Open access • Journal Article • DOI:10.1029/93PA01046

Effect of wind changes during the Last Glacial Maximum on the circulation in the Southern Ocean — Source link

John M. Klinck, David Smith

Published on: 01 Aug 1993 - Paleoceanography (John Wiley & Sons, Ltd)

Topics: Wind stress, Wind shear, Wind gradient, Thermal wind and Wind speed

8-1993

Effect of Wind Changes During the Last Glacial Maximum on the Circulation in the Southern Ocean

John M. Klinck
Old Dominion University, jklinck@odu.edu

David A. Smith

Repository Citation

Klinck, John M. and Smith, David A., "Effect of Wind Changes During the Last Glacial Maximum on the Circulation in the Southern Ocean" (1993). *CCPO Publications*. 172.
https://digitalcommons.odu.edu/ccpo_pubs/172

Original Publication Citation

Klinck, J. M., & Smith, D. A. (1993). Effect of wind changes during the last glacial maximum on the circulation in the Southern Ocean. *Paleoceanography, 8*(4), 427-433. doi: 10.1029/93pa01046

PALEOCEANOGRAPHY, VOL. 8, NO. 4, PAGES 427-433, AUGUST 1993

EFFECT OF WIND CHANGES DURING THE LAST GLACIAL MAXIMUM ON THE CIRCULATION IN THE SOUTHERN OCEAN

John M. Klinck and David A. Smith

Center for Coastal Physical Oceanography, Department of Oceanography, Old Dominion University, Norfolk, Virginia

Abstract. Present-day surface wind stress climatology is manipulated to simulate wind conditions during the last glacial maximum. These estimated wind fields force a one-layer, wind-driven numerical model of the southern ocean to determine if a change in the strength of the surface wind stress can shift the location of the Antarctic Polar Front, which is part of the Antarctic Circumpolar Current. A change in the forcing by a factor of 0.5–2.0 results in a change in the speed of the flow by an identical factor with no change in position. However, if the present-day wind climatology is shifted meridionally, there is a change in both strength of the circulation and spatial pattern. A shift of the wind stress of more than 5° of latitude is required to produce a shift in the location of the polar front.

INTRODUCTION

Geological evidence, in particular, sediment records, indicates that surface winds over the southern ocean were faster during the last glacial maximum (LGM) by a factor ranging from 30% to 70% [Petit et al., 1981; Sarnthein et al., 1981; DeAngelis et al., 1987]. The best evidence seems to be for a 70% increase in surface winds [Crowley and Parkinson, 1988]. Some estimates of surface wind stress during the LGM from climate modeling studies, although these models tend to underestimate the winds over the southern ocean, agree with this interpretation of the sediments [Gates, 1976; Manabe and Broccoli, 1985; Kutzbach and Guetter, 1986]. Furthermore, fossils recovered from sediment that was deposited during the LGM show that the Antarctic Polar Front seems to have shifted toward the equator by at least 4° to 5° of latitude [CLIMAP, 1976; Dow, 1987]. A review of conditions during the LGM is presented by Crowley [1988].

There is a strong temptation to link these facts and attribute the shift in the polar front to the increased wind stress. A possible mechanism for the shift would be the increase in the Ekman transport due to the stronger surface stress which would cause an increased advection toward the equator. However, current understanding of the dynamics of the Antarctic Circumpolar Current (ACC) is that the position of the current is determined by the bottom topography and will tend to follow isopleths of topographic vorticity f/h, which is the ratio of the Coriolis parameter and the local mean depth [Johnson and Hill, 1975]. From this point of view, increased surface stress should produce stronger circulation and, perhaps, increased production of mesoscale eddies from instability but not a shift of the location of the current.

The purpose of this study is to consider the question of the effect of changes in the surface wind stress that may have occurred during the LGM on the location and strength of the circulation in the southern ocean. The magnitude of these changes is estimated from a one-layer, wind-driven model for the southern ocean which is driven by several choices of wind stress. For each of these wind stress fields, the model is driven to steady state, and the steady pattern is analyzed for changes in the strength and position of the ACC.

The results of a series of simulations are presented. Several cases are considered that are forced with the zonal average of the present-day surface wind stress that is changed by a constant factor, representing an increase (or decrease) of wind stress without a change in the general character of the winds. A second series of simulations considers the effect of meridional shifts in the surface wind stress. The shifted winds might also represent situations where the wind strength during earlier times changed by different amounts at different latitudes. These simulations are more speculative in that there is no compelling evidence

Paper number 93PA01046.
0883-8305/93/93PA-01046$10.00

that there was a meridional displacement of the wind field during the LGM. However, this is another mechanism that might cause a lateral shift of the ACC. A final simulation considers a northward shift in the winds together with an increase in strength.

DESCRIPTION OF MODEL AND FORCING

Numerical Model

The wind-driven southern ocean numerical model used in this study is based on the vertically averaged (shallow water) primitive equations on a β plane with a free surface. Lateral friction is the only explicitly included mechanism for dissipation of momentum. These equations are solved with an alternating direction implicit scheme [Leendertse, 1967] using a staggered C grid [Mesinger and Arakawa, 1976] which handles the fast external gravity waves implicitly allowing a 1-hour time step. Complete details on the wind-driven southern ocean model, including model geometry and bottom topography, are given by Klinck [1991, 1992].

The model domain extends from 35°S to 75°S and is purposely chosen to extend far enough north so that the northern model boundary, which is free-slip, has a minimal influence on the location of the ACC. All other boundaries (land boundaries) are taken to be no-slip walls. The base latitude for the Coriolis and β parameters is 55°S. The lateral viscocity is chosen to be 2×10^4 m s^{-2}, which is as small as the model resolution (64-km grid spacing) will allow.

The bottom topography, relative to the average depth over the model domain, is reduced to 15% of its true magnitude to account for effects due to stratification. That is, the bottom topography is constructed as the sum of a spatial mean depth H and a departure from the mean η_b; the total depth is $h(x,y) = H + \epsilon\, \eta_b(x,y)$ The bottom reduction parameter ϵ has a value of 0.15 for these cases. This reduction has the effect of changing the total transport and the general path of the ACC by changing the location of planetary vorticity f/h isopleths. In general, one cannot get a perfect match between transport and path by adjusting the topography, so the reduction parameter is chosen to produce a realistic path for the ACC, which is one that matches the dynamic topography of the surface relative to a deeper pressure level, say 1400 m. Simulations for two choices of the bottom reduction parameter along with the dynamic topography from the Southern Ocean Atlas [Gordon and Baker, 1986], can be seen in the work by Klinck [1992, Figures 5, 6, and 7]. If the full magnitude of the topography is chosen, the ACC is strongly retarded by bottom form drag and the flow is constrained to follow isobaths (approximately), causing an unrealistic path for the ACC. A realistic circulation is obtained if the topography, relative to the mean depth, is reduced to 15% of its true value, although the resulting total transport is about 3 times the accepted value of 125×10^6 m^3 s^{-1} [Whitworth, 1983; Whitworth and Peterson, 1985].

All of the simulations described here use the same values for topography and dissipation parameters; only the surface wind stress is different. Each simulation is started from rest and integrated to a steady state at which time (about 6000 hours of simulation) the area-integrated potential and kinetic energy reach a steady value (since the model does not support dynamic instabilities, the energy and transport of the flow become time invariant). The volume transport, which is calculated at four locations (Drake Passage, south of Africa, south of Tasmania and south of New Zealand), is also observed to become steady.

Structure of the Surface Wind Stress

The structure of the present-day surface wind stress is taken from the climatology derived from 7 years of analyzed surface wind (1980 to 1986) from the European Centre for Medium-Range Weather Forecasting, Reading, England, forecast model [Trenberth et al., 1989]. The annual average stress is interpolated from its original 2.5° x 2.5° grid to the numerical model grid (2° longitude by 1° latitude). This present-day stress climatology is modified in two ways (discussed below) to create fields that might have existed at earlier times.

Previous experience with wind-forced circulation in the southern ocean shows that the currents are not strongly influenced by the zonal structure of the winds [Klinck, 1991]. In fact, nearly identical circulation patterns are obtained from the one-layer model when forced by the annual average winds or the zonal average of the annual average winds. Because of this insensitivity to the zonal structure, we have chosen to use the zonal average of the annual average wind stress as the basic wind field (Figure 1). This field is shifted and scaled to create the estimated surface wind stress from previous climate regimes.

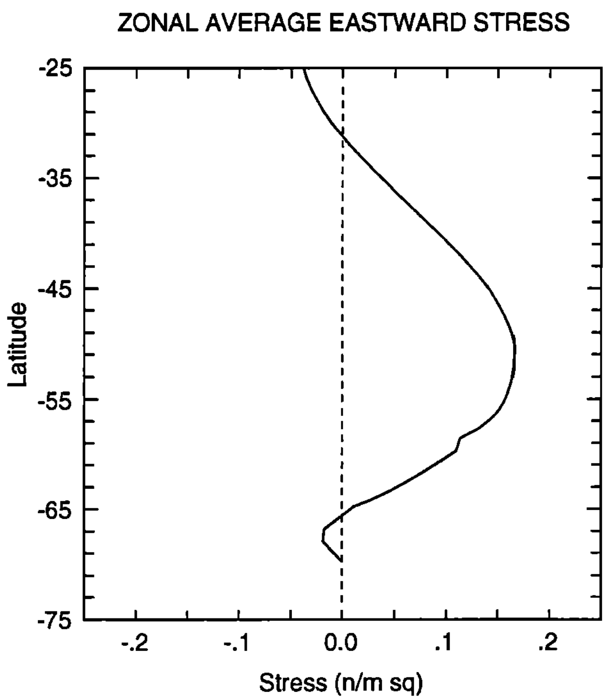

Fig. 1. Zonal average of the eastward wind stress (newtons per square meter) from the climatology created from the European Centre for Medium-Range Weather Forecasting twice daily analyses [Trenberth et al., 1989].

Numerical Simulations

Two sets of numerical experiments are considered. In the first set, the present-day wind stress is scaled by some factor to represent the increase in strength of surface winds during the LGM. The predicted increase ranges from 10% to 70% above present-day values [Gates, 1976; Petit et al., 1981; Sarnthein et al., 1981; Kutzbach and Guetter, 1986; Manabe and Broccoli, 1985; DeAngelis et al., 1987]. Simulations are made for wind stress increases of 25%, 50% and 75% to encompass low, middle, and high estimates of wind conditions during the LGM. Calculations are also made with the winds increased by 100% and reduced by 25% and 50%. These exaggerated cases are considered to allow for errors in predicted LGM values and to test the response of the modeled southern ocean to different winds.

A second set of calculations considers the effect of meridionally shifted wind fields, which is another plausible mechanism that might cause a change in location of the ACC. Meridionally shifted winds are created by simply moving values of the present-day, zonally averaged wind fields north or south by some number of degrees of latitude. The use of zonally averaged climatology diminishes the error associated with the change in structure of the winds that must occur owing to the influence of topographic features, such as the Andes Mountains, if such shifting were to occur. A final experiment considers both a northward shift and an increase in strength.

RESULTS

A general idea of the pattern of circulation in the southern ocean is obtained from the departure of the free surface from mean sea level. Because the basic dynamical balance is geostrophic, isolines of surface elevation are parallel to the stream function of the vertically averaged flow and are generally parallel to the dynamic topography. The steady circulation produced by the zonal average of the annual averaged winds shows the major current of the southern ocean (the ACC) and how this current departs from purely zonal flow owing to the influences of continental boundaries and various submarine ridges (Figure 2). The elevation across the model ACC is of the order of 2 m, which is approximately twice the accepted value; additionally, the steady transport is 350×10^6 m^{3}s^{-1}, which is about 3 times the value (125×10^6 m^{3}s^{-1}) measured in Drake Passage [Whitworth, 1983; Whitworth and Peterson, 1985]. Part of the discrepancy occurs because the model represents Drake Passage as having a larger cross-sectional area because of the reduction in the bathymetry. The Weddell Gyre is rather weak, but this is believed to be due to the relatively poor representation of wind data at extreme southern latitudes.

Despite these limitations, the calculated circulation does exhibit characteristics of the dynamic topography estimated by Gordon et al., [1978]. The flow through Drake Passage has a depth mean speed of about 0.5 m s^{-1} and is stronger on the northern side of the passage. Upon exiting Drake Passage, a branch of the ACC turns north along the coast of South America (Falkland-Malvinas Current), while a second branch continues toward the east across the Scotia Sea. The Falkland-Malvinas Current turns back to the south when it reaches the boundary of the subtropical gyre (where the wind curl vanishes) at approximately 50°S [Peterson and Whitworth, 1989]. The rest of the ACC flows generally zonally, with a tendency to slip southward in response to the wind forcing.

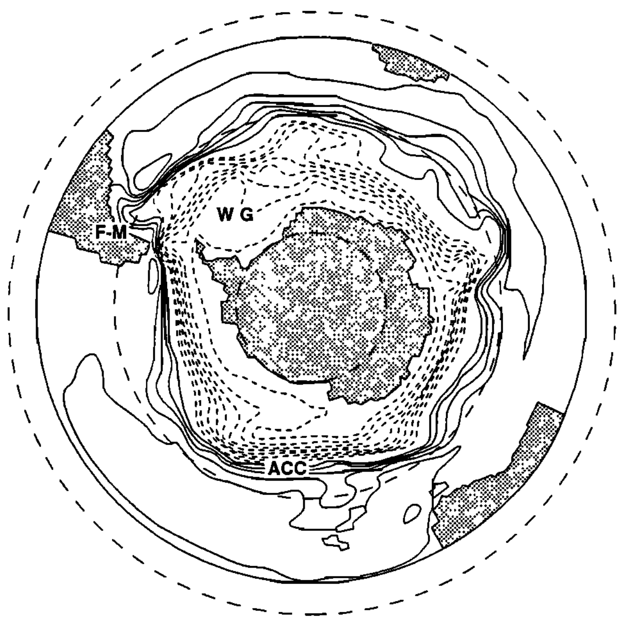

Fig. 2. Steady state surface elevation for the case forced by the annual mean, zonally averaged wind. The surface topography (meters) is indicated by solid lines; negative elevation is indicated by dashed lines. Land areas are shaded. Contour interval is 0.1 m. The Weddell Gyre is indicated by WG, the Antarctic Circumpolar Current is indicated by ACC, and the Falkland-Malvinas Current is indicated by F-M.

Wind Strength Changes

Several simulations are forced by a zonally averaged wind stress that is created from present-day stress scaled by a factor ranging from 0.5 to 2.0 which represents the change in wind stress from other times relative to present-day conditions. An integrated view of the result of such changes in the wind stress is given by the transport of the ACC for each of these simulations (Figure 3). It is clear from these transports that the response is essentially linear, that is, the transport change is proportional to the wind factor. Furthermore, the resulting surface elevation patterns at steady state have exactly the same shape as Figure 2 but are changed by the same factor as the wind.

In all of these scaling calculations, including the experiments for values well outside the range predicted for conditions during the LGM, the location of the major features of the ACC do not change. The only notable difference is that the total surface elevation across the ACC and the transport are scaled by the same factor as the wind climatology. Even the area east of Drake Passage, which would be a place at which nonlinear effects would appear, responds linearly to the forcing change.

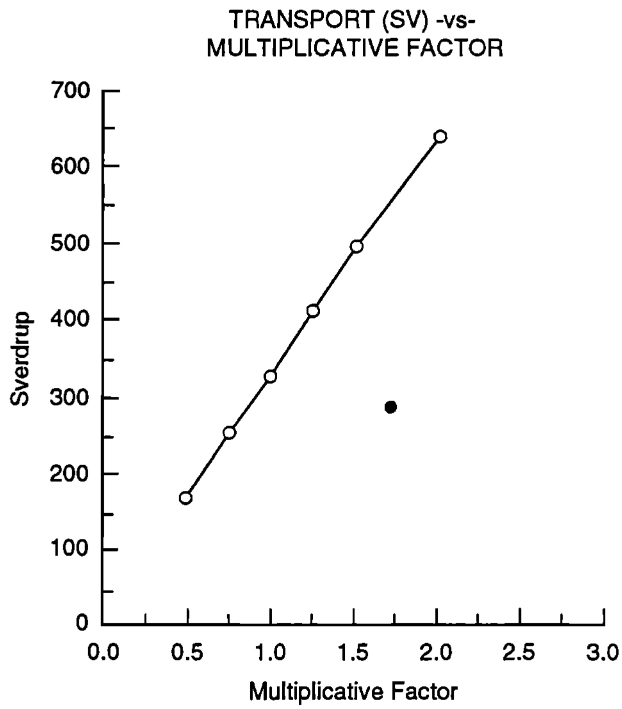

Fig. 3. The transport (in units of 1×10^6 $m^3 s^{-1}$) at steady state as a function of increase in wind strength. The average wind is multiplied by the factors 0.5, 0.75, 1.0, 1.25, 1.5, and 2.0 in constructing this figure (indicated by open circles). The solid circle is a simulation with wind increased by 70% and shifted north by 5°.

Meridional Wind Shifts

The previous simulations with different strengths for the wind stress did not result in a shift in the location of the ACC. One might ask if the wind patterns at the LGM had meridional shifts in addition to changes in strength or if the strength changes were different for different latitudes. The next set of experiments examines the circulation of the southern ocean forced by winds that are shifted meridionally from their present-day locations. Twelve simulations are considered which are forced by present-day wind climatology that is shifted by 2°, 5°, 7°, 8°, 10°, and 12° north and south. Only the experiments with shifts of ±5° and ±10° are described in detail.

The results of these simulations are presented as the total volume transport versus the amount of meridional shift of the zonally averaged wind pattern (Figure 4). As the wind pattern shifts to the south, the total transport of the ACC increases; a corresponding decrease is produced by a northward shift. Note that a shift from the present-day winds, in contrast to strength changes, produces the largest transport change, indicating the sensitivity of the southern ocean circulation, at least in terms of total transport, to the location of the winds. A displacement of the winds by 5°, which is about the amount that the oceanic polar front is estimated to have moved, produces a change in the total transport of about a factor of 2, certainly a dramatic change.

The total transport of the ACC is a bulk measure of the strength of the circulation, but the real question is whether and by how much the current changes location when there is a shift of the wind stress. The anomaly of surface elevation from mean sea level is a useful indicator of the position of currents, as the strongest currents are located at positions of the largest slope in the free surface (because of the geostrophic balance). The location of the ACC is considered for five cases (base case and shifted north and south by 5° and 10°). A meridional profile of the free surface in the south Atlantic (6.5°W) indicates the position of the currents (Figure 5). The total change in the free surface is proportional to the total transport of the current, so there is a clear increase in the transport as the wind shifts from north to south. Similar results are obtained for other locations in the ACC, but they are not provided in this paper.

The present-day climatological wind stress produces an ACC that covers the region from 45°S to 50°S latitude, and the total height change across the ACC is about 1.0 m. When the winds are shifted to the north by 10°, the circulation of the ACC becomes rather weak, with the total surface elevation change across the ACC being approximately 0.5 m. The ACC now spans the region from 43°S to 48°S and the polar gyre fills much of the southern ocean creating a two-way circulation through Drake Passage and thereby reducing the total transport. Additionally, the stronger wind speeds occur at a latitude

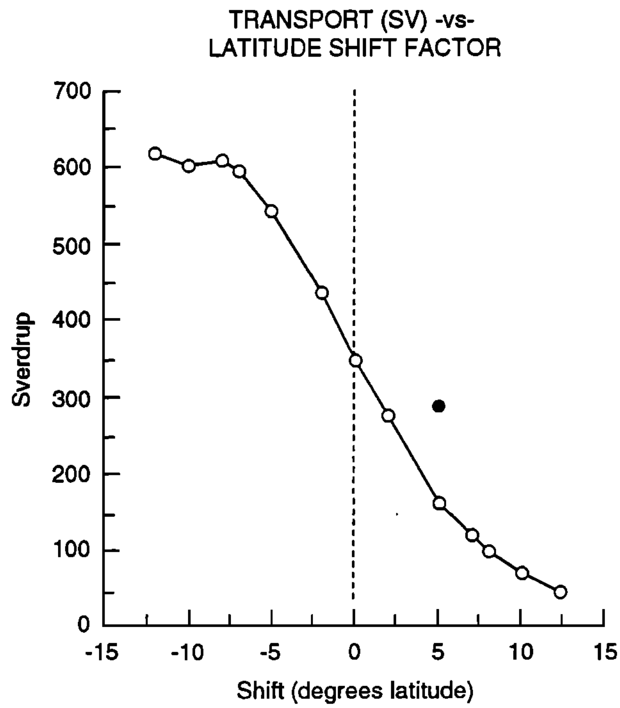

Fig. 4. The transport (in units of 1×10^6 $m^3 s^{-1}$) at steady state as a function of wind shift in degrees of latitude. This figure is constructed by shifting the wind north (positive number) and south (negative number) by 2°, 5°, 7°, 8°, 10°, and 12° (indicated by open circles). The solid circle is a simulation with wind increased by 70% and shifted north by 5°.

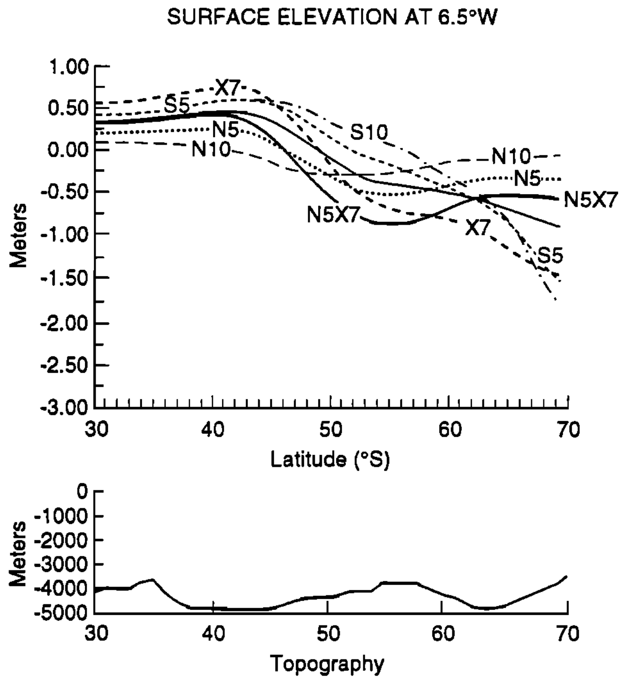

Fig. 5. Surface elevation (meters) across the ACC along 6.5°W. The thin, unmarked line is from the present-day wind climatology. The surface elevation for the winds shifted by 5° and 10° of latitude from the present-day conditions are indicated by S10, S5, N5, and N10. The line marked X7 is from the simulation with the winds increased by 70%. The line marked N5X7 is from the simulation with the winds increased by 70% and shifted north by 5°. The bathymetry is displayed along the bottom of the figure.

that is blocked by a continent, and pressure gradients can develop that oppose the wind so there is a weaker circulation. One might consider that the reduced Coriolis parameter would cause this decrease in the circulation. However, the circulation decreases by a factor of 2 while the Coriolis parameter changes by about 20% (consider a shift in latitude of 10°). When the winds are shifted to the south by 10°, the circulation of the southern ocean becomes much stronger, with a height change across the ACC of the order of 2.5 m. The current now exists as two cores or branches: one between 45°S and 50°S and a second between 55°S and 60°S. The differences among these cases is not so much that the current has shifted as that there are preferred locations for the current cores and the location of the wind has a strong effect on the strength of a given current core.

Wind Shift and Strength Change

The best estimate of wind structure during the LGM is that the winds both shifted to the north and increased in strength by 70% [Crowley and Parkinson, 1988]. Since the increase in wind strength produces an increase in the circulation and the northward shift produces a decrease, there is a question of which effect is dominant if both occur. A last simulation was run with the winds shifted north by 5° and the winds increased by 70%. The total transport for this case is 280×10^6 $m^3 s^{-1}$(indicated by the solid circle in Figures 3 and 4). This represents an overall decline in the total transport compared to the base case, so the northward shift of 5° has a stronger influence than the increase in wind strength by 70%. Note, however, that the location of the ACC, as represented by the surface elevation at 6.5°W (Figure 5), is north of the present-day ACC by 2° of latitude.

DISCUSSION

Changes in Wind Strength

It is generally accepted that the winds were much stronger during the LGM [Crowley, 1988]. In the model calculations discussed here, the southern ocean transport increases as the wind stress increases (Figure 3). Fossil records indicate an increased thermal gradient during the LGM [CLIMAP, 1976; Dow, 1987] which is in agreement with the increase in the velocity of the ACC that is found in this study.

The response of the ACC to increased forcing is a proportional increase in the volume transport with no change in ACC location. Thus this study indicates that the northward shift in the ACC during the LGM cannot be explained by simply increasing the surface wind stress to values predicted to exist during the LGM. However, this model neglects part of the dynamics that are active in the southern ocean, specifically, the effect of density variations. In a model that includes the effects of stratification, the stronger wind stress will drive an increase in circulation which will produce stronger density gradients and current shear (both horizontal and vertical). This increase in shear is expected to increase the energy sources for instabilities (barotropic and baroclinic), resulting in an increase in eddy production. The increased eddy activity is not expected to cause the location of the current to shift. However, the presence of stratification will decouple the flow, to some extent, from isobaths, allowing the current to change location.

Changes in Wind Position

The effect of changing the location of the zonally averaged winds is two-fold. The major effect is to move the boundaries of the subtropical and polar gyres by shifting the lines at which the curl of the wind stress vanishes. The strength of the circulation in the southern ocean is determined by the relative location of the gyre boundaries and the continents which block the flow. As the wind pattern is shifted to the south, less of the circulation is blocked by the continent of South America and the transport of the ACC is larger. The minor effect of the wind stress shift is due to the fact that the strength of the flow is determined by the component of the surface stress that is tangential to isopleths of planetary vorticity f/h [Johnson and Hill, 1975]. As the wind pattern is shifted, the strength of the circulation along each of these lines changes. These effects are the same, since the southward shift moves the forcing to planetary vorticity lines that are not blocked by continental walls, allowing much stronger circulation.

The first effect of the wind shift is the change in transport in proportion to the amount of shift (Figure 4); the second effect is the shift in the location of the ACC (Figure 5). If the ocean had a flat bottom and no continental boundaries, then the circulation in the channel would shift meridionally exactly in response to a change in the location of the wind forcing. If the continental boundaries are added but the bathymetry remains flat, then some of the latitudes (all of which are parallel to planetary vorticity isopleths) would be blocked by land and others would not; the flow along the unblocked latitudes would be much stronger than the flow in the blocked latitudes. When the wind stress pattern is shifted, the transport in the ACC would increase or decrease depending on whether the strongest winds occurred over the unblocked latitudes or not. Finally, when the bottom topography is included, the planetary vorticity lines follow some path around the southern hemisphere. The circulation at any place depends on the projection of the wind stress onto the path and on whether the path is blocked by a land boundary. It is interesting to note that a shift in the winds of as little as a 2° can produce a 50×10^6 $m^3 s^{-1}$ change in the total volume transport.

The surface elevation in the South Atlantic (Figure 5) illustrates this last point in that the path of the circulation in the southern ocean is dictated by the topography, and this feature of the southern ocean does not change with different climatological regimes. However, if the location of the wind stress changes, then the forcing along each of the planetary vorticity lines changes, producing a shift in the location of the current. This result is not affected by a simultaneous change in the strength and location of the forcing, since it is only the location of the forcing that determines the location of the resulting current.

Neglected Processes

The vertically averaged model neglects a number of processes, most obviously the effects of horizontal density variations. A second important component of the south polar regions which can also have an effect on circulation is ice

The effect of density stratification is to insulate the flow from topography to some extent and thereby to break the constraint that the flow be along planetary vorticity f/h isopleths. However, the southern ocean is only weakly stratified, so the flow is affected by bottom topography much more than at subtropical latitudes where there is a strong pycnocline. Stratification can allow the circulation to shift location under different wind regimes if the density structure is changed.

The effect of ice cover is more direct in that it interferes with the transfer of momentum between the wind and the ocean. In places where the ice cover is solid, the ocean is shielded from the wind, while in regions with less than complete ice cover, the ice absorbs some of the momentum so that the circulation is not as strongly forced.

These processes are thought to be less important than those that are included in the model. The ice cover would be the easiest to include as a mask over the one-layer model to represent the percentage of ice cover and thereby the reduction in the wind stress. The problem is then the estimation of the extent of ice in different climatic regimes and the parameterization of the effect of the ice on momentum transfer. Both of these problems with the ice effects are soluble but increase the number of processes being estimated in this model and are, therefore, not considered at this time. The inclusion of stratification is also possible, but it adds considerably to the cost of the model calculation and is not pursued at this time.

SUMMARY

The simple wind-driven model used in these calculations represents present-day southern ocean circulation with reasonable accuracy but fails to show that a change in the strength of the surface wind forcing, such as occured during the Last Glacial Maximum, produces a latitudinal displacement of the ACC. The model results support the conclusion that increased wind stress creates an increased transport of the ACC and hence an increase in the oceanic temperature gradients, as has been estimated from sediment cores. Meridional shifts of the wind stress offer a plausible mechanism to create the recorded shifts in the ACC positions. The basic mechanism is that the speed of flow along planetary vorticity isopleths is dependent on the wind strength tangential to the path. In order to create a shift in the location of the ACC, it is necessary to change the wind strength by different amounts in different locations. One way to do this is to shift the present-day structure of the wind stress. A second way is to have the surface wind stress change by different amounts at different latitudes (essentially the same result). Either of these mechanisms seems to be able to produce a shift in the location of the ACC in response to changes in the surface wind stress.

Acknowledgements. This work was done with the financial support of the National Science Foundation under grant OCE-8996235.

REFERENCES

CLIMAP Project, The surface of the Ice-Age Earth, *Science, 191*, 1131-1137, 1976.

Crowley, T. J., Paleoclimate Modelling, in *Physically-Based Modelling and Simulation of Climate and Climatic Change - Part II*, edited by M. E. Schlesinger, pp. 883-949, Kluwer Academic, Hingham, Mass., 1988 .

Crowley, T. J., and C. L. Parkinson, Late Pleistocene variations in Antarctic sea ice II: Effect of interhemispheric deep-ocean heat exhange, *Clim. Dyn.*, *3*, 93-103, 1988.

DeAngelis, M., N. I. Barkov, and V. N. Petrov, Aerosol concentrations over the last climatic cycle (160 kyr) from an Antarctic ice core, *Nature, 325*, 318-321, 1987.

Dow, R. L., Radiolarian distribution and the late Pleistocene history of the southeastern Indian Ocean, *Marine Micropaleontol.*, *3*, 203-227, 1987.

Gates, W. L., Modeling the ice-age climate, *Science*, *191*, 1138-1145, 1976.

Gordon, A. L. and T. N. Baker, *Southern Ocean Atlas*, 31 pp., Amerind, New Delhi, 1986.

Gordon, A. L., E. Molinelli, and T. Baker, Large-scale relative dynamic topography of the southern ocean, *J. Geophys. Res.*, *83*, 3023-3032, 1978.

Johnson, J. A., and R. B. Hill, A three-dimensional model of the southern ocean with bottom topography, *Deep Sea Res.*, *22*, 745-751, 1975.

Klinck, J. M., Vorticity dynamics of seasonal variations of the Antarctic Circumpolar Current from a modelling study, *J. Phys. Oceanogr.*, *21*, 1515-1533, 1991.

Klinck, J. M., The effects of wind, density, and bathymetry on a one-layer, southern ocean model, *J. Geophys. Res.*, *97*, 20,179-20,189, 1992.

Kutzbach, J., and P. J. Guetter, The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18000 years, *J. Atmos. Sci.*, *43*, 1726-1759, 1986.

Leendertse, J. J., Aspects of a computational model for long period water-wave propagation, *Memo. RM-5294-PR*, 165 pp., The Rand Corp., Santa Monica, Calif., 1967.

Manabe, S., and J. Broccoli, A comparison of climate model sensitivity with data from the last glacial maximum, *J. Atmos. Sci.*, *42*, 2643-2651, 1985.

Mesinger, F., and A. Arakawa, Numerical methods used in atmospheric models, v. 1, *GARP Pub. Ser.*, *17*, 1-64, 1976.

Peterson, R. G., and T. Whitworth III, The subantarctic and polar fronts in relation to deep water masses through the southwestern Atlantic, *J. Geophys. Res.*, *94*, 10,817-10,838, 1989

Petit, J., M. Briat, and A. Royer, Ice age aerosol content from east Antarctic ice core samples and past wind strength, *Nature*, *293*, 391-394, 1981.

Sarnthein, M., G. Tetzlaff, B. Koopmann, K. Wolter, and U. Pflaumann, Glacial and interglacial wind regimes over eastern subtropical Atlantic and north-west Africa, *Nature*, *293*, 193-293, 1981.

Trenberth, K. E., J. G. Olson, and W. G. Large, A global ocean wind stress climatology based on ECMWF analyses, *Rep. NCAR/TN-338+STR*, 93 pp., Nat. Cent. for Atmos. Res., Boulder, Colo., 1989.

Whitworth, T, III, Monitoring the transport of the Antarctic Circumpolar Current at Drake Passage, *J. Phys. Oceanogr.*, *13*, 2045-2057, 1983.

Whitworth, T., III, and R. G. Peterson, Volume transport of the Antarctic Circumpolar Current from bottom pressure measurements, *J. Phys. Oceanogr.*, *15*, 810-816, 1985.

J. M. Klinck and D. A. Smith, Center for Coastal Physical Oceanography, Department of Oceanography, Old Dominion University, Norfolk, Virginia 23529.

(Received October 23, 1992;
revised April 8, 1993;
accepted April 14, 1993.)