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Deep Water Formation and Poleward Ocean Heat Transport in the Warm Climate Extreme of the Cretaceous (80 Ma)

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Abstract. An ocean simulation of the "greenhouse" climate of the Late Cretaceous, about 80 million years ago (Ma), demonstrates that warm salty water, consistent with proxy climate data, can be formed by cooling in the high latitude Southern Hemisphere. This is contrary to the long standing hypothesis of deep water formation due to evaporation over low latitude marginal seas. A reduced equator to pole temperature gradient is maintained with a poleward ocean heat transport that is not larger than today's.

Introduction

During the Campanian stage of the Late Cretaceous (80 Ma), evidence suggests mean annual temperatures were 7-14 K warmer than today [DeConto, 1996]. There is no evidence of significant ice at high latitudes [Frakes et al., 1992] and meridional thermal gradients were very low in the oceans [Barrera et al., 1987, Huber et al., 1995] and on land [Parrish and Spicer, 1988]. Late Cretaceous atmospheric CO_2 was much higher than today, with levels estimated from 2 to 9 times present day [Berner, 1990]. Earlier Atmospheric General Circulation Model (AGCM) simulations of Cretaceous climate showed higher CO_2 was needed to warm the poles sufficiently and larger poleward heat transport in the one layer 'slab' ocean model was required to maintain a reduced equator to pole surface temperature gradient consistent with marine and continental fossil and isotopic evidence [Barron et al., 1995]. Although larger slab ocean heat transport produces reduced surface temperature gradients in AGCMs, it is difficult to understand how larger ocean heat transport can occur in a Cretaceous ocean with reduced thermal gradients.

In addition to the warmer surface climate, oxygen isotope estimates from deep sea sediment cores suggest that the deep ocean was as much as 15 K warmer during the Cretaceous [Savin, 1977]. To become dense enough to sink to great depths, it is speculated this warm water must have been quite saline. This has suggested extensive tropical and midlatitude marginal seas in areas of high excess evaporation, were the formation sites of very dense warm saline bottom water (WSBW) [Chamberlin, 1906]. It is further speculated that this formation may have a role in maintaining the reduced Cretaceous equator to pole temperature gradient by enhancing the poleward transport of heat in the oceans.

In order to investigate the formation of WSBW and the role of ocean circulation in maintaining Late Cretaceous warmth and low meridional thermal gradients, Campanian ocean circulation has been simulated using an Ocean General Circulation Model (OGCM) forced from a new simulation of Campanian climate [DeConto et al., 1998] using the GENESIS AGCM Version 2.0 [Thompson and Pollard, 1997]. Our results challenge these notions. We find that WSBW can be formed by cooling warm salty water in the high latitude Southern Hemisphere in a manner similar to deep water production in the North Atlantic today consistent with both warmer polar surface temperatures and a poleward heat transport that is not enhanced over today's.

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Model Description

The OGCM is a rigid lid, hydrostatic, Boussinesq, primitive equation code [Semtner and Chervin, 1992] modified to accelerate the deep levels to equilibrium [Bryan, 1984] with a horizontal resolution of 2º latitude x 2º longitude and 20 vertical levels. The continental configuration and bottom bathymetry (fig. 1) is obtained from a new reconstruction for the Campanian (80Ma) [Hay et al., 1996]. For comparison, a control run with present day bottom topography is forced exactly the same way as the Campanian run except that surface forcing was obtained from a present day GENESIS v. 2.0 AGCM run coupled to a slab ocean model.

The OGCM is 'spun up' from rest to near equilibrium for 455 surface years, and with deep acceleration, 3840 deep water years. The OGCM is forced at the surface using standard bulk formulae. The surface fresh water flux is derived from monthly mean AGCM evaporation minus precipitation fields corrected globally to obtain no net global fresh water flux. The surface heat flux is computed from OGCM SST and monthly mean AGCM winds, air temperatures, specific humidity, and downward radiation. These AGCM quantities are averaged over the last 8 years of CASE 2, a 35 yr. simulation of Campanian climate and vegetation [DeConto, 1996, Thompson and Pollard, 1997] using the GENESIS V. 2.0 Global Climate Model [DeConto et al., 1998] coupled to a predictive Equilibrium Vegetation Ecology (EVE) model [Bergengren and Thompson, 1997] and a slab model with a diffusive parameterization for ocean heat transport. The GENESIS-EVE simulation is based on a comprehensive reconstruction of Campanian solid-earth boundary conditions [Hay et al., 1996] and atmospheric CO_2 was prescribed as 1500 ppm.

Results

The GENESIS-EVE simulation reproduces the overall warmth, low meridional thermal gradients, and warm continental interior temperatures characteristic of the Late Cretaceous

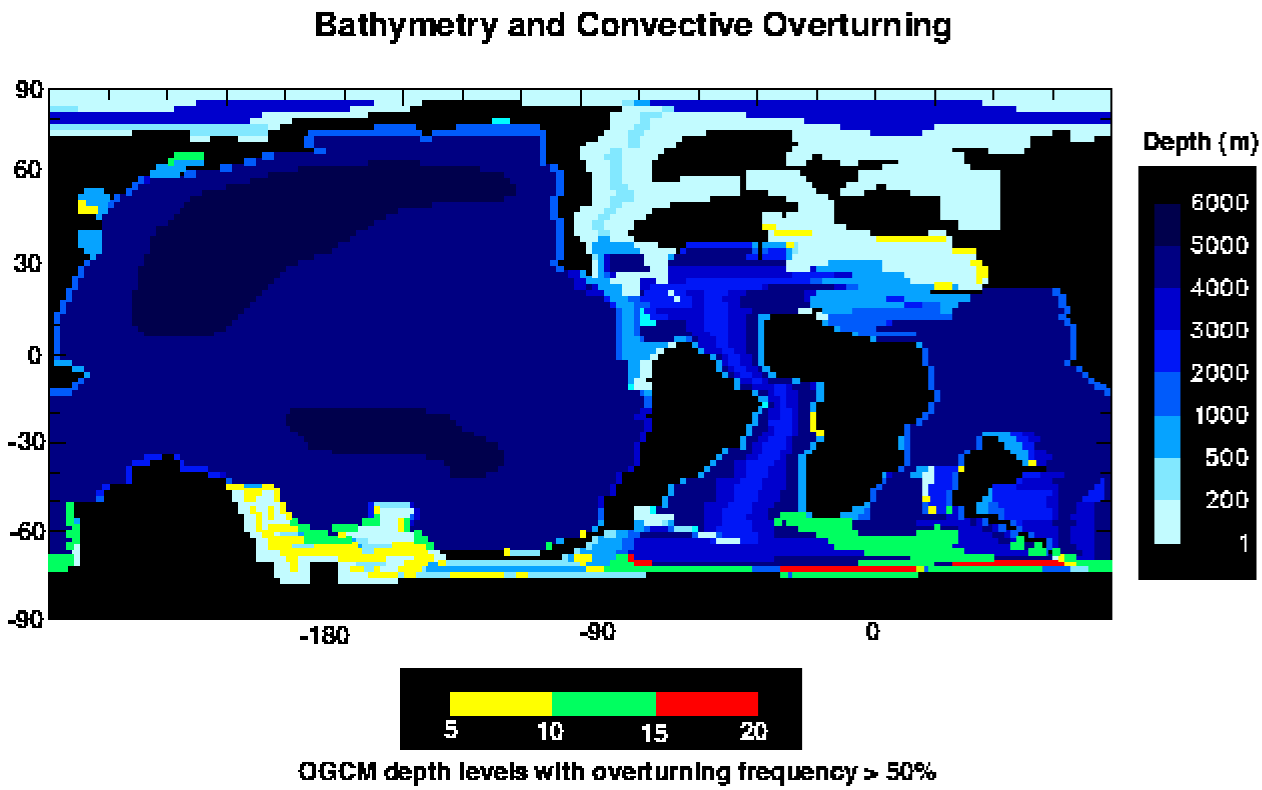

Figure 1. Model bathymetry with areas of convection ocurring more frequently than 50% overlaid. Campanian paleogeography, including the location of continents and shorelines, is based on a new global plate tectonic model for the Cretaceous. Paleobathymetry is based on a reconstruction of Campanian crustal ages using magnetic lineation data, an age-depth relationship for oceanic lithosphere, and a correction to account for sediment accumulation. The shallow marginal seas have been filled in and smaller land masses have been connected to reduce the computational expense. Convection reaching depths between 135 and 710m is shown in yellow, between 710 and 2750m is in green, and between 2750 and 5200m is in red.

geologic record [Thompson and Pollard, 1997]. Seasonal surface temperatures, precipitation distributions and predicted vegetation distributions are well correlated with the geologic record at all latitudes for which data exist. The simulated global average surface temperature is 24.1° C (about 9° C warmer than present day). Simulated mean annual surface temperatures are 8° C and 2° C at the North and South poles respectively, resulting in a meridional thermal gradient about 60% smaller than today.

The Campanian ocean simulation predicts a global mean annual sea surface temperature (SST) of 25.8° C which is about 8° C warmer than present day [Levitus, 1982]. Compared to the present day profile of zonally averaged SSTs (fig. 2), the Cretaceous SSTs in the equatorial region are 5 to 6° C warmer. In the high latitudes (60-90° latitude), the Cretaceous SSTs are 10-12° C warmer. This polar amplification produces an equator to pole SST gradient for the Cretaceous (fig. 2) that is lower than present day.

Deep Convection

The areas of deepest convection (Fig. 1), occur in the high latitude Southern Hemisphere. In this sub-Antarctic region convection reaches to the very deepest levels of the model (3300m to 5000m). A large meridional overturning circulation (fig. 3) and corresponding conveyor circulation is associated with this deep convection and results in the sinking of salty water to great depths. This water is much warmer than deep water formed today at high latitudes, however like today in the North Atlantic, the main cause

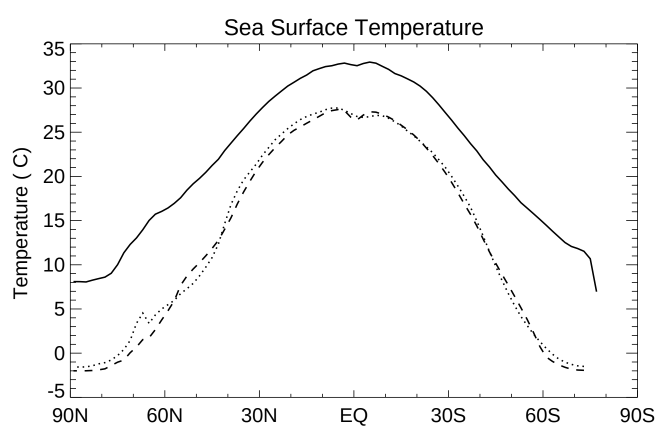

Figure 2. Zonally averaged sea surface temperature for Campanian simulation, shown by solid line, is compared to present day Levitus shown by dotted line, and the control run shown by dashed line.

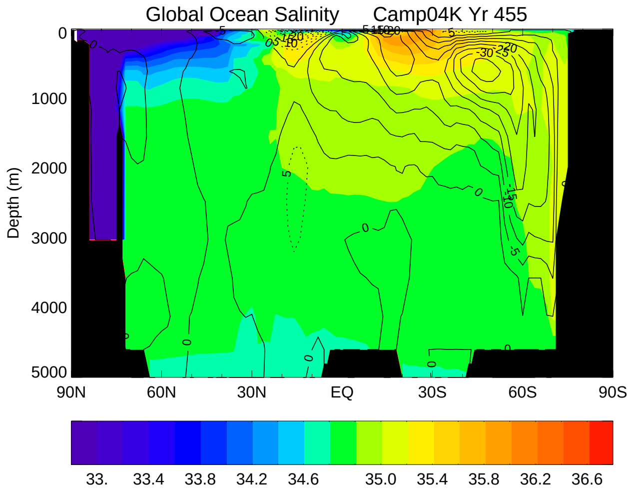

Figure 3. Latitude-depth plot of meridional overturning streamlines (solid lines) superimposed on salinity for the Campanian simulation. Color bar indicates the contours of salinity which are evenly spaced at .2 except between 34.8 and 35.0 where the spacing is .1. Mass transport values are in units of 10^6 m^3 s^{-1}.

for buoyancy loss is cooling. The water mass acquires its initial warmth and relative saltiness in the South Atlantic subtropical gyre where there is a very strong net evaporation (maximum 6 mm/d). This warm salty water is advected poleward in the western boundary current and begins to convect and sink upon reaching a region of strong net surface cooling. The maximum strength of the large overturning cell is 38.5 x 10^6 m^3 s^{-1}, which is twice as large as present day estimates of the meridional overturning circulation in the North Atlantic [Schmitz, 1996] but is only slightly larger than occurs in the North Atlantic in a present day control run.

Other areas of convection (fig. 1) occur in the Eastern Tethys Sea, in the Angola basin off the west coast of Africa and in the Western North Pacific. The first two are areas of strong net evaporation and the last is an area of net cooling. The convection in these areas is much shallower (down to only 730m at the deepest) and much less extensive than the sub-Antarctic area. The surface water formed in the Tethys and the Angola basin is very saline, up to 39.5 psu (practical salinity units) in the Angola basin. But the water is much warmer and hence less dense than the water formed in the Sub-Antarctic. The North Pacific convection is associated with weak meridional overturning (fig. 3).

Areas of deep convection found in a previous study [Barron and Peterson, 1992] compare well to the weaker areas of convection noted here. However, the earlier simulation lacked the deepest water formation shown here in the sub-Antarctic. In the earlier study, very coarse horizontal and vertical resolution (5º x 5º x 4 levels) and a narrower and shallower basin in the S. Atlantic (500m) may have precluded the formation of a South Atlantic gyre which can greatly contribute to the water mass characteristics of deep water formed at high latitudes. Other model differences such as different AGCM forcing and different paleogeography may contribute to the differences in model results.

Poleward Heat Transport

Both present day and Campanian simulations show a maximum poleward heat transport of about 1.6 x 10^{15} W in the hemisphere where deep water production by meridional overturning occurs (fig. 4). In both OGCM runs, the dominant mechanism by which heat is transported poleward is by the meridional overturning circulation which advects warm water poleward and relatively cold deep water equatorward. The heat transport by meridional overturning is dominant because the overturning circulation is so strong. The result that the maximum heat transports were similar for the two cases agrees with an earlier study with a coupled AGCM-OGCM climate model study [Manabe and Bryan, 1985] which found little difference in poleward ocean heat transport and strength of the meridional overturning circulation over a wide range of higher CO_2 concentrations (1 to 8 times present day) even though meridional SST gradients were reduced with higher CO_2.

Discussion and Conclusions

Recently, isotopic evidence has been put forth that challenges the notion of extreme Cretaceous warmth in the tropics [Sellwood et al., 1994, D'Hondt and Arthur, 1996]. The meridional profile of surface air temperature of the AGCM simulation used to force the OGCM fell at the warm end of the traditional range [DeConto et al., 1998]. This may be a result of the assumptions implicit in the slab model used in the AGCM simulation. Or, it is possible that the sensitivity of the tropical surface temperatures in the AGCM to increased CO_2 is greater than it should be due to a lack of a negative feedback mechanism such as the tropical thermostat [Ramanathan and Collins, 1977]. Because this leads to tropical SSTs on the warm end of the range, it is possible our results of deep water formation are sensitive to these drawbacks in the AGCM simulation.

Marginal seas may be required to produce warm water with sufficient salinity to deeply convect at low latitudes. However, the correct exchange processes between marginal

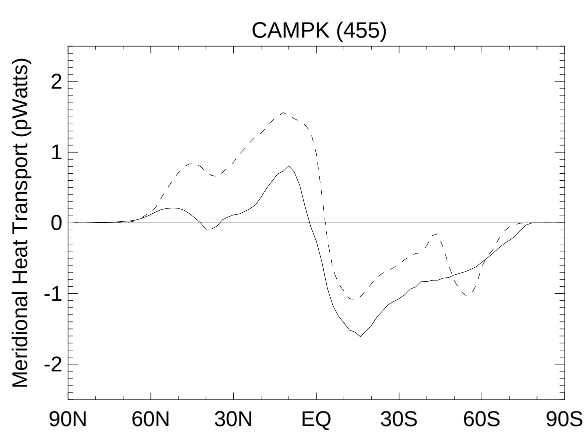

Figure 4. Zonally integrated meridional ocean heat transport plotted as a function of latitude. 1 pWatt is 1.0 x 10^{15} Watts. Dashed line represents the total for the present day control simulation; and the solid line represents the total for the Campanian simulation.

seas and the open ocean are not included in this OGCM. Thus, our results do not preclude the existence of other modes of deep water formation. Our results suggest that low latitude sites of deep convection are not required to maintain a general Cretaceous climate state of warm deep and polar water. Instead, warm saline deep water can be formed by deep convection at high latitudes in a process quite similar to deep water formation in the present day North Atlantic with no accompanying increase in poleward heat transport.

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