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ADJOINT ANALYSIS OF MERIDIONAL OVERTURNING SENSITIVITY TO WIND STRESS FORCING

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1. INTRODUCTION

The control of the meridional overturning circulation (MOC) by winds in the latitude band of the Drake Passage has been documented in studies by Toggweiler and Samuels (1995), and subsequently by Gnanadesikan (1999). Their reasoning leads to an elegant scaling, developed in Gnanadeskian (1999), in which the MOC's strength is highly sensitive to wind-stress inputs in the Antarctic Circumpolar Channel.

Separate work by Gordon (1986) also implicates Southern Hemisphere winds as able to influence MOC. In this case the wind stress off the southern tip of Africa modulates the transport of buoyancy anomalies from the Indian Ocean into the South Atlantic. Gordon's work also suggests the possibility that the MOC may be highly sensitive to wind stress in the Southern Hemisphere.

In the present study, we employ a climatological ocean circulation model and its adjoint to evaluate numerically the sensitivity of the MOC to surface wind stress. The adjoint model allows us to calculate global maps of sensitivity. These maps provide a geographic picture of where on the planet wind stress perturbations have the greatest impact on the meridional overturning.

2. THE MODEL

Two scenarios are investigated, allowing us to assess the impact of feedbacks between the ocean and the atmosphere. The first scenario is an ocean-only experiment, in which an ocean general circulation model is forced by passive fluxes derived from climatologies. The second scenario is a minimal "coupled" experiment, in which a simple energy and moisture balance atmosphere (Wang, 1999) is coupled to the ocean model to represent basic feedbacks between the ocean and the atmosphere.

The ocean model used in both scenarios is the MIT OGCM (Marshall et. al. 1997). It is configured with a realistic geography and bathymetry on a constant 4^ox4^o resolution horizontal grid with fifteen vertical layers. The Gent Mc-Williams eddy parameterization scheme is used in all simulations. Prior to performing sensitivity calculations, the model is integrated to an equilibrated state. The equilibrium spin-up is initialized from the Levitus climatology (Levitus 1994) and integrated forward for a period of 3000 years, after which the model is essentially equilibrated. The spun-up ocean-only climatology compares favorably with accepted estimates. The MOC's maximum volume transport is around 29Sv.

The coupled model is integrated for a further 3000 years. The equilibrated ocean state shows only minor differences from the ocean only case. Because of the zonal nature of the energy balance model, the sea surface temperature distribution is slightly more zonal than observations would suggest. The MOC peaks at 26Sv in the coupled model.

3. THE ADJOINT MODEL

Adjoint models provide the sensitivity of a diagnostic, often called cost function, to all model parameters in a single integration. In contrast, traditional sensitivity analyses are performed by repeated integrations of the so-called "forward" model, perturbing slightly the value of a single parameter at each integration. Our system of adjoint equations is developed from a differentiated form of the original model equations. It is generated automatically with the Tangent Linear and Adjoint Model Compiler (TAMC) (Giering & al., 1998). A more detailed description of this procedure can be found in Marotzke & al. (1999).

3.1. *Cost Function*

In this study we focus exclusively on the sensitivity of the MOC to the mean wind stress on centennial time-scales. The cost function is calculated by averaging the meridional streamfunction where it reaches its peaks, between 52 and 60^o N in the Atlantic basin:

$$\psi(\phi, z) = r \cdot \cos(\phi) \cdot \int_{\lambda_1}^{\lambda_2} \int_{z}^{z_B} v dz' d\lambda' \qquad (1)$$

$$\psi_{MAX} = \overline{\psi}(52 - 60^o N, 80 - 0^o W, 1055 - 1395m)$$

3.2. *Equilibration of the Adjoint Model*

For parameters that are time invariant such as the wind stress, sensitivities can be expected to asymptote to a constant value over time scales sufficiently long to include all the processes likely to influence the cost function. The sensitivity of the cost function to perturbations applied for a duration of 1-800 years is shown in figure 1 for two points selected at different latitudes.

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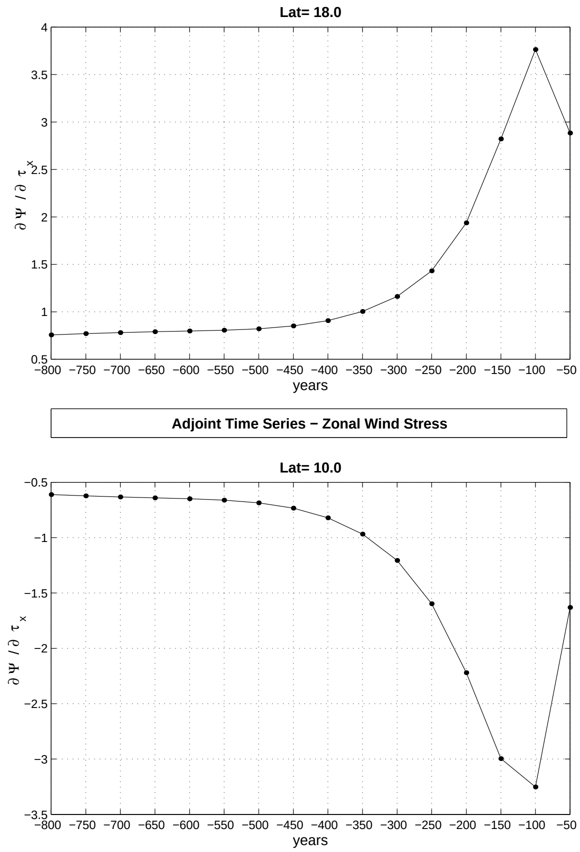

Figure 1. Time series of the sensitivity of ψ_{MAX} to the zonal wind stress $\partial\psi_{MAX}/\partial\tau_x$ in $SvN^{-1}m^2$ for points at two different latitudes

The equilibrium sensitivity to a constant wind stress perturbation imposed at 18^o N (top) is $\frac{\partial\psi_{MAX}}{\partial\tau_x}=0.8\frac{Sv}{Nm^{-2}}$. It is clear from this figure that most of the information, which will be obtained with the adjoint model, is present after approximately 400 years. The total integration time chosen for the adjoint calculations described in this article is, therefore, 400 years.

4. WIND STRESS SENSITIVITY

Several possible mechanisms exist by which wind stress can influence the MOC. Three hypotheses are discussed here.

4.1. The "Drake Passage" Mechanism

In a latitude band with no continental barriers, notably in the Antarctic Circumpolar Channel, zonal pressure gradients must vanish. Toggweiler and Samuels (1995) outlined the following hypothesis: the divergence of the Ekman transport in the latitude band of the Drake Passage can only be balanced geostrophically below the depth of the topographic ridges. The vertical flows associated with this circulation could draw up much of the deep water formed in the Northern part of the Atlantic.

4.2. The "gateway" mechanism

This hypothesis relies on a direct control of the properties, in particular of the salinity, of the water allowed to enter or leave the Atlantic basin. It rests on the premise that the Atlantic is the saltiest of the world's oceans. There are several "gateways", which are regions that control the flow of water in and out of the Atlantic basin. In particular, the Agulhas current and the Drake Passage allow water to flow into the Atlantic from the Indian and Pacific basins, the Indonesian archipelago allows the exchange of water between the Pacific and Indian oceans.

4.3. Equatorial upwelling

A final mechanism allows the wind stress to play an important role in the equatorial region. Wind induced Ekman upwelling increases the ocean's stratification, while the easterlies further shoal the thermocline on the eastern side of the basins at the equator. Both processes increase the efficiency of the vertical mixing of heat, which is balanced, in part, by upwelling.

5. SENSITIVITY EXPERIMENTS

The adjoint model can be used to evaluate which of the mechanisms outlined above the ocean circulation model favors.

5.1. The Ocean-Only Experiment

Three regions show high sensitivities to wind stress (figure 2): the region, which includes the Agulhas current, and the Agulhas retroflection south of the Cape of Good Hope, the Indonesian throughflow and the Chilean coastline

Toggweiler and Samuels (1995) hypothesized a control of the MOC's intensity through upwelling of North Atlantic Deep Water in the Southern Oceans. The Ekman transport is convergent near 40^oS and divergent South of 50^oS. This induces the Deacon cell with upwelling between Antarctica and 50^oS. Eddy-induced transports cancel much of the Deacon cell, but do not suppress it completely (Danabasoglu and McWilliams, 1995) Increasing the winds where they peak, near 50^oS, tends to intensify the Deacon cell. One could, therefore, anticipate positive sensitivities in that region throughout the Antarctic Circumpolar Channel, which is only partially verified. The absence of a strong band of positive sensitivities can be related to the surface boundary conditions used in this study.

Ekman upwelling is proportional to the curl of the wind stress, which in the Southern Oceans can be approximated by the meridional gradient of the zonal wind-stress.

$$\frac{1}{\rho f}\cdot\frac{\partial\tau_x}{\partial y}=w_E \qquad (2)$$

A perturbation analysis indicates that changes in wind stress can be balanced by upwelling and/or changes in the surface density:

$$\frac{1}{\overline{\rho} f} \cdot \frac{\partial \tau'_x}{\partial y} = w'_E + \frac{\rho'}{\overline{\rho} f} \cdot \frac{\partial \overline{\tau}_x}{\partial y} \qquad (3)$$

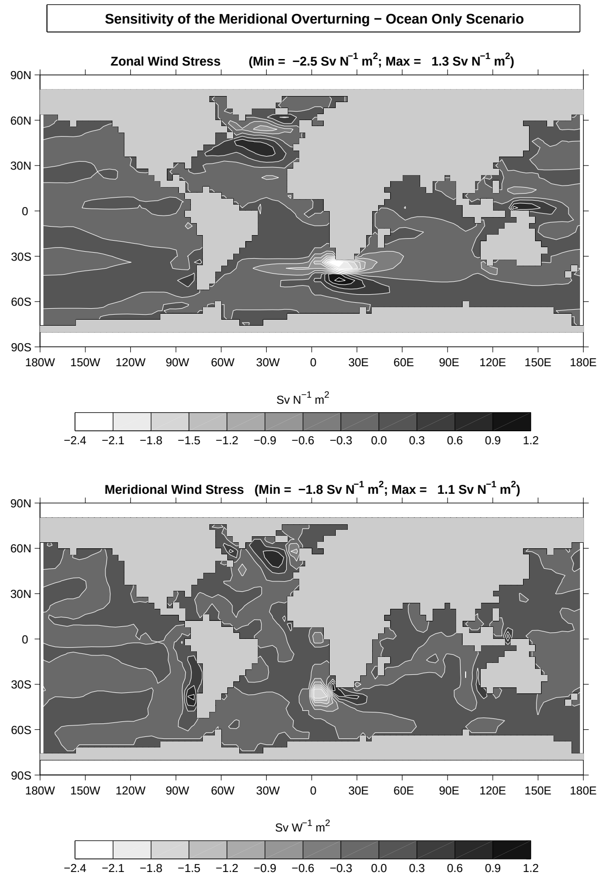

Figure 2. Sensitivity of ψ_{MAX} to the wind stress, both zonal and meridional: $\partial\psi_{MAX} / \partial\tau_{x,y}$ in $SvN^{-1}m^2$ in the ocean model.

Under the restoring boundary conditions used by Toggweiler and Samuels (1995), the surface density is nearly fixed and changes in the wind stress have to translate directly into changes in Ekman upwelling. However, under the mixed boundary conditions used here, a substantial fraction of the changes in wind stress can be compensated by local changes in density. In other words, baroclinic eddy transports can compensate much of the perturbation in the Ekman upwelling. For this reason no significant sensitivity of the MOC to Ekman upwelling is apparent in figure 2.

Strikingly the adjoint sensitivities do pick out the “gateway” regions very clearly. The sign of the sensitivity at the gateways is such that reducing the import of fresher water into the Atlantic basin enhances the meridional overturning. A westerly wind stress perturbation applied in the Agulhas current region reduces the import of fresher water into the Atlantic, eventually strengthening the meridional streamfunction. The same perturbation applied just south of the Agulhas retroflection promotes the export of salt out of the Atlantic, thereby eventually weakening the thermohaline circulation.

5.2. *Coupled Scenario*

The sensitivity of the cost function to the zonal and meridional wind stress in the coupled model is shown in figure 3.

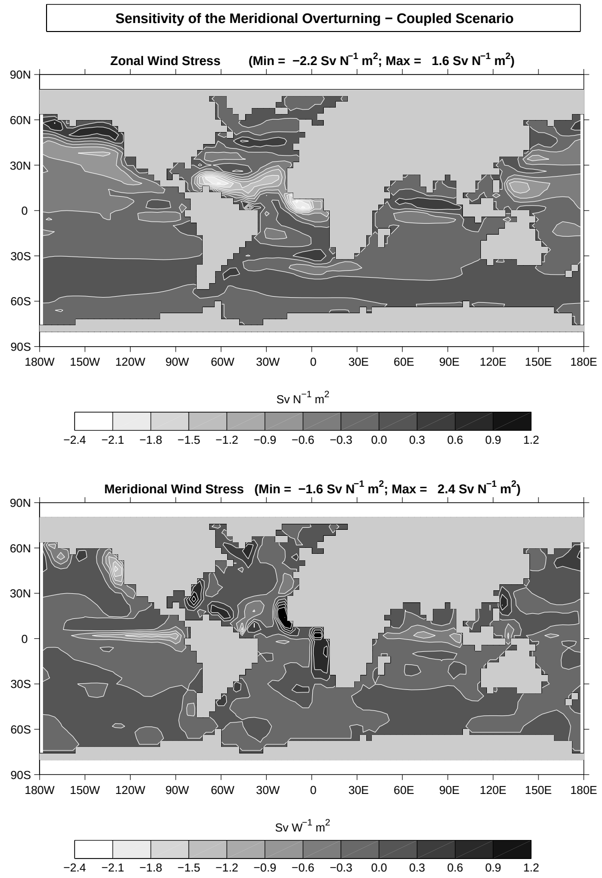

Figure 3. Sensitivity of ψ_{MAX} to the wind stress, both zonal and meridional: $\partial\psi_{MAX} / \partial\tau_{x,y}$ in $SvN^{-1}m^2$ in the coupled model.

The coupled model fixes only the net amount of heat and freshwater entering the world’s oceans. By allowing the surface density to respond freely to changes in wind stress, the sensitivity to τ_x in the Southern Oceans disappears completely (figure 3). Instead, the sensitivity is concentrated in the equatorial region where wind stress sustains the meridional overturning through direct Ekman upwelling and by increasing the ocean’s stratification and the effectiveness of diapycnal mixing. There is no evidence of either Drake Passage or gateway effects. The latter mechanism invoked a purely oceanic salt advection effect. While advective feedbacks are still present in the coupled model, they are dwarfed by the atmospheric feedbacks that link directly the tropics and the polar region where convection is taking place.

6. DISCUSSION

The absence of a band of strong sensitivities to wind stress in the Antarctic Circumpolar Channel, and in particular in the Drake Passage, suggests that the Drake Passage effect is an artifact of the restoring boundary conditions used by Toggweiler and Samuels (1995). More evidence was found in support of the “gateway” hypothesis and the role of the Agulhas region in controlling the exchange of water between the Atlantic and the other oceans. The role played by the gateways should be re-examined within the framework of a more complex coupled atmosphere-ocean model. It is potentially important, but can be short-circuited by the rapid transfer of energy and moisture in the atmosphere. In the model presented here it appears that it is equatorial rather than high-latitude wind-stresses that command the biggest influence on the MOC.

Our study shows that, in a climatological ocean model, air-sea boundary conditions are a crucial determinant of the wind-stress sensitivity. The climatology of the forward ocean model is credible and quite similar in both scenarios. However, including interactive atmospheric transports of heat and moisture changes the manner in which the ocean model state adjusts to changes in wind stress. Considering the role of both the atmosphere and the ocean when studying the climatological behavior of the MOC is, therefore, clearly important. Models which keep one or the other component fixed can lead to very different conclusions from models in which both components are represented.

It is quite possible that studies with higher resolution numerical tools that capture more processes explicitly will paint a different picture. For now, however, we are lead to conclude that the MOC is much more sensitive to wind induced dynamical processes in the equatorial belt than in the Southern Oceans

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