Evidence for increased latent heat transport during the Cretaceous (Albian) greenhouse warming

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ABSTRACT

Quantitative estimates of increased heat transfer by atmospheric H_2O vapor during the Albian greenhouse warming suggest that the intensified hydrologic cycle played a greater role in warming high latitudes than at present and thus represents a viable alternative to oceanic heat transport. Sphaerosiderite $\delta^{18}O$ values in paleosols of the North American Cretaceous Western Interior Basin are a proxy for meteoric $\delta^{18}O$ values, and mass-balance modeling results suggest that Albian precipitation rates exceeded modern rates at both mid and high latitudes. Comparison of modeled Albian and modern precipitation minus evaporation values suggests amplification of the Albian moisture deficit in the tropics and moisture surplus in the mid to high latitudes. The tropical moisture deficit represents an average heat loss of ~75 W/m^2 at 10°N paleolatitude (at present, 21 W/m^2). The increased precipitation at higher latitudes implies an average heat gain of ~83 W/m^2 at 45°N (at present, 23 W/m^2) and of 19 W/m^2 at 75°N (at present, 4 W/m^2). These estimates of increased poleward heat transfer by H_2O vapor during the Albian may help to explain the reduced equator-to-pole temperature gradients.

Keywords: latent heat, sphaerosiderites, oxygen isotopes, paleoclimatology, Cretaceous.

INTRODUCTION

Quantifying global transfers of sensible heat by the oceans and dry static and latent heat by the atmosphere is necessary to explain reduced equator-to-pole temperature gradients and warmer polar temperatures during greenhouse periods of Earth history (Upchurch et al., 1999). Increased global mean temperatures significantly increase the vapor-holding capacity of the troposphere and modify latent heat transfer from low to high latitudes via atmospheric convection cells (Hay and DeConto, 1999). Furthermore, as water vapor is a greenhouse gas, the increased vapor content of the lower atmosphere becomes an important feedback mechanism reinforcing the greenhouse effect (Rind and Chandler, 1991). Sensible heat transfer by the oceans has been the primary mechanism proposed for conveying heat away from the tropics to high latitudes during greenhouse climatic phases (Barron, 1981; Barron et al., 1995; Schneider et al., 1985). General circulation model (GCM) simulations of the warm Cretaceous, however, have shown that although increased ocean heat transport does help warm the high latitudes, the actual temperature changes are small (Poulsen et al., 1999). The coupled and uncoupled ocean-atmosphere models underestimate the polar warmth that is indicated by middle Cretaceous proxy records (DeConto et al., 2000). Latent heat transfer by atmospheric water vapor may have played a greater role in the global heat budget during the Cretaceous (Hay and DeConto, 1999; DeConto et al., 1999) and, combined with the paleogeography, *p*CO_2 levels, and ocean heat transport, may be the key mechanism to help explain the reduced equator-to-pole temperature gradients.

The $\delta^{18}O$ values of meteoric water as shown by sphaerosiderites from lowland paleosols of late Albian age from the Cretaceous Western Interior Basin and North Slope, Alaska, range from −4‰ (relative to the Peedee belemnite isotope standard [PDB]) at 34°N paleolatitude to −16‰ (PDB) at 75°N (Ludvigson et al., 1998; White et al., 2001; Ufnar et al., 2002) (Fig. 1). The observed latitudinal gradient in Albian meteoric $\delta^{18}O$ values is steeper and more depleted in ^{18}O than modern meteoric water of coastal lowlands vs. latitude (Rozanski et al., 1993). The Albian $\delta^{18}O$ latitudinal values are 5.5‰–13.6‰ less than those predicted by using modern empirical temperature vs. $\delta^{18}O$ relationships (e.g., Dansgaard, 1964; Yurtsever and Gat, 1981; Rozanski et al., 1993) (Fig. 1). It has been suggested that greater global rainout effects could account for the steeper meteoric $\delta^{18}O$ gradient (Ludvigson et al., 1998).

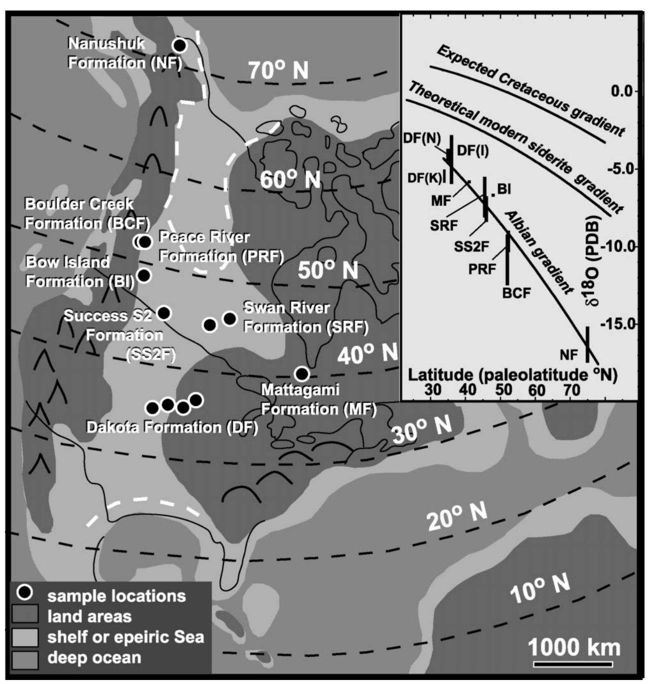

Figure 1. Aptian–Albian paleogeographic reconstruction of North America. Light gray areas represent approximate maximum extent of epeiric seas, and white dashed lines represent maximum extent of continental deposition. Inset illustrates Albian gradient in meteoric-water $\delta^{18}O$ values based on siderite (PDB—Peedee belemnite), theoretical $\delta^{18}O$ gradient that would be expected in modern siderite (from empirical meteoric $\delta^{18}O$ values of Rozanski et al., 1993), and predicted warm-Cretaceous meteoric water $\delta^{18}O$ gradient (Dansgaard, 1964). DF (I—Iowa; K—Kansas; N—Nebraska); MF—Ontario; SRF—Manitoba; BI—Alberta; SSF2—Saskatchewan; PRF—Alberta and British Columbia; BCF—British Columbia; NF—North Slope, Alaska.

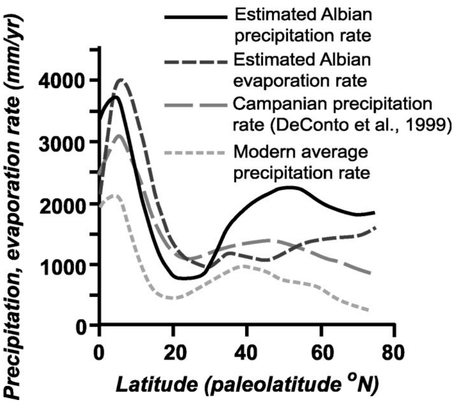

Figure 2. Modeled precipitation and evaporation rates for Cretaceous Albian Stage and modeled modern precipitation rates compared to atmospheric general circulation model–predicted precipitation rates for Cretaceous Campanian Stage (DeConto et al., 1999).

TABLE 1. PRECIPITATION AND EVAPOTRANSPIRATION FLUXES OBTAINED FROM STABLE ISOTOPE MASS-BALANCE MODELING OF THE NORTH AMERICAN ALBIAN HYDROLOGIC CYCLE

Latitude (°N)	Modern precip. flux	Modern evap. flux	Modern P − E*	Modern (modeled) precip. rates (mm/yr)	Albian precip. flux	Albian evap. flux	Albian P − E	Albian (modeled) precip. rates (mm/yr)
0	0.68	0.33	0.35	1825	1	0.59	0.41	3321
5	0.39	0.33	0.06	2008	0.55	0.61	−0.06	3748
10	0.2	0.33	−0.13	1643	0.25	0.63	−0.38	2532
15	0.11	0.34	−0.23	1168	0.1	0.66	−0.56	1364
20	0.1	0.34	−0.24	840	0.09	0.65	−0.56	802
25	0.12	0.27	−0.15	730	0.12	0.48	−0.36	786
30	0.17	0.13	0.04	767	0.18	0.17	0.01	905
35	0.24	0.08	0.16	876	0.38	0.1	0.28	1642
40	0.3	0.05	0.25	913	0.5	0.06	0.44	1960
45	0.34	0.03	0.31	931	0.54	0.04	0.5	2133
50	0.32	0.02	0.3	876	0.5	0.03	0.47	2278
55	0.29	0.02	0.27	767	0.43	0.03	0.4	2249
60	0.26	0.01	0.25	657	0.33	0.02	0.31	2022
65	0.22	0.01	0.21	548	0.26	0.02	0.24	1894
70	0.18	0.01	0.17	438	0.2	0.01	0.19	1798
75	0.14	0.01	0.13	365	0.14	0.01	0.13	1843

*P − E—precipitation minus evaporation.

Sphaerosiderite proxy data have been used to constrain a mass-balance model of precipitation isotopic values to quantify changes in the Albian hydrologic cycle of the Western Interior Basin between 35°N and 75°N paleolatitude (Ufnar et al., 2002). The estimated Albian precipitation rates are much higher than present, and are consistent with precipitation rates modeled for the Campanian (DeConto et al., 1999; Fig. 2).

The intensified hydrologic cycle provides a mechanism for exporting large amounts of tropical heat to higher latitudes. The purpose of this study is to show that heat transfer through the atmosphere was much greater during the Albian than it is currently and to provide quantitative estimates of enhanced rates of latent heat transfer during the Albian greenhouse warming.

Changes in the distribution of heat at Earth's surface are necessary to account for reduced equator-to-pole temperature gradients (Huber et al., 1995). Three mechanisms have been proposed to reduce latitudinal temperature gradients and increase transfer of heat toward the poles (Schmidt and Mysak, 1996): (1) sensible heat transfer via the atmosphere, (2) latent heat transfer via the atmosphere, and (3) sensible heat transfer via the oceans. Numerous modeling studies have concluded that ocean heat transport could be the primary mechanism responsible for the reduced temperature gradients (Barron et al., 1989, 1995; Barron, 1983; Covey and Barron, 1988; Crowley, 1991). However, investigators have had difficulty identifying a viable physical oceanographic mechanism to explain the reduced equator-to-pole temperature gradients in greenhouse-world climates (DeConto et al., 1999; Sloan et al., 1995).

The Cretaceous was a time of unusually high basalt production both at spreading centers and through the eruption of large igneous provinces (Larson, 1991; Tarduno et al., 1991). The release of gases (e.g., CO_2, SO_2, Cl, F, H_2O) from Earth's interior accompanying the basaltic eruptions likely had a significant effect on the amounts of these gases in the atmosphere (Larson, 1991; Tarduno et al., 1998). The mass of CO_2 in the mid-Cretaceous atmosphere may have been four times present values based on a geochemical carbon model (Berner, 1990). In order to match the warmest tropical paleotemperature estimates, some GCM simulations of the Cretaceous indicate that atmospheric pCO_2 may have been as much as 12 times present-day levels; however, the error bars in these simulations are large (Bice and Norris, 2002). Alternatively, some investigators have speculated that latent heat flux (LHF) through the atmosphere contributed significantly to greenhouse-world heat transfer (Hay and DeConto, 1999; DeConto et al., 1999; Schmidt and Mysak, 1996). With moderate pCO_2 levels (about three times present-day levels), the Hadley coupled ocean-atmosphere model results show a warmer Cretaceous where latent heat is a key heat transport mechanism (Valdes and Markwick, 2002). Our empirical data indicate that there was a significant increase in LHF in the Albian and provide an independent proxy record upon which to further test these models.

METHODS

In this study, the equator-to-pole evapotranspiration and precipitation fluxes coupled with the calculated precipitation rates derived from Ufnar et al. (2002) were used to calculate LHF values for the Western Interior Basin during the Albian (Table 1). Precipitation and evaporation fluxes were calculated as dimensionless fractional amounts of water added to or removed from an initial air mass with an arbitrary dimensionless starting value of one. Transfer functions using the flux values (Table 1), Cretaceous temperature profiles (Wolfe and Upchurch, 1987; Barron, 1983; Poulsen et al., 1999), and calculated saturation vapor pressure values were used to estimate Albian precipitation and evaporation rates (Fig. 2). In this study we used the precipitation (P) and evaporation (E) fluxes to calculate the net moisture flux (P-E balance) value for each incremental step in paleolatitude. The calculated P-E balance and precipitation rate were then used to calculate the net moisture fluxes in millimeters per year. The net moisture fluxes (in mm/yr) were then used to calculate the latent heat values.

In our calculations, each incremental step in latitude was arbitrarily set to represent a volume in cubic meters, where the vertical dimension is represented by the vertical accumulation of precipitation-evaporation (in meters) for the year over 1 m^2 of Earth's surface. The time frame of 1 yr results from model calibrations using present annual precipitation rates. The volume of water in each incremental step was then converted to mass (in kilograms); a water density of 1 g/cm^3 was assumed. Then, by using the calculated water volume for each incremental step, the temperature-dependent equation for the latent heat of vaporization, $Q = Lm$ (Q = heat in calories, m = mass of H_2O in kilograms, and L is a temperature-dependent variable), was used to calculate heat loss or gain along the latitudinal trajectory. L varies as a linear function between 0 and 100 °C [$-0.57(T) + 597$ cal/g; T = temperature in Celsius]. The paleotemperature values were obtained from Wolfe and Upchurch (1987). The LHF values were then converted to watts per square meter. In our model, we cannot account for temperature gradients within clouds, sea-surface tempera-

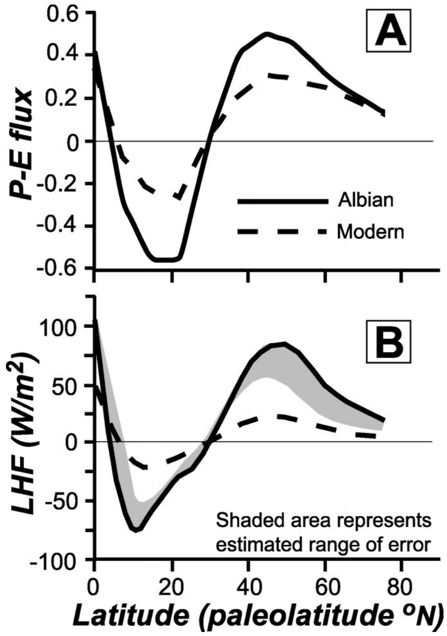

Figure 3. A: Zonal profiles of precipitation minus evaporation (P-E) values from modern and Albian mass-balance model simulations that reconstruct modern and Albian meteoric $\delta^{18}O$ gradients (Ufnar et al., 2002). B: Zonal profiles of latent heat flux (LHF) values, calculated from P-E profiles, coupled with empirical temperature profiles and precipitation estimates. Positive values represent areas that underwent a net gain in water mass and latent heat; negative values = net loss.

tures, or wind speeds during the Albian. Thus, our estimates represent long-term average annual latent heat flux rates (W/m^2) for the Northern Hemisphere along a longitudinal transect through the Cretaceous Western Interior Basin.

RESULTS

The LHF values at the equator were doubled in the Albian compared with the modern (105 W/m^2 at 0° vs. 50 W/m^2, respectively); however, the heat gained at the equator in the Albian rapidly declined to a net heat loss that reached a maximum at 10°N. The net annual heat loss was ~−75 W/m^2 at 10°N compared to −21 W/m^2 at 15°N currently, an increase of 243% (Fig. 3). Maximum heat gain in the Albian midlatitudes was at ~50°N, where the value was 83 W/m^2, compared to 23 W/m^2 at 45°N currently, an increase of 260%. At 75°N the heat gain in the Albian atmosphere was 19 W/m^2 as compared to 4 W/m^2 currently, a 375% increase. The Albian heat increase at 75°N may have been as low as 25% if more conservative paleotemperature estimates (Spicer and Parrish, 1990a, 1990b; Parrish and Spicer, 1988a, 1988b) are used in the modeling experiments. A limitation of this model is the dependence of the sphaerosiderite proxy records on independently determined paleotemperature estimates.

DISCUSSION

Comparison of the modeled modern and Albian P-E profiles (Fig. 3A) illustrates the vast differences in net mass transfer of atmospheric water, and consequently the transfer of latent heat, between the present and the greenhouse-world conditions of the Albian (Fig. 2). Our results suggest that during the Albian North American LHF values were two to three times greater than present rates. The LHF values calculated from the P-E rates (Fig. 3B) clearly indicate that heat was removed from the tropical dry belt regions (which have negative LHF values) and transferred toward higher latitudes (which have positive LHF values). An estimate of two to four times as much heat was removed from the area between 10° and 25°N paleolatitude compared to present LHF rates. The LHF values illustrated in Figure 3B indicate that some heat was transported back to the equator, as the Albian LHF values are doubled at the equator compared to the present values. The net latent heat transport in the Hadley Cell is toward the equator; however, total atmospheric transport at low latitudes is poleward. The dry static heat of the ascending and poleward branch of the Hadley Cell exceeds the equatorward latent heat transport (Peixoto and Oort, 1992). The excess tropical heat may have contributed to the intensified evaporation and aridity that is predicted between 10° and 25°N paleolatitudes. The Albian, Campanian, and modern precipitation curves all show peaks in precipitation rates just north of the equator at ~5°N. However, the positions of the modeled Albian and Campanian midlatitude precipitation maximums are shifted northward. This shift may have resulted from expansion of the equatorial belt as expected in a warmer greenhouse world (Henderson-Sellers, 1993).

Our estimates of high precipitation and large LHF values in the high latitudes may in part be related to the effects of high-latitude vegetation on the regional climate and hydrologic cycle. High-latitude forests played an important role in reducing Cretaceous meridional temperature gradients and maintaining warmer temperatures in the continental interiors (Upchurch et al., 1999; DeConto et al., 1999; Wolfe and Upchurch, 1987; Barron and Peterson, 1990). The Boreal-type forests had LHF rates as high as 50 W/m^2 (DeConto et al., 1999), consistent with the LHF values of 19 W/m^2 estimated for the Nanushuk Formation of the North Slope, Alaska (present values of 4 W/m^2 at 75°N lat; Ufnar et al., 2004).

Coupled ocean-atmosphere models show that increased latent heat transport by the atmosphere may account for the extra heat needed to maintain warm high latitudes during greenhouse periods (Schmidt and Mysak, 1996). Some simulations, however, suggest that in warmer climates the increased atmospheric H_2O vapor content is offset by reduced eddy activity and thus LHF changes very little relative to the present (Pierrehumbert, 2004). We have used empirical data to quantify LHF estimates for the Albian greenhouse warming, and our estimates clearly indicate that heat transport via the atmosphere was significantly greater than at present. The intensified precipitation rates north of 40° paleolatitude transferred large amounts of tropical heat to the higher latitudes (3.6 times more heat than at present between 40° and 50°). Furthermore, a more vigorous hydrologic cycle and the enhanced aridity predicted by our model for the low latitudes would help maintain salinity gradients and reinforce production of warm saline bottom waters in the tropics, driving thermohaline circulation (Brady et al., 1998; Schmidt and Mysak, 1996). The results of this study contribute to resolution of the long-standing paleoclimatic data-model misfit regarding Cretaceous tropical overheating and provide quantitative empirical evidence that latent heat transfer through the atmosphere is one of the primary mechanisms for reducing equator-to-pole temperature gradients during warm periods in Earth history.

CONCLUSIONS

1. Mass-balance modeling of the Albian hydrologic cycle in the Cretaceous Western Interior Basin and North Slope, Alaska, and calculated precipitation and evapotranspiration rates (Ufnar et al., 2002, 2004) allow calculation of the Albian LHF and show significant increases in latent heat transfer during the Albian greenhouse warming.

2. Albian P-E ratios suggest that there is a significant (twofold to threefold) increase in the exchange of water between the surface and the atmosphere. The Albian was characterized by a net heat gain of 105 W/m^2 at the equator via LHF compared to 50 W/m^2 currently (110% increase), a net heat loss of −75 W/m^2 at 10°N compared to −21 W/m^2 at 15°N currently (257% increase), a maximum heat gain of 83 W/m^2 at 50°N compared to 23 W/m^2 at 45°N currently (261% increase), and a heat gain of 5–19 W/m^2 at 75°N compared to 4 W/m^2 at 75°N currently (25%–375% increase).

3. Increased latent heat flux through the atmosphere during greenhouse episodes of Earth history—coupled with changes in paleogeography, increased pCO_2, and increased ocean heat transport—contributes to the reduced Albian equator-to-pole temperature gra-

dients and polar warming. Our mass-balance modeling of the Albian hydrologic cycle of the Western Interior Basin and the North Slope, Alaska, allows us to constrain the LHF values under a more vigorous hydrologic cycle. The empirically based LHF values presented here may be useful in constraining precipitation and LHF rates in future atmospheric general circulation model simulations of the middle Cretaceous.

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