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Circulation and stratification of the early Turonian Western Interior Seaway: Sensitivity to a variety of forcings

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ABSTRACT

Five forcing fields potentially controlled the circulation of the early Turonian Western Interior Seaway: the wind field, latitudinal temperature gradient, precipitation minus evaporation, runoff, and mixing of Boreal and Tethyan waters. A suite of numerical experiments designed to evaluate the influence of each forcing type was conducted using CIRC, a three-dimensional, turbulent flow, coastal-ocean model, subject to various atmospheric forcings hindcast for the Turonian by GENESIS, an atmospheric general circulation model coupled to surface models of soil, snow, sea-ice, and a slab ocean. Results show that the extreme aspect ratio of the seaway creates a simple circulation pattern regardless of forcing type. A large vertically mixed, cyclonic gyre occupies the middle two-thirds of the seaway, the strength of which is largest when forced by runoff. Despite initial conditions of salinity and/or temperature that are vertically stratified and stable, turbulent mixing within the seaway destroys that stratification within a few model days. Thus, the contrasting water masses, mean annual temperatures, winds, and hydrology hindcast from GENESIS are insufficient to maintain a stable water column, and by inference, bottom-water anoxia.

INTRODUCTION

As the result of intensive field investigation over several decades, the geological record of environmental change in the Cretaceous Western Interior Seaway (KWIS) is remarkably rich (Eicher, 1965; Hart, 1980; McNeil and Caldwell, 1981; Kauffman, 1984, 1986; Pratt, 1985; Arthur et al., 1985; Hay et al., 1993; Caldwell et al., 1993; Kyser et al., 1993; Fisher et al., 1994). Numerous well-documented intervals of basinwide anoxia, isotopic and trace-metal excursions, and species extinction have been identified in the seaway's deposits and correlated worldwide (Arthur et al., 1985, 1987). Detailed work on the stratigraphic and facies distribution of fossil taxa indicate rapid oscillations in the redox state of bottom waters (Kauffman, 1988, and references therein; Eicher and Diner, 1989; Sageman, 1991), and fossil distributions suggest the presence of long-lived fronts between water masses of contrasting temperature and/or salinity (Watkins, 1986; Kauffman, 1984, 1986; Hay et al., 1993; Fisher et al., 1994). The oceanographic origin of these rapid oscillations and fronts remains largely conjectural, however.

A complete understanding of the causes of these phenomena requires understanding the Seaway's oceanography. This is made all the more difficult because the KWIS has no modern analog. Stretching nearly 3,000 km, it linked tropical Tethyan waters in the south to Boreal waters in the north (Fig. 1). Mixing of Tethyan and Boreal waters undoubtedly occurred within the seaway (Eicher and Worstell, 1970; Frush and Eicher, 1975; Kauffman, 1985; Pratt, 1985; Eicher and Diner, 1985; Fisher, 1991; Hay et al., 1993), yet the extent to which this mixing controlled the circulation is unclear. Exchange of oceanic and seaway waters may have been inhibited by the presence of sills at the northern and southern entrances (Jeletsky, 1970; Scott, 1977; Kauffman, 1984, 1988; Young, 1986). Then too, wind-generated flows, especially during storms, may have mixed the entire water column, precluding a Mediterranean-type thermohaline circulation (although see Jewell, 1993, for a contrary argument).

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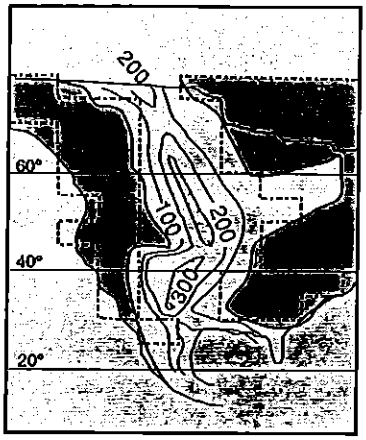

Figure 1. Base map showing land areas of Turonian North America (dark grey), ocean areas (light grey), and KWIS bathymetric contours (m; after Sageman and Arthur, 1994). Bold line defines land as seen by GENESIS. Continents and latitude lines in Turonian configuration of Barron (1987).

In lieu of a modern analog, KWIS researchers have proposed a diversity of conceptual models for the circulation of the seaway (Eicher and Worstell, 1970; Frush and Eicher, 1975; Kauffman, 1975; Parrish et al., 1984; Kauffman, 1985; Pratt, 1981, 1984, 1985; Eicher and Diner, 1985; Barron et al., 1985; Hattin, 1985; Arthur et al., 1986; Watkins, 1986; Kauffman, 1988; Fisher, 1991; Hay et al., 1993; Glancy et al., 1993; Kyser, et al., 1993; Pratt et al., 1993; Jewell, 1993; Sethi and Leithold, 1994). What has been missing until very recently has been a quantitative study of the response of the seaway's circulation to the variety of physical forcings acting upon it. Did the mixing of Boreal and Tethyan waters create a stably stratified seaway with anoxic, cold, dense deep waters and warmer surface waters? If so, how did this feature persist in the face of forces, such as wind mixing, that tend to destratify water bodies of such tremendous size but relatively shallow depth?

For several years, these questions have motivated a numerical modeling effort by our group at The Pennsylvania State University. Initial work used a three-dimensional, turbulent flow, coastal-ocean circulation model, modified from Leendertse and Liu (1977), which divided the seaway into vertical layers but did not include density stratification (Ericksen and Slingerland, 1990). The sensitivity of KWIS circulation to variations or unknowns in paleobathymetry, paleogeography, tidal amplitudes, wind stresses, and bed friction was investigated using 22 numerical experiments. The results of these experiments indicated that storms dominated over tidal forces in determining KWIS circulation; tidal currents were weak, with most of the seaway experiencing microtidal conditions. However, because the model did not simulate density stratification, fundamental questions about KWIS circulation remained unanswered.

Subsequent work (Kump et al., 1993; Slingerland et al., 1994, 1996) has focused on adding both vertical density stratification and imposed thermal and hydrological forcings to the model. A general result of these efforts is reported in Slingerland et al. (1996). In that study the mean annual wind and temperature fields, precipitation-minus-evaporation balances, and continental runoff fields from a global, atmospheric, general circulation model experiment for the mid-Cretaceous was used to provide for a coastal circulation model, called CIRC. Results show that runoff from eastern drainages exited the seaway as a north-flowing coastal jet; runoff from western drainages exited as a south-flowing coastal jet. Both jets simultaneously drew in surface Tethyan and Boreal waters, creating a strong counterclockwise gyre occupying the whole north-south extent of the seaway (Fig. 2). The gyre was created principally by freshwater runoff along both margins, although as will be shown below, other forcing factors contributed to the pattern as well. The coastal jets created wedges of lower-salinity water along the coasts but no "freshwater lid." Thus, despite an initial condition of density stratification, waters were essentially vertically homogeneous in salinity and temperature.

The origin of the KWIS circulation revealed by Slingerland et al. (1996) is investigated here by studying the response of the model to each of the major forcings in the absence of others. First, we briefly describe the numerical models used to perform the experiments. Then we progress step-by-step through a series of experiments where the KWIS responds in turn to initial density stratification, wind-stresses, hydrological imbalances, and temperature gradients.

MODEL DESCRIPTION

GENESIS atmospheric general circulation model

The global climate model used to provide the environmental forcing factors is GENESIS, which stands for Global Environmental and Ecological Simulation of Interactive Systems (Pollard and Thompson, 1992). GENESIS is an extensively modified version of the National Center for Atmospheric Research Community Climate Model version 1. The initial and boundary conditions for our simulation are given in Table 1. The model was allowed to spin up for 12 model years. Mean annual results were calculated for years 13–17, and used as forcing factors for the KWIS circulation experiments reported here.

How much credence one should give to the results of climate modeling of the geological past is an open question. Ongoing analysis of GENESIS by our group indicates that the model does a reasonable job of reproducing modern temperature and hydrological distributions when viewed at the large watershed to continental scale. For example, GENESIS predicts the present precipitation minus evaporation excess over North America as 6,400 km^3/yr. This is about 116% of the observed runoff value of 5,530 km^3/yr. In contrast, there is no unambiguous test of the model when applied to the Cretaceous. We proceed with the recognition that there is great uncertainty about the actual climatic conditions of the KWIS but with the belief that there is much to learn from what may be viewed as an heuristic modeling approach. It is reassuring that the distribution of various Turonian

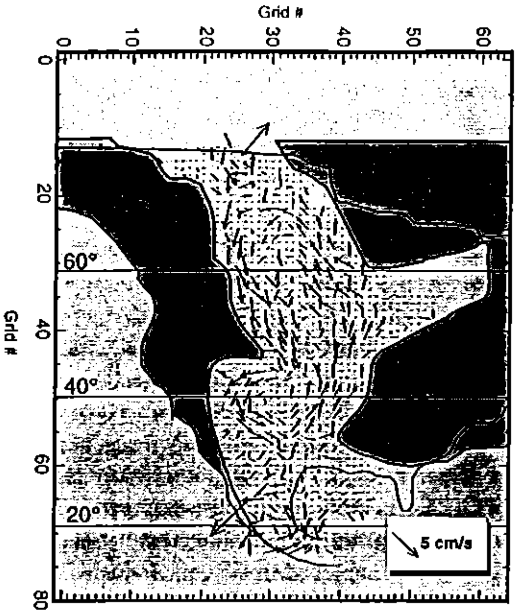

Figure 2. Circulation in upper 10 m of water column as computed by CIRC when forced by freshwater runoff, evaporation and precipitation, latitudinal temperature gradient, and mean annual wind field (after Slingerland et al., 1996). Grid numbers refer to computation grid.

paleoclimate indicators such as kaolinite and coal deposits and floral and faunal data are consistent with our results.

CIRC Seaway circulation model

To compute the circulation, stratification, and water properties of the seaway as it responded to the atmospheric winds, moisture fluxes, and heat balance hindcast by GENESIS, requires an ocean circulation model. The model we use is a three-dimensional formulation of turbulent flows in coastal seas (Leendertse and Liu, 1977; Ericksen and Slingerland, 1990; Keen and Slingerland, 1992), modified to allow for density stratification, surface temperature forcing, surface water balance, and runoff (Slingerland et al., 1996).

For each simulation we specify basin bathymetry and planform, as detailed in Slingerland et al. (1996). The water column is divided into 9 layers: 3 surface layers of 10-m thickness, another surface layer 20 m thick, 3 intermediate layers of 50-m thickness, and deep layers of 100 m and 700 m. The deepest part of the basin is 300 m; the 700-m layer is used for the Tethyan and Arctic ocean boundaries at the south and north of the seaway. Depending on the type of simulation, wind speed and direction at each surface node, initial water temperatures and salinities at each node, river discharges at boundary nodes, and evaporation or precipitation fluxes off the seaway surface are also specified, based on the mean-annual results of the GENESIS simulations. Table 2 lists the various simulations and their initial and boundary conditions. Output of the model consists of U, V, and W velocities, temperature and salinity, and water surface elevations.

RESULTS

Circulation due to differing Boreal and Tethyan water masses

The purpose of this experiment (Run 5) was to test the proposition that the seaway acted as a giant strait between the Boreal and Tethys Oceans, allowing denser Boreal waters to flow south in an underflow as Tethyan waters flowed north near the surface. The run begins with a wedge of Boreal waters ($S = 34.5$, $T = 5$ °C, $\sigma_t = 27.2$) underlying Tethyan waters ($S = 37.5$, $T = 25$ °C, $\sigma_t = 25.5$) as depicted in Figure 3A. As Figure 3B and C show, through time the density contours steepen to near vertical and the water column becomes progressively more vertically homogeneous. Defant (1961) shows that in modern (but much smaller) straits, one might expect that this density distribution would favor flow of Boreal water into the Tethyan basin, while superelevation of the water surface in the south would favor a return flow of Tethyan surface water to the north. At equilibrium the pycnocline surface would tilt toward the east as well as south in response to the Coriolis force, and the water surface would dip west and north. The expected longitudinal slope of the boundary between water masses is primarily a function of density contrast and water depth. In our experiments the "fronts" are vertical within the resolution of the model. The Strait of Bab el Mandeb in the Red Sea has a comparable water depth to the KWIS, and a density interface that separates waters of comparable densities. The slope of this interface is 3m/km. The Straits of Gibraltar are somewhat deeper, but display a similar interface slope of 4.2 m/km. Given that a grid cell in this CIRC simulation is 112 km on a side, these fronts, displayed with the same vertical exaggeration, would appear vertical (cf. Fig. 3C).

So, instead of a coherent Boreal underflow and Tethyan

TABLE 1. BOUNDARY CONDITIONS FOR TURONIAN GENESIS CLIMATE MODEL RUN

Boundary Condition	Value
Solar constant	Held constant at present day average: 1370 W m^{-2}
Orbital parameters: Eccentricity, precession, obliquity	Held constant at present day values.
Ozone mixing ratios	Held constant at present day values.
Soil texture	Intermediate value (6).
Soil color	Intermediate value (5)
Vegetation type	Mixed canopy and groundcover everywhere (Savannah, 6)
Land-sea distribution	From Barron, 1987; Scotese and Golonka, 1992; Ziegler et al., 1983.
Topography	From Scotese and Golonka, 1992; Ziegler et al., 1983.
Atmospheric CO$_2$	Four times present value of 340 ppm (after Berner, et al., 1983; Arthur et al., 1991).
Oceanic poleward heat flux	0.15x Carrismo et al., 1985, observations.

TABLE 2. EXPERIMENT NUMBER AND INITIAL AND BOUNDARY CONDITIONS FOR SIMULATIONS USING PALEOCEANOGRAPHIC MODEL

Run	Conditions
5	Strait with Boreal waters (34.5 psu and 5°C) underlying Tethys water (37.5 psu and 25°C) north of row* 62. The pyncnocline is at k = 3 at row 19 and decreases lineraly to k = 5 at row 62.
12	Circulation of homogeneous water column under mean annual wind field.
13	Circulation of homogeneous water column under precipitation and evaporation over seaway.
10	Circulation due to fresh water river input at 25°C, and evaporation and precipitation over seaway as predicted by GENESIS. Initial seaway homogeneous at 37.5 psu and 25°C.
14	Circulation due to latidudinal atmospheric temperature gradient.

*Rows refer to grid-cell rows in the model, numbered from north to south (see Fig. 1).

overflow, the broad, shallow seaway turbulently mixes the two water masses, creating a seaway water mass that is of intermediate density. A near-vertical density front is established at the northern sill; some higher density water remains at depth in the southern seaway, and is overlain by a mass of lower-density Tethyan water that penetrates 1,000 km into the seaway. We conclude that the seaway is simply too long and shallow to act like a large strait.

Circulation due to mean annual winds

The mean annual, surface wind field hindcast by GENESIS for North America in the early Turonian consists of easterly winds in the north and southwesterly winds along the southern margin, with a zone of convergence over the central seaway (Fig. 4). Maximum values are weak and on the order of 1 to 2 m/s. Midlatitude winter storms track quite far south, crossing over the seaway at about 35 ° N.

Initial conditions in this experiment (RUN 12) included a laterally uniform but vertically stratified temperature and salinity distribution, with deep water (S = 34.5 and T = 5 °C) and surface water (S = 37.5 and T = 25 °C). These salinities and temperatures yield calculated densities for the two water masses of 1.027 kg m^{-3} for the deep waters and 1.025 kg m^{-3} for the surface waters. No other forcing was applied and the seaway was initially at rest.

The initial vertical stratification of the water column was completely destroyed within a few model days as the result of turbulent mixing. Water-surface elevation gradients were established (Fig. 5) that dip radially in toward the axis of the seaway. These gradients reflect geostrophic flows (Fig. 6) in which the transverse pressure-gradient force is sufficient to balance the combination of wind stress and Coriolis force. The cyclonic gyre (Fig. 6) contains stronger flows (~2 cm/sec) around the perimeter of the seaway and weaker flows near the center. Flows are accentuated along the margins of the seaway because of the accelerating effects of the shoaling water depths.

Circulation due to precipitation and evaporation over the seaway

As much as 1.1 mm per day (41 cm/yr) of net evaporation is hindcast by GENESIS over the southeastern portion of the seaway, while the northwestern arm saw a maximum of 2 mm per day (73 cm/yr) net precipitation (Fig. 7). These contrasts in water balance would have tended to create depressions and domes in the water surface, which should have promoted surface flows. To explore the circulation resulting from these depressions and domes, a water-balance boundary condition (RUN 13) was applied to CIRC by converting the net evaporation and precipitation fluxes to vertical velocities (Slingerland et al., 1996). These velocities were then included in the calculation of the water-surface elevations. The initial conditions were T = 25 °C and S = 37.5 everywhere. Note that this simulation does not include runoff from the adjacent land.

Fresh water inputs and removals over the seaway cause minor changes (less than 0.1 psu) in salinity. However, water-surface elevations respond to the water balance (Fig. 8), with a 2-cm depression centered over the region of most rapid evaporation in the southeast, and a 1.5-cm dome over the region of greatest net precipitation in the northwest (relative to elevations

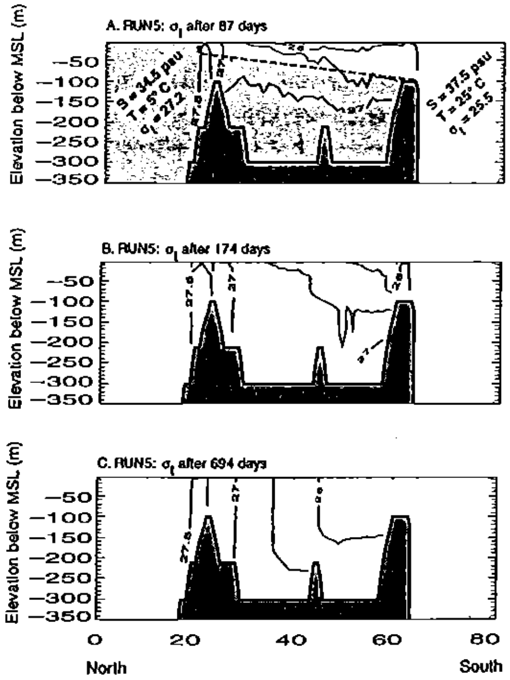

Figure 3. Longitudinal cross section along thalweg of KWIS (seafloor dark grey) showing: A, initial thermohaline conditions (Boreal waters light grey) and CIRC computed density contours (σ_t units) after 87 days; B, CIRC computed density contours (σ_t units) after 174 days; CIRC computed density contours (σ_t units) after 694 days.

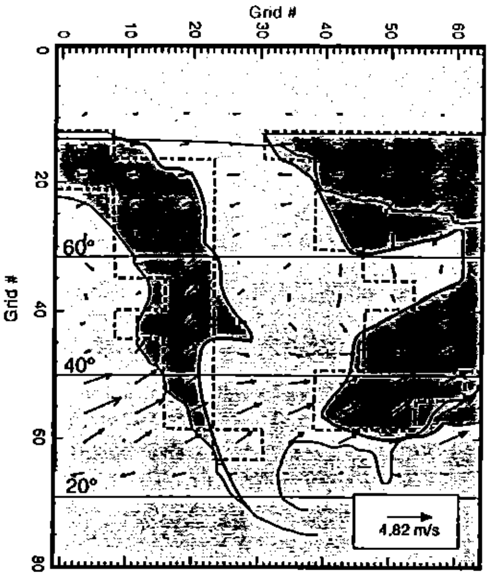

Figure 4. Mean annual wind field as computed by GENESIS for the Turonian (after Slingerland et al., 1996).

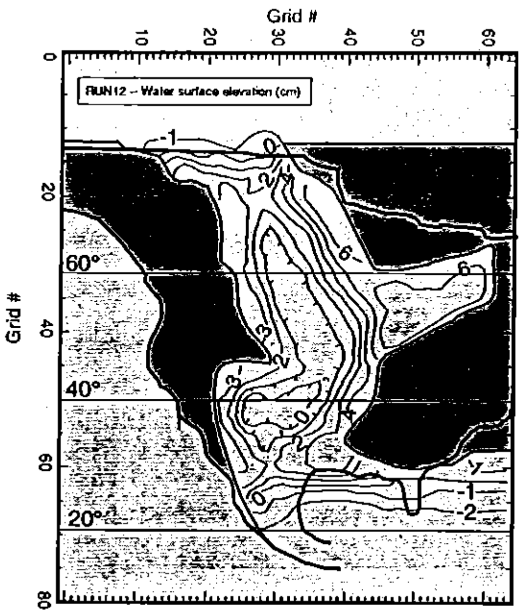

Figure 5. Quasi-steady state water surface elevation computed by CIRC under the mean annual wind field of Figure 4 (contours in cm).

without hydrological forcing). The resulting flows are as expected from the balance between the pressure gradient force, which would cause a northwesterly flow across the seaway, and the Coriolis effect, which deflects this flow to the right (Fig. 9). Therefore flow is to the south along the flanks of the northeastern high on the western side of the seaway, and to the north along the eastern margin of the water-surface depression. The overall pattern is, as in the wind-forced experiment, a cyclonic gyre, although the gyre is somewhat displaced to the southeast of the seaway (compared to the gyre generated by wind stress), and of lower velocity (typically <1cm/s).

Circulation due to precipitation, evaporation, and runoff from land

Over the North American land mass, GENESIS hindcasts an annual average net precipitation (precipitation minus evaporation) from 0.7 to 3.1 mm per day (27 to 113 cm/yr) with the wettest areas on the margin of Tethys. Much of this water must have run off into the seaway, eventually to mix and exit to the Boreal and Tethys Oceans. What type of circulation would it have created?

The boundary conditions for this experiment (RUN 10) were evaporation and precipitation off the top of the seaway as given in Figure 7, plus runoff into the seaway from streams equally spaced every 450 km along both the east and west coasts. At this spacing lateral mixing erases any spatial signature of the arbitrarily applied riverine boundary condition. The runoff rate is equal to the precipitation rate accumulated over rectangular east-west watersheds, extending east to the Appalachians and west to the divide of the Sevier Mountains. The total net evaporative loss over the seaway is 2.4×10^{11} m^3 of water during the year. This water loss is more than balanced by riverine input; overall the net input of runoff to the seaway is 20 times the net evaporative loss. Therefore, the KWIS, like the Black Sea today, may have been a substantial exporter of fresh water (Slingerland et al., 1996).

After spin-up, the seaway reaches dynamic equilibrium wherein the mass of water entering the seaway through precipitation, runoff, and counterflow at the entrances is balanced by the mass leaving by evaporation and surface flows to the world ocean. The water-surface elevations along the shelves are super-elevated by as much as 50 cm, creating a seaward-dipping slope on both east and west coasts (Fig. 10). The origin of these slopes is obvious after noting that waters on the eastern shelf flow to the north while waters on the western shelf flow to the south (Fig. 11). These are geostrophic flows of buoyant fresh water flowing down an alongshore pressure slope and deflected to the right by the Coriolis force. Water piles up along the coast until the offshore pressure force arising from the water surface slope just balances the Coriolis force. Then the water flows isobathyally along shore. These flows are on the order of 7–10 cm per second, or as much as five times those created by the wind stress (Fig. 6), seaway water balance (Fig. 9), or latitudinal temperature gradient (see below). Water on the shelves is fresher, but the surface waters in the center of the seaway are little different from normal marine waters. No freshwater "lid" is developed in response to these substantial riverine inputs. Perhaps most importantly, the overall flow is once again a cyclonic gyre.

Circulation due to a latitudinal atmospheric temperature gradient

Given the wide latitudinal extent of the seaway, it is reasonable to expect that its surface waters would be in contact with a pro-

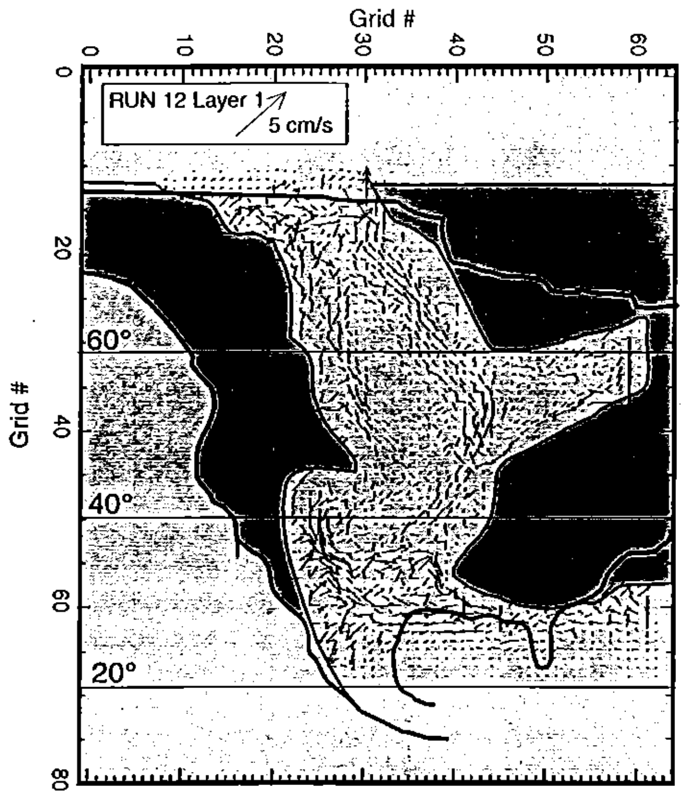

Figure 6. Velocities in upper 10 m as computed by CIRC when forced by mean annual wind field.

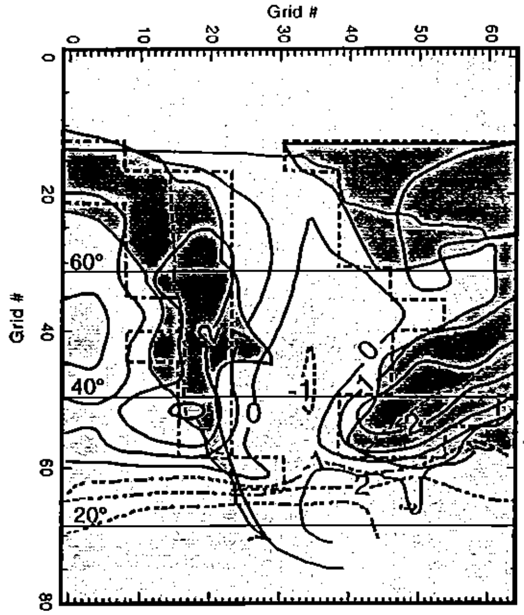

Figure 7. Precipitation minus evaporation predicted by GENESIS for the early Turonian (after Slingerland et al., 1996).

gressively cooler atmosphere from south to north. This northward cooling might be expected to cause densification of surface waters, lateral pressure gradients, and a resulting circulation. When an initially isothermal water body with no water-surface elevation gradient undergoes cooling of one region relative to adjacent regions, a water-surface elevation gradient will become established dipping from the warm to the cool region. Surface waters will begin to flow from the warm to the cold regions in response to this gradient, while return flows will occur at depth. These flows will be deflected in opposite directions by the Coriolis force. Therefore one would predict from these simple oceanographic principles that surface waters in the KWIS should flow northward and deflect towards the eastern coastline where it would pile up, creating a geostrophic coastal jet moving to the north and a return flow to the south along the western margin of the seaway.

To test this conceptual model a CIRC experiment (RUN 14) was conducted using GENESIS output to constrain the initial and boundary conditions. GENESIS hindcasts average northern summer temperatures in its lowest layer that decrease monotonically northward from 26 °C at the Tethys entrance of the seaway to 8 °C in the Boreal Ocean. December, January, and February average atmospheric temperatures over the seaway range between 20 and 4 °C. The atmospheric 0-°C isotherm over water lies entirely within the Boreal Ocean in both seasons. Atmospheric wintertime temperatures over the adjacent land are below zero above 60° N.

For this experiment initial conditions in the seaway consisted of a uniform salinity of 35 psu everywhere and vertically homogeneous temperatures of 6 °C in the Boreal Ocean increasing in 5 blocks to 25 °C at the Tethyan opening (Fig. 12). Subsequently the mean annual temperature field (Fig. 13) was used to force CIRC. Temperature balance in a given surface grid cell was the net of inputs by diffusion or advection from surrounding cells, and a loss or gain of heat with the atmosphere. The latter heat flux was proportional to the temperature difference between the atmosphere and the upper ocean layer, with a relaxation time constant of 30 days.

Results show that indeed, a dynamic water-surface elevation gradient is established sloping to the north from +27 cm to about -19 cm (Fig. 14). Once again, the resultant flow is cyclonic (Fig. 15). Colder waters penetrate farther south along the western coast as the result of advection with the cyclonic flow, both at the surface (Fig. 16) and at depth (Fig. 17). The flows are not as strong as those generated by runoff, but achieve velocities of 5 cm/s, values much greater than those generated by wind stress.

SUMMARY

A recurring feature of all these experiments is the development of a cyclonic gyre that controls surface flows over much of the seaway. While it may be argued that GENESIS errs in hindcasting the wind-stress field and surface-water balance of the KWIS, the two strongest forcing factors, freshwater runoff and latitudinal temperature gradients, are unlikely to have differed in their important characteristics from the values used here. Both forcings generate a cyclonic gyre arising from simple force balances between pressure gradients and the Coriolis force. Any

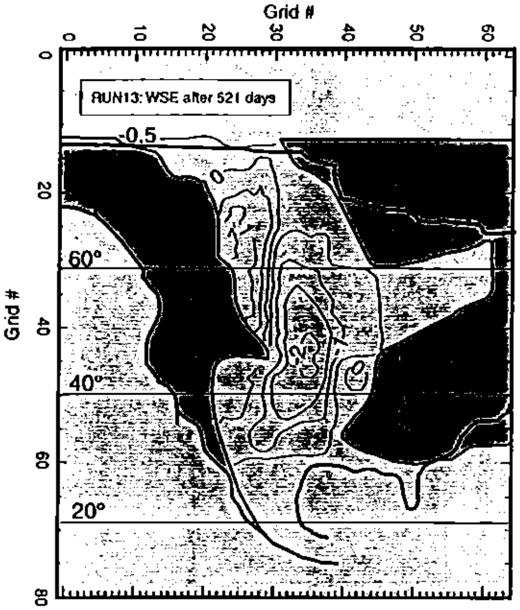

Figure 8. Steady-state water surface elevations (WSE) computed by CIRC when forced by evaporation and precipitation over the seaway.

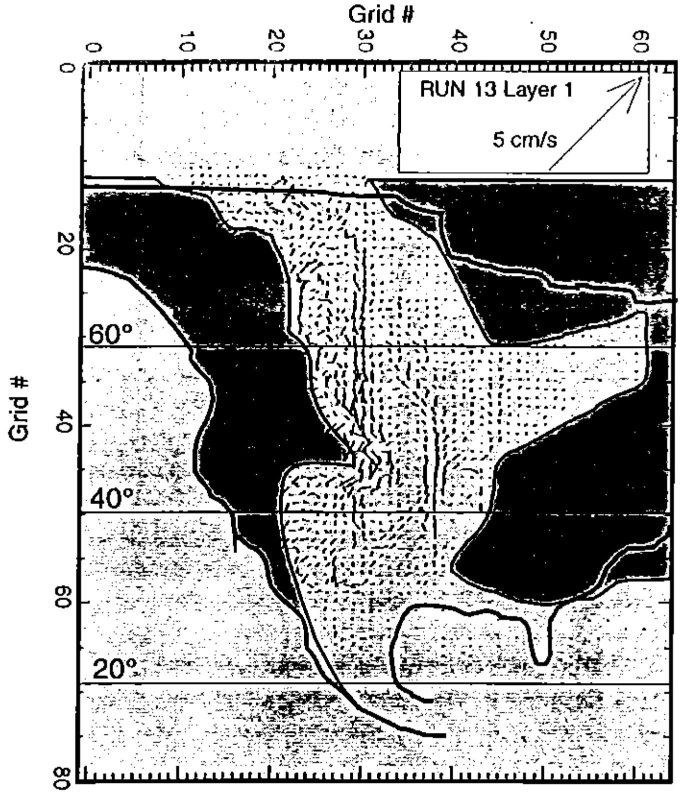

Figure 9. Steady-state circulation in the upper 10 m as computed by CIRC when forced by evaporation and precipitation over the seaway.

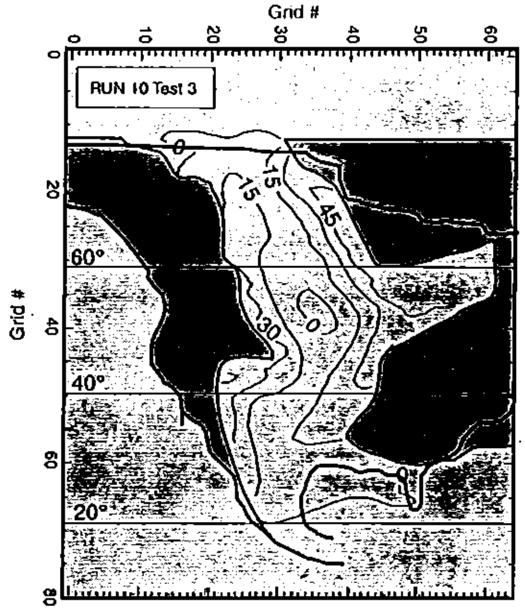

Figure 10. Water surface elevations computed by CIRC when forced by runoff from the adjacent land and evaporation and precipitation over the seaway.

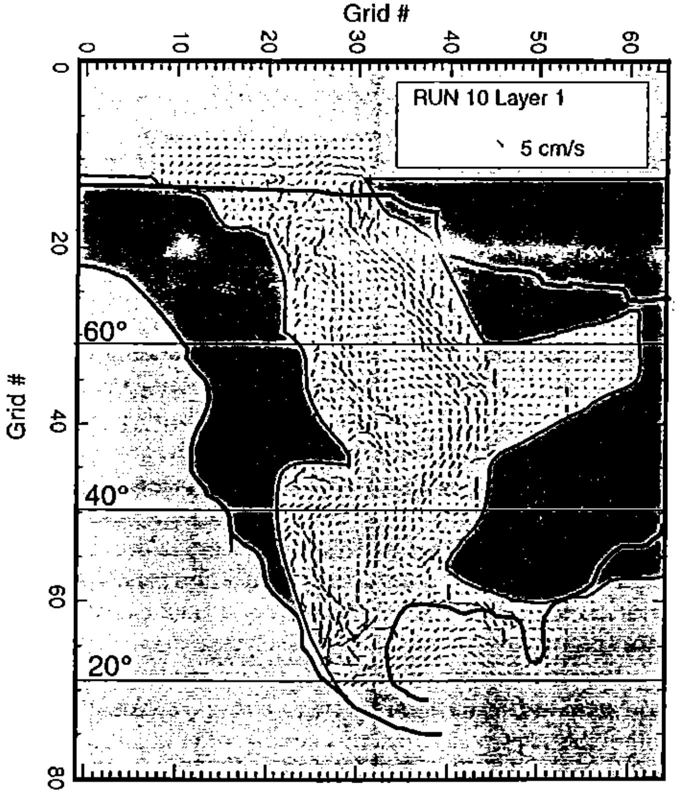

Figure 11. Circulation computed by CIRC when forced by runoff from the adjacent land and evaporation and precipitation over the seaway.

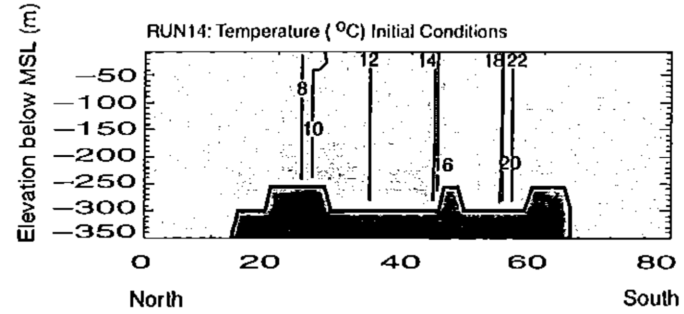

Figure 12. Longitudinal cross section showing initial temperature conditions in seaway for RUN14 (see Fig. 2).

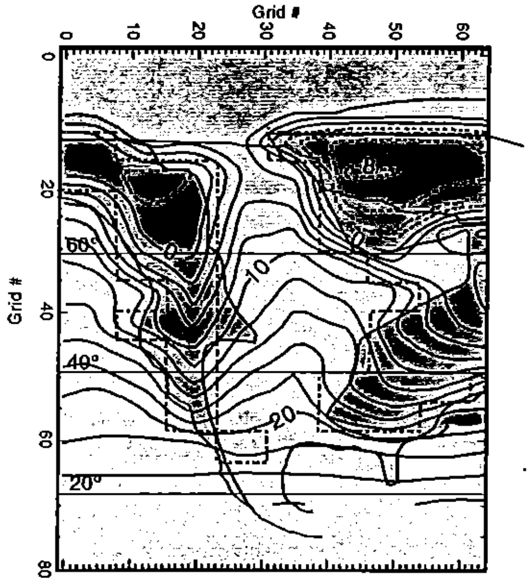

Figure 13. Mean Annual atmospheric temperatures hindcast by GENESIS and used as an upper boundary condition for CIRC RUN14.

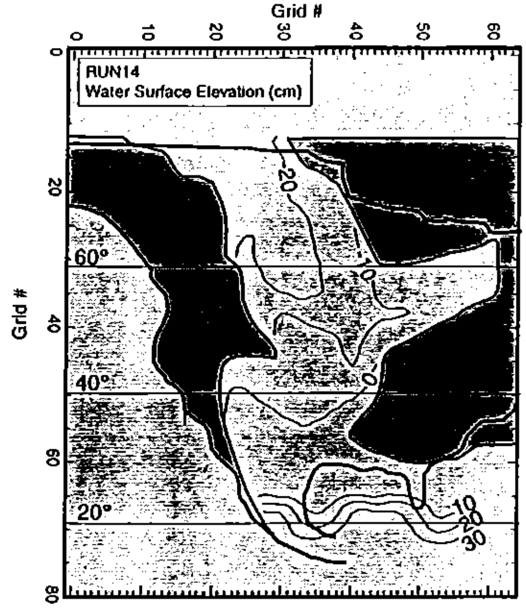

Figure 14. Steady state water surface elevations as computed by CIRC in response to atmospheric temperature gradient of Figure 13.

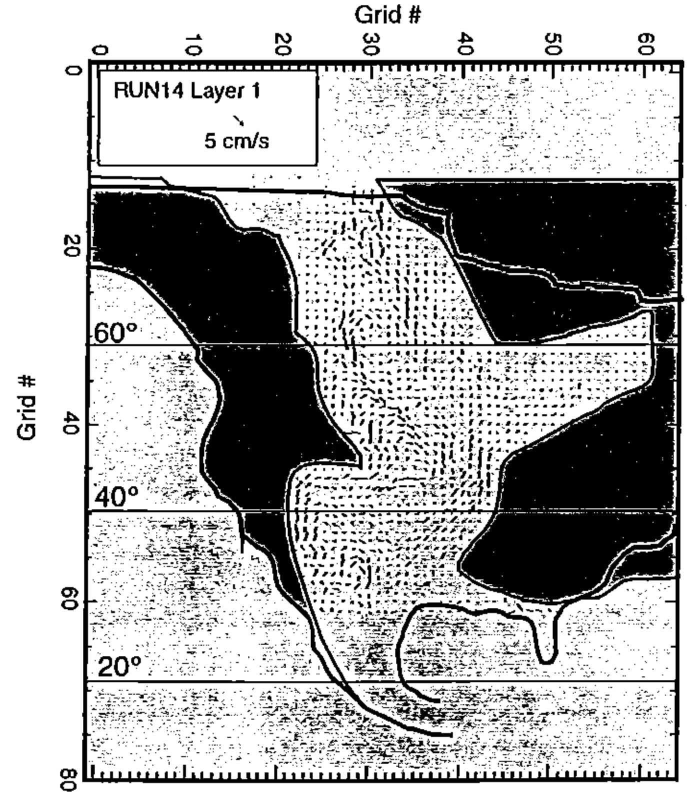

Figure 15. Steady state circulation in upper 10 m as computed by CIRC in response to atmospheric temperature gradient of Figure 13.

input of freshwater from the margins will tend to move in this manner, as will any flow generated by air temperatures that decrease with latitude. Thus the conclusion that the KWIS surface circulation was cyclonic is fairly robust.

Of course, large storms would have temporarily modified or destroyed this flow; the modeling work of Ericksen and Slingerland (1990) demonstrates this quite conclusively. Also, the experiments described here utilize mean annual forcings; substantial seasonal fluctuations about these mean annual patterns could have occurred.

Despite initial conditions of salinity and/or temperature that were vertically stratified and stable, turbulent mixing within the seaway destroyed its stratification in all cases, and within a few model days. Thus, the imposition of boundary conditions such as contrasting water masses, mean annual temperature, wind, and hydrological forcings is insufficient to generate the stable water column necessary to generate bottom-water anoxia. If indeed the seaway was vertically strat-

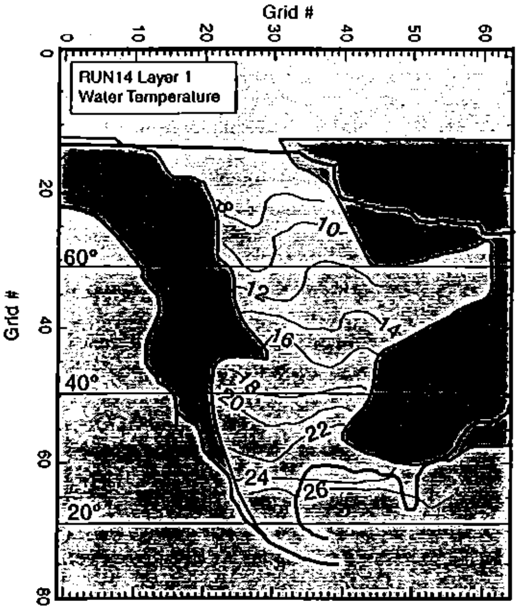

Figure 16. Steady state water temperature distribution in the upper 10 m as computed by CIRC in response to atmospheric temperature gradient of Figure 13.

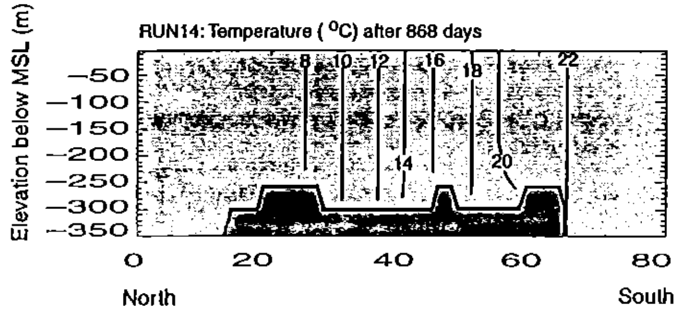

Figure 17. Longitudinal cross-section of Seaway showing steady state temperature distribution computed by CIRC in response to atmospheric temperature gradient of Figure 13.

ified, that condition was the result of forcings not included in the model. A likely candidate is strong seasonal contrasts not only in temperature forcing, and thus the establishment of a seasonal thermocline, but also in wind stress and water balance. Finally, the possibility that all forcings might differ substantially when the atmospheric model is run under different insolation conditions (resulting from adjustments in the eccentricity, obliquity, and precessional characteristics of the Earth's orbit about the Sun) needs careful examination (c.f. Glancy et al., 1993).

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