OCEAN MODEL DIAGNOSIS OF LOW FREQUENCY CLIMATE VARIABILITY IN THE SOUTH ATLANTIC REGION

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1. INTRODUCTION

The South Atlantic experiences significant climate variability on interannual to interdecadal time scales (e.g, Venegas et al., 1996, 1997) often with marked warm and cool events near coastal areas, such as the Benguela current region. The more pronounced warm events are known to have a strong impact on coastal fisheries and might cause rainfall variability over Southern Africa (Rouault et al., 2003).

There are a variety of possible mechanisms leading to significant warming and cooling in those regions. Some warm (cool) events occur during an El Niño (La Niña) event implying a relationship with ENSO (Reason et al., 2000). However other warm (cool) events appear to be unrelated to ENSO suggesting that other mechanisms such as internal basin modes,coupled modes and local windstress anomalies could play a role in creating these events.

In the following, we use the ORCA2 OGCM to identify the leading modes of the South Atlantic upper ocean temperature and will investigate in detail the physical processes, atmospheric forcing, heat and volume transports associated with these modes.

2. MODEL AND METHODS

ORCA is the global version of the OPA 8.1 Ocean modelling system. The OPA OGCM was developed at LODYC, Paris (Madec et al., 1998). It is a Cox-type OGCM and solves the primitive equations with a non-linear equation of state on a C-grid. Its spatial resolution is roughly equivalent to a geographical mesh of 2° by 1.5° (with a meridional resolution of 0.5° near the Equator).The 52 year simulation is forced by monthly NCEP climatological winds and heat fluxes.

Climate patterns of mixed layer temperatures, derived from the ORCA2 model output, NCEP/ NCAR SST and GISST SST are examined using varimax rotated empirical orthogonal functions (REOFs).

The temperature tendency equation for the mixed[1] layer temperature (see also Seager et al., 2003) has been used to investigate possible forcing mechanisms. It is given as:

$$\frac{\partial T_m}{\partial t} = -\left[\left(u_m\frac{\partial T_m}{\partial x}+v_m\frac{\partial T_m}{\partial y}\right)-\left(\frac{T_m-T_h}{h}\right)\left(u_m\frac{\partial h}{\partial x}+v_m\frac{\partial h}{\partial y}\right)\right] - \left[\left(\frac{T_m-T_h}{h}\right)\left(\frac{\partial h}{\partial t}+w_h\right)+\left(\frac{\overline{w'T'}}{h}\right)_h\right]+\frac{Q^{net}_{sfc}-Q^{pen}_h}{\rho c_p h} \tag{1}$$

where, *T_m*; *u_m*; *v_m* are the temperature and horizontal velocities vertically averaged over the depth *h* of the mixed layer, *T_h* is the temperature just below the mixed layer and *w_h* is the vertical velocity at the base of the mixed layer, *w_0*; *w'T'* are deviations from the mean, thus, the term describes the turbulent or Reynolds flux. *Qnet_scf* is the net surface heat flux, while *Qpen_h* is the amount of shortwave radiation that penetrates through the base of the mixed layer, *cp* is the specific heat capacity of ocean water, and *ρ* is the density of sea water.

3. OCEAN VARIABILITY

The rotated EOF analysis appears to divide the South Atlantic into four subdomains, each with typical time and spatial scales (Figure 1). These modes are (a) the tropical mode, with primarily interannual variability mainly located in the tropics and northern Benguela, (b) the north eastern subtropical mode, with variability between interannual and inter-decadal time scales, (c) the midlatitude mode, with variability on both interannual and inter-decadal time scales, forming an east-west oriented dipole in the midlatitudes and (d) the south western subtropical/ midlatitude mode, that fluctuates on an interannual and inter-decadal time scale. Correlation analyses between these modes and windstress suggests that all modes are primarily driven by the atmospheric circulation.

3.1 FORCING MECHANISMS

The forcing mechanisms behind the four modes have been investigated using lagged field-index regressions between all terms arising

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in Equation 1 and the expansion coefficients. Typical values for the four modes are calculated by taking averages over positive and negative values of the resulting regression fields respectively (Figure 2).

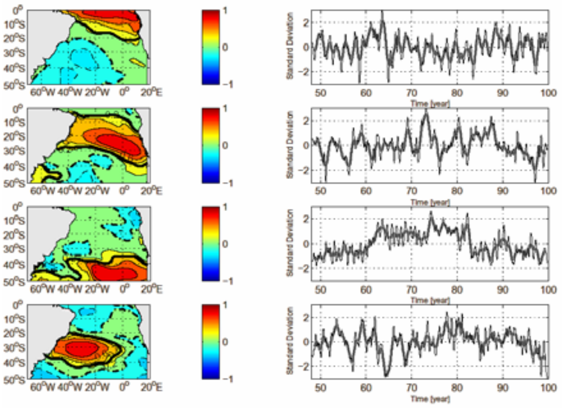

Figure 1: From top to bottom: First four rotated EOFs of ORCA2 MLT. Left: Spatial pattern as homogenous correlation maps, positive (negative) contour lines are solid (dashed), zero contour line is dashed-dotted, the contour interval is 0.2. Right: Corresponding time series normalized by their standard deviation. The raw time series is in shown black. The grey line represent the time series smoothed with a one year running mean. Significant regions are within the thick line.

First REOF

The first mode is connected to anomalous northeasterly windstresses that reduce the prevailing trades in the central to western tropical region. Hence, surface latent heat fluxes are reduced, leading to warming there. Furthermore, these anomalous winds tend to reduce the zonal component of the south-westward directed upper ocean mean currents. Thus, less cold water is transported towards the western tropics, favouring warming there.

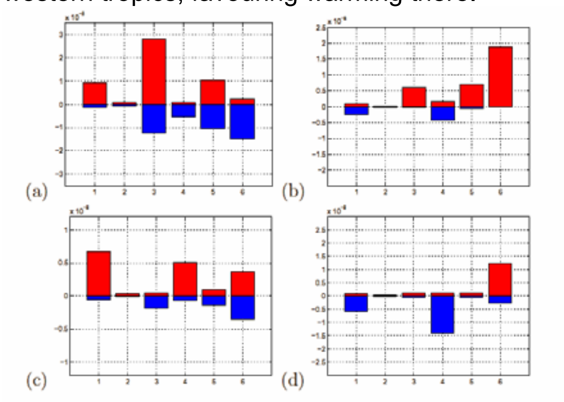

Figure 2: Bar diagram of the lagged regression analyses between the different terms of Equation (1) and the first four REOF(MLT).

The windstress anomalies do not favour warming over the eastern tropics and northern Benguela region, suggesting non-local atmospheric influences such as equatorial Kelvin wave propagation being responsible in creating these temperature anomalies (as suggested by Carton and Huang, 1994; Florenchie et al., 2003). In fact, strongest warming associated with this mode occurs during 1963, which was a 'Benguela-Nino' year (Shannon et al., 1986), suggesting a possible connection between this mode and these events. However, although other strong warm events such as the one in 1984 are captured by the time series of this mode, they are not as extreme as the one in 1963. Nevertheless, the above analysis suggests that warming in the central to eastern tropics is connected to reduced upwelling mainly due to reduced vertical entrainment and, to lesser extent, reduced turbulent mixing. The mode analysed in this paper shows strong similarities with the Atlantic Zonal Gradient Mode (also Equatorial Mode), described by Zebiak (1993); Enfield and Mayer (1997); Carton et al. (1996); Ruiz-Barradas et al. (2000).

Second REOF

The second mode is connected to reduced trade winds over the subtropics. These lead to changes in the latent heat flux, which in turn alter upper ocean temperatures. Changes in horizontal advection and vertical mixing processes make smaller contributions to the observed ocean temperature changes. The timing and spatial structure of this mode suggests a connection to ENSO, which is in agreement with Reason et al. (2000), Sterl and Hazeleger (2003), Colberg et al. (2004). In addition, it is found that trade wind modulations significantly alter the Ekman related meridional volume and heat transport, which in turn lead to changes in the gyre circulation and thus geostrophic related volume and heat transports. These anomalous transports are strongest in the Benguela ocean current region and reach depths of up to 300m.

Third REOF

For the third mode, the midlatitude westerlies are weakened and result in a reduced northward directed Ekman heat transport, which leads to warming in the central to eastern midlatitudes. Wind induced mixing here becomes increasingly important, in agreement with Sterl and Hazeleger (2003). However, inter-decadal variability is associated with changes in the geostrophic currents that alter the north (south)-ward owing Falklands/ Malvinas (Brazil) current, bringing cooler (warmer) water into the area. This mode may be connected to the interdecadal SST signal found by Wainer and Venegas (2001).

Fourth REOF

Upper ocean temperature anomalies for the fourth mode respond to changes in the net heat flux, which is increased (reduced) during warm (cold) phases. Associated with this mode are changes in the strength of the South Atlantic anticyclone, which mainly acts to enhance (reduce) entrainment during positive (negative) phases and thus dissipates the observed temperature anomalies.

4. CONCLUSIONS

The results of this study suggest that the ORCA2 model output can be usefully applied to diagnose the major modes of South Atlantic variability and the mechanisms associated with them. The advantage of the model output becomes most apparent when examining the meridional heat transport associated with the second leading mode and in the analyses of the midlatitude mode, where advection of heat is partly due to the baroclinic structure of the ocean, which cannot be diagnosed from surface based data sets. The results also emphasize the importance and dependence on the choice of statistical tools used to diagnose the leading modes. The rotated EOF analyses results in more localized structures of the analysed fields, and as a consequence, the tropical and subtropical modes are clearly separated from each other.

There are implications for both regional and global scales suggested by this study, e.g., the second leading mode is associated with anomalous heat and volume transports and gyre modifications, which in turn may affect the global heat balance and thus the thermohaline circulation. This study provides evidence that upper ocean temperature anomalies in coastal regions, e.g., the Benguela, are strongly affected by the large scale modes, implying variability on interannual to decadal time scales there and this has implications for understanding of the occurrences of extreme warm/ cool events in this region. The Benguela upwelling system contains one of the richest regional fisheries in the world and supports a high marine biodiversity, thus better understanding of the variability and sensitivity to large scales modes is a high priority.

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