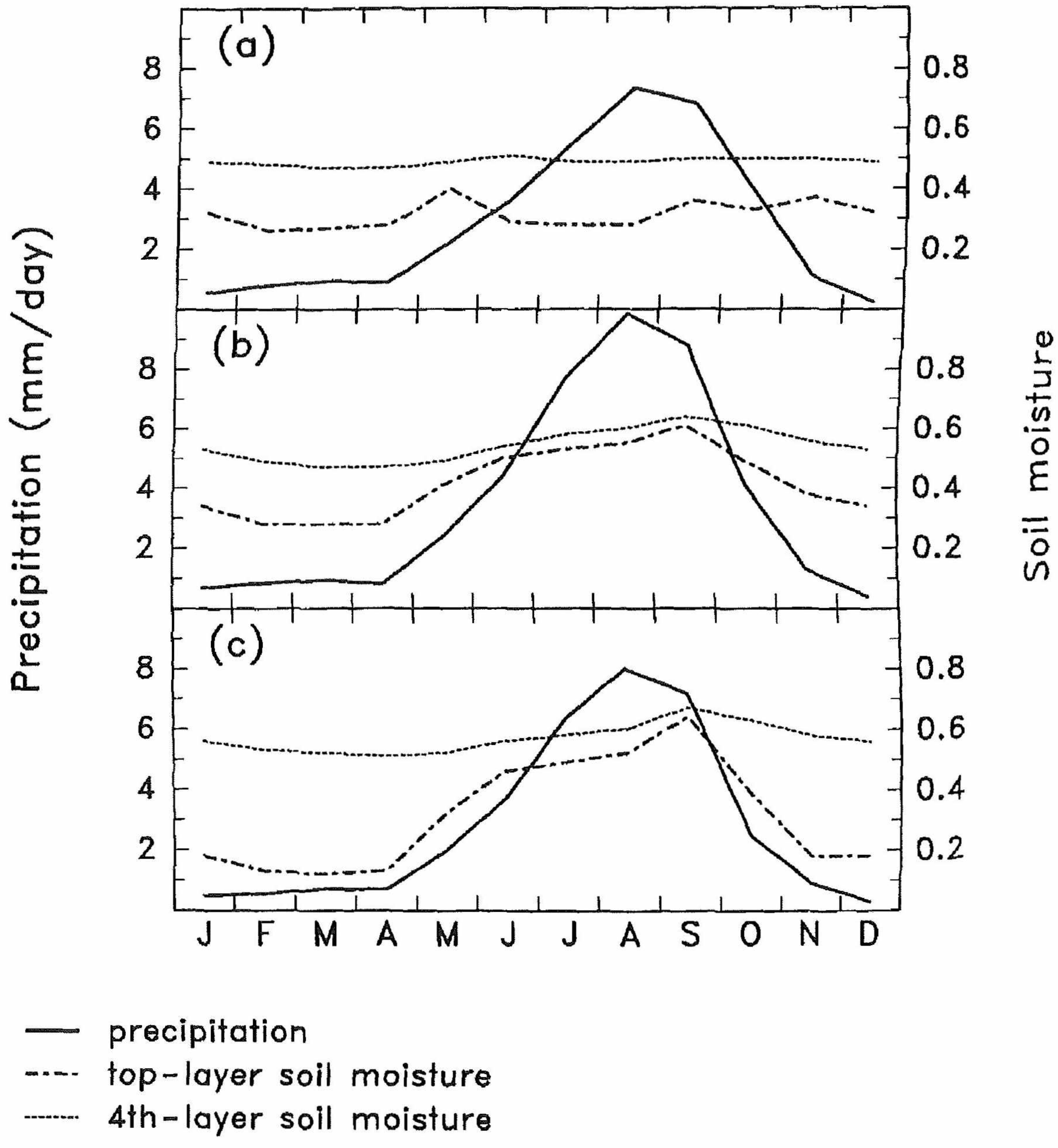

Fig. 4. Monthly mean precipitation, surface-layer (0-5 cm) and fourth-layer (35-75 cm) soil moisture by month for years 11-15 of the Carnian simulation. Soil moisture is expressed in terms of the proportion of pore space filled with water. (a) "Germany", paleolatitudes 14-26° N, paleolongitude 58-50° W; (b) all land at paleolatitude 15° N, between paleolatitudes 14-16° N and paleolongitudes 106-50° W; (c) "Central Laurasian Lowland" (= northern Canada): between paleolatitudes 12-18° N and paleolongitudes 100-84° W.

The simulation for the Carnian indicates that precipitation at the paleolatitude of Germany was highly seasonal. Fig. 4 shows precipitation by month for Germany, for a band across the continent at 14-16° N, and for the central lowland of the continent that corresponds to northern Canada. The rainy season in Germany was May through October, with a peak in precipitation (almost 8 mm/day) in August. The dry season lasted from November through April and was almost rainfall-free.

The Carnian simulation displays a more complex distribution of soil moisture, as shown in Fig. 4. In Germany the soil moisture of the surficial layer remained relatively constant throughout the year. In contrast, the surficial soil moisture in the "central lowland" (northern Canada) was subject to much stronger seasonal variations. The deeper soil layers have a more constant soil moisture.

The mean annual distribution of soil ice for lowest soil layer (1.75-4.25 m) for the Carnian simulation is shown in Fig. 5. The distributions of soil ice by monthly averages do not differ significantly from the mean annual distribution, indicating that the soil ice is permanent, and should be termed permafrost. The permafrost boundary for both the Scythian and Carnian reconstructions lies approximately along the 60° N and S parallels. Referring to Fig. 1, it will be noted that the distribution of coals is mostly between 60° and 45° N and S latitude. The location of coals along and immediately equatorward of the permafrost boundary suggests that the formation of soil ice may have played a critical role in providing the soil moisture conditions required for coal formation.

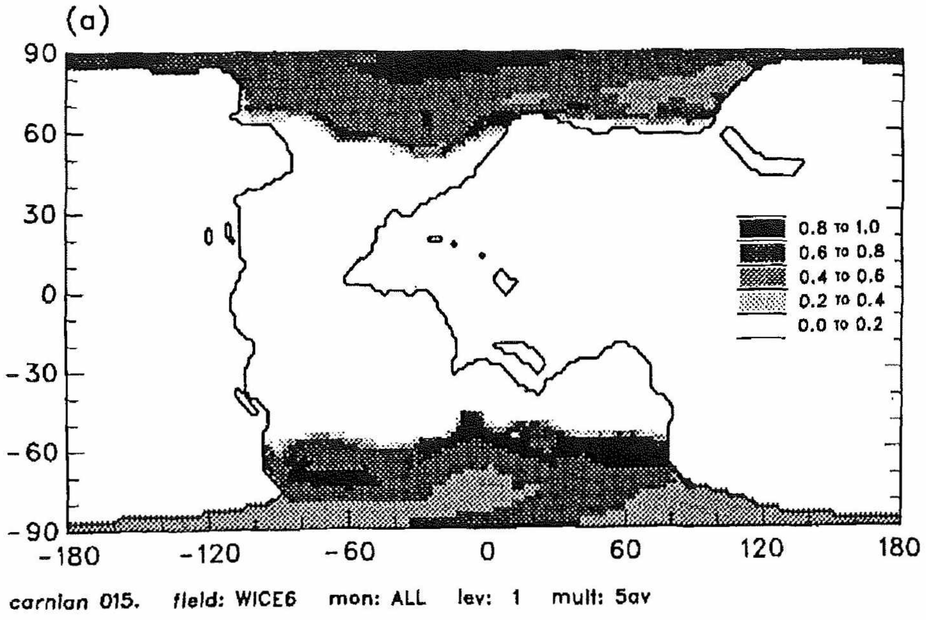

Fig. 5. Soil ice in the lower soil layer (1.75-4.25 m), annual mean over years 11-15 for the Carnian simulation.

Discussion

Simulations of ancient paleoclimates were intitially directed toward gaining insight into the causes of the major climatic differences that characterized different geologic periods. Examination of the results of the GENESIS simulations of Triassic paleoclimate suggests that they may have another, much more important role to play in geology and paleontology. The paleoclimate simulations suggest the kinds of conditions that may have been characteristic of widespread areas of the Earth in the past. The extreme seasonal temperature and precipitation variations indicated by the Triassic simulations are very different from conditions existing anywhere on the Earth today except in some of the most extreme areas of Siberia. The simulations suggest that such conditions were widespread over very large areas of the continents during the Triassic. The reason that distribution of Triassic sediments, with detrital terrestrial redbeds spread over such large areas, seems so unusual to us today, is that the Triassic Earth was indeed very different from the planet today. If the paleogeography and boundary conditions are correct, the simulations should describe the conditions under which the sediments were deposited. We can now explore the problem of Triassic conditions from another viewpoint. Are the conditions indicated by the paleoclimate simulations a reasonable description of the conditions under which Triassic sediments might have formed? Can the widespread deposition of redbeds be explained by the extreme seasonal temperature and precipitation variations indicated by the paleoclimate simulations? What were the soil moisture conditions required for growth of land plants in the Triassic?

The greatest problem in paleoclimate studies involving AGCMs is the accurate description of the paleogeography. The position of the shoreline and the paleotopography are critical factors for the climate model results. There needs to be more attention given to developing better methods for locating paleoshorelines and for quantitative reconstruction of paleotopography.

Acknowledgements. The development of the GENESIS model was supported by Grant EAR-9007202 from the Earth Sciences Section of the U. S. National Science Foundation. This paper was prepared while W. W. HAY was supported by a Senior Research Scientist Award from the Alexander von Humboldt Foundation.

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