GEOPHYSICAL RESEARCH LETTERS, VOL. ???, XXXX, DOI:10.1029/,

Ocean circulation and climate in an idealised Pangean OAGCM

R.S. Smith

Southampton Oceanography Centre, European Way, Southampton, UK

Max-Planck Institute for Meteorology, Bundesstrasse 53, Hamburg, Germany

C. Dubois

Southampton Oceanography Centre, European Way, Southampton, UK

J. Marotzke

Max-Planck Institute for Meteorology, Bundesstrasse 53, Hamburg, Germany

---

R.S. Smith, Max-Planck Institute for Meteorology, Bundesstrasse 53, Hamburg, Germany (smith@dkrz.de)

An idealised Pangean configuration is integrated in a coupled ocean atmosphere general circulation model to investigate the form of the ocean circulation and its impacts on the large scale climate system. A vigorous, hemispherically symmetric overturning is found, driven by deep water formation at high latitudes. Whilst the peak mass transport is around 100 Sv, a low vertical temperature gradient in the ocean means that the maximum heat transport is only 1.2 PW. The geographical change in the coupled model is found to produce a global average warming of 2°C, despite an increase in global surface albedo. This occurs through changes in the atmospheric water vapour and cloud distributions. There is also reduction in the equator-pole temperature gradient, largely attributable to the same causes, avoiding the paradox of low meridional temperature gradients without increased polar heat transport.

1. Introduction

Knowledge of past climates can provide important lessons about the current and future behaviour of our environment. This is a particularly pressing issue in light of the current debate about climatic change in our immediate future. The proxy data record is, however, sparse and open to varying interpretations; the use of numerical models is essential to tying together the data points in a physically consistent manner and providing further insight into the feedbacks and processes at work.

The period around the Permian-Triassic boundary (200-250 Ma) is a particularly interesting case to study, with all the landmasses grouped together to form the supercontinent of Pangea and a very warm, greenhouse climate, subject to extreme monsoons [*Parrish*, 1993]. Whilst proxy data (e.g. *Enos* [1993]) are available to constrain land/atmosphere models of the time, apart from the possibility of deep ocean anoxia [*Kajiwara et al.*, 1994] little evidence of the ocean circulation exists. The ocean circulation and associated heat transports would be expected to play an important role in this, as in any other climate [*Crowley and North*, 1991], and a number of modelling studies have been conducted to ascertain them (e.g. *Kutzbach and Guetter* [1990]; *Zhang et al.* [2001]; *Winguth et al.* [2002]). The question of Pangean climate has not yet been addressed with a coupled ocean atmosphere general circulation model [OAGCM] however, and the impact of an interactive ocean in such a configuration has not been studied.

Here we use a coupled OAGCM with an idealised Pangean geography to investigate the ocean circulation present with this very different basin configuration and the climate feedbacks that result. The idealised nature of the experiment allows us to focus more clearly on the role played by the ocean in the wider climate system.

2. Experiment Setup

We use the FORTE coupled ocean-atmosphere model [*Sinha and Smith*, 2002], run at T21L22 resolution in the atmosphere and 4°x4°x15 vertical levels in the ocean; this resolution allows the model to be integrated over millennial timescales. The FORTE model uses the IGCM3 spectral atmosphere [*Forster et al.*, 2000], coupled to the MOMA [*Webb*, 1996] ocean via the OASIS coupler [*Terray et al.*, 1999]. Mixing in the ocean is a vertical/horizontal scheme with a vertical diffusivity of 1 cm^2/s, and there is a simple sea-ice parameterisation to insulate the ocean below sub-freezing air. Vegetation is non-interactive, with a two level diffusive soil model - see *Forster et al.* [2000] for more details. Excess water from the soil model is transferred instantly to coastal points defined by a runoff grid. The model was spun up using the periodic coupling method of *Sausen and Voss* [1996] (the atmosphere model being switched off for certain periods whilst stored boundary conditions are recycled) for 1360 years from a stable coupled aquaplanet climate, then run with fully synchronous coupling for another 100 years. The data presented here are from a climatology constructed from the last 30 years of integration. Although not at full thermal equilibrium, the coupled system exhibits no qualitative drift in climate or behaviour; there is an imbalance of 0.8 W/m^2 at the top of the atmosphere.

In order to take account of model inaccuracies when analysing the Pangean climate, the results are compared to the model state at the end of an 800 year run with a modern geography, with interpolations of realistic land orography, ocean floor topography and vegetation patterns. This simulation was carried out with isopycnal mixing [*Gent and McWilliams*, 1990] in the ocean but otherwise the model is as described above. Flux adjustments are not applied; model errors lead to a warm bias at high latitudes in this configuration. This scenario is also not in equilibrium and there is an imbalance of 4.1 W/m^2 at the top of the atmosphere. Transport diagrams diagnosed from energy flux divergences presented later for both runs have been corrected by the subtraction of the average residual from all gridpoints.

The physical configuration of the idealised Pangea can be seen outlined in figure 1, with the land surface stretching from pole to pole. There are also thin polar islands over both poles; these are a common ocean-modelling procedure to avoid the problem of grid convergence. The width of the ocean basin reflects that of the main Panthalassic ocean; there is evidence that the low latitude Tethys sea may have been enclosed by peninsulas and a ring of islands that would have restricted exchange with the main ocean [*Scotese*, 2001]. In keeping with the idealised nature of the experiment, all surfaces (land and ocean) are entirely flat, with an arbitrary uniform desert albedo on land. All other parameters (i.e. CO_2 concentration, solar luminosity etc.) were kept at modern values.

3. Climate

The Pangean climate produced is generally warmer than that of the modern simulation, with an increase in the annual average surface air temperature from 19.4°C for the modern climate to 21.3°C for the idealised Pangea (figure 1a). The northern hemisphere winter surface air temperature for Pangea shows an extreme seasonal response on the landmass (figure 1b), with summer highs of 50°C and a winter minimum of -28.1°C. The equator-pole temperature gradient at the surface is also reduced (figure 2), despite the warm polar bias the model already has compared to the modern climatology.

The global warming cannot simply be accounted for by the changed surface albedo of the idealised setup: the change in surface specification leads to an increase of 0.03 in surface albedo, from 0.14 for the model's current climate configuration to 0.17. Were this to result in an equal rise in planetary albedo, it would imply a surface temperature drop of around 3°C, as opposed to the increase seen. Instead, changes in the atmosphere lead to a decrease in global planetary albedo of 1.7% (due to a decrease in total cloud fraction, particularly in the tropics) and a small global increase in longwave absorption of about 0.5%, which together lead to the warming seen.

The meridional temperature gradient is shallower than that of the modern configuration, both at the surface and throughout the system, a result of high latitude warming rather than tropical cooling. Two factors affect this gradient: local radiative properties and meridional energy transport in the system. The total system (ocean+atmosphere) energy transport is little different in strength for the Pangean geography (figure 3), having shifted slightly toward the northern hemisphere, removing the northward bias of the modern transport. The distribution of water vapour in the two atmospheres has changed significantly however (figure 4), showing increased water vapour in the high latitudes of the Pangean simulation which absorbs more longwave radiation, providing a local warming. Taken in isolation as for the above albedo calculation, the increase in longwave absorption of 25% at 75°N is equivalent to a 40 W/m^2 surface forcing, given that the outgoing longwave flux at the top of the atmosphere does not significantly change. This is enough to raise the temperature at this latitude to the levels seen. The meridional profile of surface albedo is also flatter than for the modern scenario but the profile of outgoing shortwave at the top of the atmosphere is little changed, suggesting that compensating effects in the Pangean atmosphere reduce the impact of this factor. That the Pangean tropics do not cool as a result of the atmospheric changes can be attributed to the reduced reflection of solar insolation in this region, mentioned above. The change in atmospheric water vapour distribution is mirrored in changes in the distribution of surface evaporation; the reduction in the temperature gradient is thus due more to the local radiative properties than the meridional transport of the system. From this end state data it is difficult to say whether the increased water vapour was a cause of warmth in the system or a response to some other initial factor, but we believe the mechanism described above provides a consistent explanation for the simulated steady state of the Pangean climate.

4. Ocean Circulation

The ocean circulation has a pattern familiar from theory: the basin here is essentially a single rectangular one, and the standard form of gyres and western boundary currents obtains. The meridional overturning circulation [MOC] shows a hemispherically symmetric pattern, with no cross-meridional flow which transports up to 102 Sv in the main deep polar overturning maxima (figure 5). Studies such as *Marotzke and Willebrand* [1991] have shown that symmetric overturning forms, whilst theoretically possible, are not often found in models with flux boundary conditions as they are unstable and prone to collapse into asymmetric modes with only a small initial asymmetry in freshwater forcing. Analysis of the Pangean overturning here (following *Hirschi et al.* [2003], with further decomposition of the density term into thermal and saline components) shows the dominant forcing to be the thermally-forced density gradients; the minimal part played by salinity in forcing this overturning may explain why it does not collapse into an asymmetric state, as the perturbations in freshwater fluxes responsible for the above instability would have relatively little influence.

The majority of the deepwater formation occurs at polar latitudes and there is no sign of low latitude, evaporation-forced deepwater production. The high strength of the overturning is a result of the large basin dimensions (following the scaling arguments derived in *Klinger and Marotzke* [1999]) and FORTE's overestimation of modern day overturning (around 25 SV of North Atlantic deepwater formation). The temperature of the deepest waters for the Pangean simulation is 8.5°C. Although FORTE has a warm bias at depth compared to observations with deep water of 5.7°C (the choice of mixing scheme in the modern run affects the shape of the vertical temperature profile, but has little effect on the bottom value), the Pangean deep water is warmer still, reflecting the warm polar surface waters brought down by the vigorous overturning. This produces a rather weakly stratified ocean.

The high strength of the MOC in the Pangean simulation does not produce an extreme meridional heat transport, with a maximum oceanic heat transport of only 1.2 PW (see figure 3). This is a consequence of the relatively shallow vertical temperature gradient between the rather deep northward flowing waters and the return flow. Compared to the global ocean heat transport for the modern simulation, the Pangean transport is hemispherically symmetric, with increased transport to the southern hemisphere and the very high northern latitudes. Although the total system transports are not responsible for the meridional temperature gradient of the whole system, the changes in ocean heat transport will play a role in setting the gradient at the surface. The oceanic transport may also have an important role to play in initialising the climate regime seen here. Analysis of the spin up of the Pangean run shows an initial maximum of more than 200 Sv for the MOC, which slowly reduces to the level presented here. This suggests that an initial increase in poleward heat transport in the ocean may have led to the increase in high latitude evaporation, setting the new water vapour distribution.

5. Discussion

Previous studies of Pangean ocean circulation have been done with models with more sophisticated basin shapes, but less interactive boundary conditions. Like *Kutzbach and Guetter* [1990], and the warmer scenarios of *Winguth et al.* [2002], the oceanic overturning circulation found here is hemispherically symmetrical, although rather more vigorous. Despite that, the total ocean heat transport is comparable to both studies, slightly weaker than *Kutzbach and Guetter* [1990] and a little stronger than *Winguth et al.* [2002]. There is evidence for warm bottom water temperatures of around 15°C [*Stevens and Clayton*, 1971] for this period, and the vigorous circulation here is consistent with high bottom and polar water temperatures without producing an unrealistic transport. At 8°C the waters are too cool however, and the model used here already has a bias towards warm bottom waters; the 2.8°C warming from the reference climate is not of the order that would be required from a model without this bias.

Zhang et al. [2001] find a thermally forced, asymmetric overturning form and also a haline mode with low latitude sinking under certain freshwater forcings and vertical diffusion profiles, suggesting the possibility of multiple climate states for the period. The sensitivity of the MOC is a notoriously model dependent quantity, but the very weak role played by salinity forcing in the overturning seen here suggests that the climate produced by this simulation would have to undergo a large freshwater perturbation to produce such an overturning. Evidence for deep ocean anoxia [*Kajiwara et al.*, 1994] during this period has been linked with overturning regimes varying from those driven by polar convection [*Sarmiento et al.*, 1988], to low-latitude evaporation [*Railsback et al.*, 1990] and complete stagnation [*Knoll et al.*, 1996]. This study thus adds to the body of model studies that suggest a polar convective overturning for this configuration.

Whilst this study lacks many features of a complete Pangean climate simulation, looking solely at the effects of the change of geography in a coupled OAGCM produces some interesting climatic results. There is a global average warming and significant meridional temperature gradient change, maintained by changes in water vapour and cloud distribution. That the water vapour effect accounts for the reduced latitudinal temperature gradient, also found in *Hay and DeConto* [1999], means that the paradox between warm polar temperatures and changes in system heat transport often noted for warm paleoclimates (e.g. *Huber and Sloan* [2001]) is not an issue here - this mechanism may thus also apply to the problem for other paleoclimates.

Acknowledgments. This work formed part of a PhD thesis at the Southampton Oceanography Centre and was funded as part of a UK NERC PhD Studentship with a contribution from the Max-Planck Institute for Meteorology, Hamburg. We would like to thank Joel Hirschi and Bablu Sinha for useful discussions about the results. The manuscript also benefited greatly from the comments of Uwe Mikolajewicz, Karen Bice and an anonymous reviewer.

References

Crowley, T., and G. North (1991), *Paleoclimatology*, Oxford University Press, New York.

Enos, P. (1993), The Permian in China, in *Permian of Northern Continents*, Springer-Verlag, New York.

Forster, P. d. F., M. Blackburn, R. Glover and K. Shine (2000), An examination of climate sensitivity for idealised climate change experiments in an intermediate general circulation model, *Clim. Dynam.*, *16*, 833–849.

Gent, P. and J. McWilliams, (1990), Isopycnal mixing in ocean circulation models. *J. Phys. Ocean.*, *20*, 150–155.

Hay, W. W. and R. M. DeConto (1999), Comparison of modern and late Cretaceous meridional energy transport and oceanology, in *Special Paper 332*, pp. 283–300, Geological Society of America.

Hirschi, J., J. Baehr, J. Marotzke, J. Stark, S. Cunningham, and J.-O. Beismann (2003), A monitoring design for the Atlantic meridional overturning circulation.*Geophysical Research Letters*, *30*(7), 66.1–66.4.

Huber, M. and L. Sloan (2001), Heat transport, deep waters, and thermal gradients: Coupled simulation of an Eocene Greenhouse Climate, *Geophys. Res. Lett.*, *28*, 3481–3484.

Kajiwara, Y., S. Yamakita, H. Ishida, H. Ishiga and A. Imai (1994), Development of a largely anoxic stratified ocean and its temporary massive mixing at the Permian/Triassic boundary supported by the sulfur isotopic record., *Palaeogeography, Palaeoclimatology, Palaeoecology*, *111*, 367–379.

Klinger, B. and J. Marotzke (1999), Behavior of double-hemisphere thermohaline flows in a single basin, *J. Phys. Ocean.*, *29*, 382–399.

Knoll, A. H., R. K. Bambach, D. E. Canfield and J. P. Grotzinger (1996), Comparative Earth history and Late Permian mass extinction, *Science*, *273*, 452–457.

Kutzbach, J. and P. Guetter (1990), Simulated circulation of an idealized ocean for Pangaean time, *Paleoceanography*, *5*(3), 299–317.

Marotzke, J. and J. Willebrand (1991), Multiple equilibria of the global thermohaline circulation, *J. Phys. Ocean.*, *21*, 1372–1385.

Parrish, J. (1993), Climate of the supercontinent Pangea, *J. Geology*, *101*, 215–233.

Railsback, L.B., S.C. Ackerly, T.F. Anderson and J.L. Cisne (1990), Palaeontological and isotope evidence for warm saline deep waters in Ordovician oceans, *Nature*, *343*, 156–159.

Sarmiento, J.L., T.D. Herbert and J.R. Toggweiler (1988), Causes of anoxia in the world ocean, *Global Biogeochem. Cycles*, *2*, 115–128.

Sausen, R. and R. Voss (1996), Techniques for asynchronous and periodically synchronous coupling of atmosphere and ocean models, *Clim. Dynam.*, *12*, 313–323.

Scotese, C. (2001), *Atlas of Earth History, Volume 1, Paleogeography*, 52pp., PALEOMAP Project, Arlington, Texas.

Sinha, B. and R. Smith (2002), Development of a fast coupled general circulation model (FORTE) for climate studies, implemented using the OASIS coupler, *Tech. Rep. 81*, Southampton Oceanography Centre.

Stevens, G. and R. Clayton (1971), Oxygen isotope studies on Jurassic and Cretaceous belemnites from New Zealand and their biogeographic significance, *New Zealand Journal of Geology and Geophysics*, *14*, 829–897.

Terray, L., S. Valcke and A. Piacentini (1999), OASIS 2.3 user's guide, *Tech. Rep. TR/CGMC/99-37*, CERFACS, Toulouse.

Webb, D. (1996), An ocean model code for array processor computers, *Computers and Geosciences*, *22*(5), 569–578.

Winguth, A. M. E., C. Heinze, J. E. Kutzbach, E. Maier-Reimer, U. Mikolajewicz, D. Rowley, A. Rees and A. M. Ziegler (2002), Simulated warm polar currents during the middle Permian, *Paleoceanography*, *17*, 9.1–9.18.

Zhang, R., M. J. Follows, J. P. Grotzinger and J. Marshall (2001), Could the Late Permian deep ocean have been anoxic, *Paleoceanography*, *16*, 317–329.

Figure captions

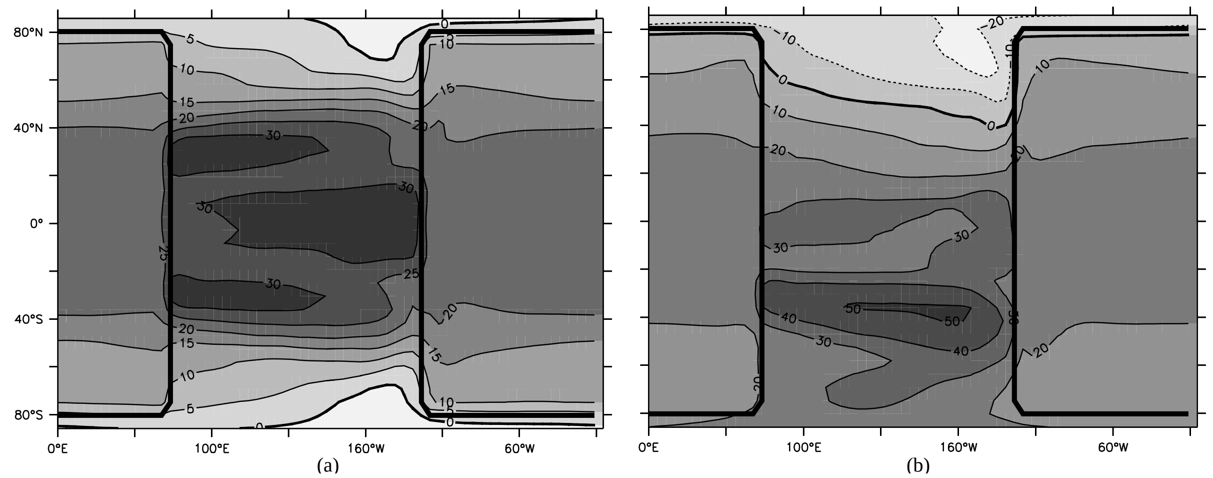
Figure 1: Surface air temperature (°C). The coastlines are contoured in heavy black (land area is central). a) Annual average, b) Northern hemisphere winter

Figure 2: Annual average zonal temperature profiles (°C). Pangean climate (heavy), modern climate (light), climatologically forced IGCM3 run (dashed)

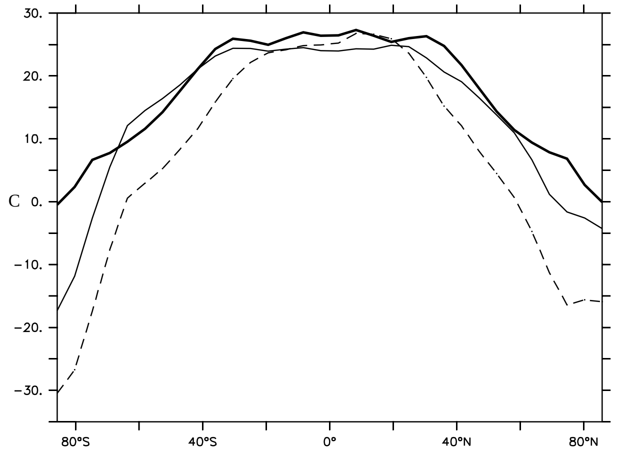
Figure 3: System energy transports (PW) for the Pangean simulation (heavy) and the modern climate (light). Solid line are total system (ocean+atmosphere) transports, dashed are global ocean heat transports

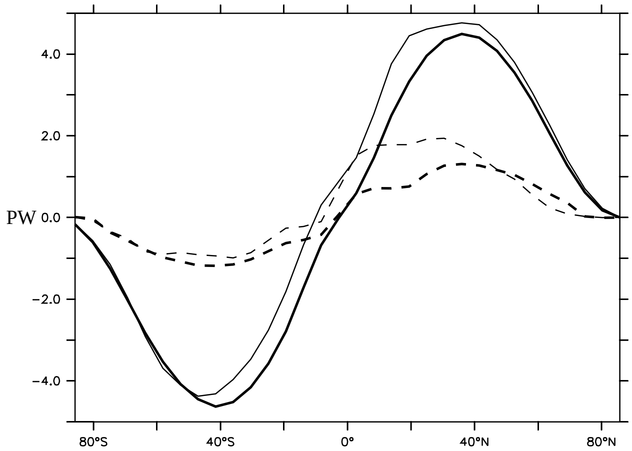
Figure 4: Zonal average specific humidity (g/kg) throughout the atmosphere. Pangean (heavy), modern climate (light)

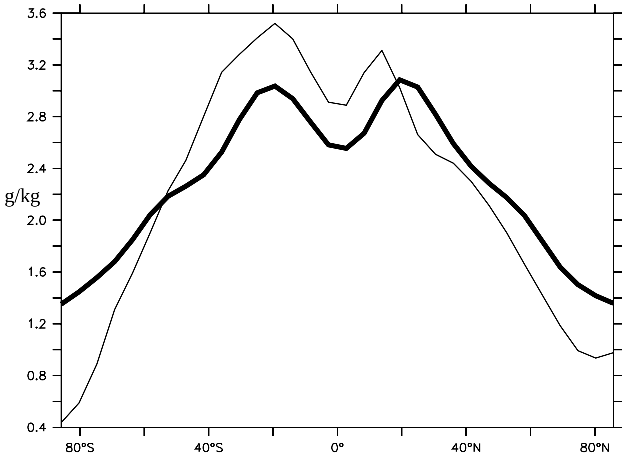
Figure 5: Average oceanic meridional overturning (Sv)

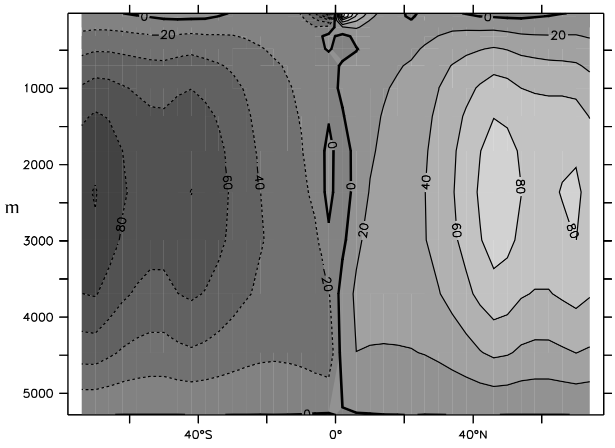

80°N
40°N
0°
40°S
80°S
0°E
100°E
160°W
60°W

(a) (b)


30.
20.
10.
C 0.
−10.
−20.
−30.
80°S
40°S
0°
40°N
80°N


4.0
2.0
PW 0.0
−2.0
−4.0
80°S
40°S
0°
40°N
80°N


3.6
3.2
2.8
2.4
g/kg
2.0
1.6
1.2
0.8
0.4
80°S
40°S
0°
40°N
80°N


0
20
0
20
1000
2000
m
3000
4000
5000
80
60
40
0
0
20
20
40
60
80
80
0
40°S
0°
40°N