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Southern Ocean Intrinsic and Forced Modes of Low Frequency Variability in an Ocean General Circulation Model

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Abstract

A coupled Ocean-Sea ice General Circulation Model (OGCM) is used to identify a Southern Ocean southeast Pacific intrinsic mode of low frequency variability. This mode is co-located with a major region of Sub-Antarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) formation. Using CORE data a comprehensive suite of experiments were carried out to elucidate excitation and amplification mechanisms of this intrinsic mode by low frequency forcing (ENSO, SAM) and stochastic forcing due to high frequency winds. Subsurface thermocline anomalies were found to teleconnect the Pacific and Atlantic regions of the Antarctic Circumpolar Current (ACC). The Pacific region of the ACC is characterised by intrinsic baroclinic disturbances that respond to both SAM and ENSO, while the Atlantic sector of the ACC is sensitive to higher frequency winds that act to amplify thermocline anomalies propagating downstream from the Pacific resonant with eastward travelling Rossby waves. This simulation study identifies plausible mechanisms that determine the predictability of the Southern Ocean climate on multi-decadal timescales.

Introduction

The domain of the Southern Ocean encircles the globe and is characterised by large variability with a considerable low frequency component. The Southern Ocean directly links all the major ocean basins allowing water mass exchange at depth shallower than Drake Passage via the eastward flowing Antarctic Circumpolar Current (ACC). In addition the Southern Ocean is a region in which key climate water mass formation occurs - Antarctic Bottom Water, Antarctic Intermediate Water and Sub-Antarctic Mode Water masses - that substantially influence the ocean heat uptake and carbon sequestration [8]. In addition the expansive seasonal sea-ice zone affects surface albedo and ice-ocean-atmosphere heat exchanges. Thus, the Southern Ocean is an important control on mean global climate and in transmitting climate signals around the globe.

Interannual variability has been often observed at high southern latitudes. Observations of oceanic Rossby waves [3] suggest that such features propagate eastwards around the Southern Ocean. Hughes (1995) [3] modelled Rossby waves in the Southern Ocean showing that they occur at a natural scale of approximately 300 km, and in two distinct regions: within the CORE of the ACC (strong interaction with the mean flow and eastward propagating with the current) and outside the ACC (nearly linear and westward propagating). Their study divides the Southern Ocean into two dynamical flow regimes subcritical and supercritical with regard to the wave speed. The eastward travelling waves point along the direction of the mean flow acting to accelerate the eastward flowing jets. Hughes (1995) [3] further showed that such waves exist in the southeast Pacific sector of the Southern Ocean in TOPEX/POSEIDON altimetry data. They demonstrated that Rossby waves are an important conduit for propagating information within the boundaries of the ACC and that eastward propagating ACC Rossby waves had maxima in the region of $58^\circ S$:$150^\circ W$.

Dijkstra and Ghil (2005) [2] showed that intrinsic oceanic mechanisms alone can, under certain conditions exhibit strong low-frequency variability in highly nonlinear western boundary current extensions. A recent process study by Quattrocchi et al (2012) [7] employed an eddy-permitting reduced-gravity nonlinear shallow water model of an idealized North Atlantic Ocean to analyse the low-frequency variability due to intrinsic oceanic processes of the Gulf Stream. This study found that, for the Gulf Stream extension, intrinsic low-frequency variability was between two preferred latitudinally varying states. Further analysis of the variability in terms of dynamical systems theory showed a complex transition sequence from a steady state to irregular low-frequency variability emerges characterised by Hopf and global bifurcations. Pierini (2011) (see Quattrocchi et al (2012) [7] and references therein) introduced the concept of coherent resonance to describe the effect of including a time dependent wind forcing on the intrinsic low-frequency variability of the Kuroshio Extension (KE).

While there is a now a body of literature using idealised model studies to suggest that intrinsic low-frequency variability and multiple equilibria due to nonlinear mechanisms internal to the ocean system may be present in both the North Atlantic and North Pacific western boundary current extensions there are no studies that we are aware of using state of the art primitive equation models and definitely no studies of intrinsic processes in the Southern Ocean (SO) and the Antarctic Circumpolar Current (ACC). It is therefore of great theoretical and practical interest to investigate how nonlinear internal ocean dynamics contributes to the low frequency variability of the SO.

To identify any intrinsic processes/modes capable of producing low frequency variability in the Southern Ocean we use climatological or nominal year atmospheric forcing provided by time-independent surface wind stresses obtained from the CORE1 surface wind fields. We then take a systematic approach, separately adding SAM, ENSO and higher frequency components to the nominal year forcing. In this manner we identify the mechanisms that drive ocean low frequency variability in the ACC and in particular the Pacific and Atlantic in sectors.

Model description

The model we use is the Australian Community Climate Earth System Simulator-Ocean (ACCESS-o) configuration of the GFDL MOM4p1 ocean-ice code [1]. Our configuration is mass conserving - non Boussinesq using p^* pressure coordinates scaled with height in the vertical. Weak restoring is applied to the surface salinity of the top layer (equivalent thickness of 10 m) which is relaxed to world ocean atlas (WOA09) fields with a time scale of 60 days to reduce drift. We use the TEM [5] generalization of the Eliassen and Palm flux approach to transport of passive tracers, temperature and salinity and the KPP mixing scheme in the vertical.

We employ the tripolar ACCESS-o ocean model grid [9]. This grid is a 360×300 logically rectangular horizontal mesh, overlying an orthogonal curvilinear grid whereby a singularity at the north pole is avoided by using a tripolar grid following Murray (1996) [6]. This approach also provides reasonably fine resolution in the Arctic Ocean while at the same time enhancing computational efficiency. Along the curvilinear zonal direction ACCESS-o has a regular spaced grid with 1° resolution. In the meridional direction the grid spacing is nominally 1° resolution, with the following three refinements:

- tripolar Arctic north of $65^\circ N$
- equatorial refinement to $1/3^\circ$ between $10^\circ S$ and $10^\circ N$ and
- a Mercator (cosine dependent) implementation for the Southern Hemisphere, ranging from 0.25° at $78^\circ S$ to 1° at $30^\circ S$. In the vertical direction, ACCESS-o implements the z^* coordinate available in MOM4, with 50 model levels covering 0-6000 meters with a resolution ranging from 10 meters in the upper layers (0-200 meters) to about 333 meters for the abyssal ocean. Although not eddy resolving this model has sufficient resolution to resolve Southern Ocean Rossby waves and energy transfers associated with transient disturbances that may become resonant with the resolved Rossby waves. Because of the prohibitive computational cost of eddy resolving models and the need for $> 1000yr$ spinup runs to achieve steady state the model resolution described represents a practical compromise to enable the study of decadal to climate timescale ocean dynamics.

CORE experiment design and diagnostics

Experiment configurations

This study employs atmospheric fields from the Coordinated Ocean-ice Reference Experiments (COREs) [4] for global ocean-ice modelling. For our experimental configuration we use the CORE.v1 nominal year forcing and the CORE.v2 interannually varying forcing (1948-2007) (hereafter CORE1 and CORE2 respectively). Both CORE1 and CORE2 are supported at NCAR and GFDL for use in studying global ocean-ice dynamics and the CORE datasets, support code, and documentation were accessed from the GFDL MOM4 Data Sets website (http://data1.gfdl.noaa.gov/nomads/forms/mom4/COREv1.html and COREv2.html).

The spinup uses CORE1 forcing with climatological atmospheric fields that are converted to air-sea fluxes with bulk formulas. The initial condition for temperature and salinity fields come from World Ocean Atlas 09 (WOC09), and the model was run until a quasi-steady state with negligible drift was achieved (of the order of 1000 years). The spun up ocean state is used as an initial condition for all experiments reported herein. Intrinsic modes of variability are analysed with CORE1 forcing and inter-annual variability using CORE2 forcing. In addition to these experiments, we examined the dynamical mechanisms driving the Southern Ocean variability with experiments forced with CORE1 fields plus various combinations of the constituent modes of low frequency variability from the CORE2 data, namely the Southern Annular Mode (SAM) and the El-Nino Southern Oscillation (ENSO). Winds over the Southern Ocean from the CORE2 data set were reduced to empirical orthogonal functions (EOFs), with the first component the SAM and a combination of the second and third components ENSO. The zonal winds in the experiment testing the SAM mechanism were constructed by adding a 12-month smoothed first EOF component of CORE2 winds to CORE1 over the Southern Ocean south of 30°S with CORE1 forcing applied everywhere else. ENSO winds were similarly constructed by adding the second and third EOF components. The meridional component of the winds of these two modes were constructed by regressing the zonal winds of the two modes on the full meridional winds. Additional high-frequency configurations are used to examine the response to the stochastic weather noise atmospheric forcing over the Southern Ocean. Two high-frequency fields were considered: (1) CORE2 with the SAM and ENSO variability removed (CORE2-SAM-ENSO) and (2) a 12- month boxcar filter has been applied to the CORE2 winds to remove all low frequency inter-annual variability (CORE1+HFREQ). In all "mode" experiments only the winds are changed while the CORE2 experiment a full set of interannually varying forcing fields is used.

Diagnostics

Our initial diagnostics involve principal component analysis (PC) (Fig. 1) to ascertain the spatial patterns and explained variance for each model simulation and forcing configuration. In all cases the seasonal cycle has been removed from the anomalies prior to calculating the EOFs and PCs. In order to diagnose whether the growth, relative strength and pathways of ACC anomalies are due to barotropic and/or baroclinic disturbances of the mean flow we examined two mean-transient energy transfer terms (Mean Kinetic Energy (MKE) to Transient Kinetic Energy (EKE) (not shown); Mean Potential Energy (MPE) to Transient Potential Energy (EPE)) by expressing all variables into time-means (overbar) and fluctuations (prime). For potential energy this term can be expressed as:

$$MPE \to EPE = \frac{\overline{u'\rho'}\frac{\partial\tilde{\rho}}{\partial x} + \overline{v'\rho'}\frac{\partial\tilde{\rho}}{\partial y}}{\frac{\partial\tilde{\rho}}{\partial z}} \quad (1)$$

where ρ is the potential density and $\tilde{\rho}$ is the reference state approximated as the horizontal average of the time mean. u and v are the horizontal velocity components x and y the zonal and meridional directions respectively. These energy transfer terms are calculated using 100 (CORE1) and 60 (CORE2 and component simulations) years of output from the ACCESS-o Ocean-Ice configuration. The transfer rate between mean kinetic energy and transient kinetic energy, that is the work of the Reynolds stresses on the mean shear, can be associated with growing barotropic disturbances (positive values). Eq. 1 represents the transfer of mean potential energy to transient potential energy through baroclinic disturbances about the mean flow. Positive (negative) values in Eq. 1 indicates the generation (dissipation) of potential energy respectively of the mean flow. Transient mechanisms are involved with both the generation and dissipation of potential energy to and from the mean flow.

Mechanisms

In comparison to the CORE1 experiment, the CORE2 experiment features more extensive regions of coherent kinetic energy transfers and in particular in the region of the ACC $150^\circ E$ and $180^\circ W$ south of the Tasman Sea (not shown). For CORE2 significant barotropic disturbances occur in the region $150-130^\circ W$, $50-60^\circ S$ where the ACC flows over the East Pacific Rise including the Eltanin ($52^\circ S$) and Udinstev ($58^\circ S$) fracture zones and at $10^\circ W$, $58^\circ S$ in the Atlantic. In the Pacific barotropic disturbances are typically weaker in CORE1 relative to CORE2 and there are no significant regions of barotropic transfers in CORE1 outside of the Pacific. Potential energy (PE) transfers were found to illustrate the role of inter-annual atmospheric forcing in amplifying baroclinic processes in the ACC, and in particular in the Pacific, with apparent wave train

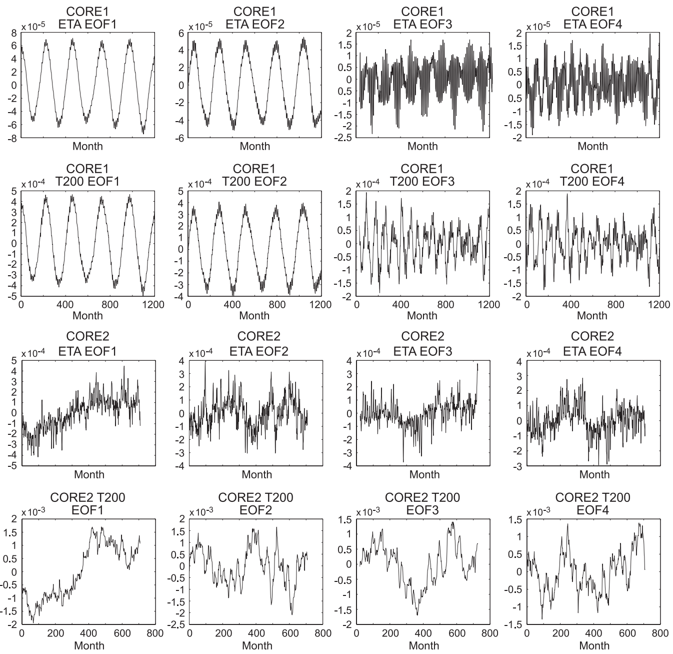

Figure 1: Principal components corresponding to the 1st 4 EOFs (left to right). (Row 1) CORE1 sea surface height (SSH), (Row 2) CORE1 temperature at 200m (T200), (Row 3) CORE2 SSH, (Row 4) CORE2 T200

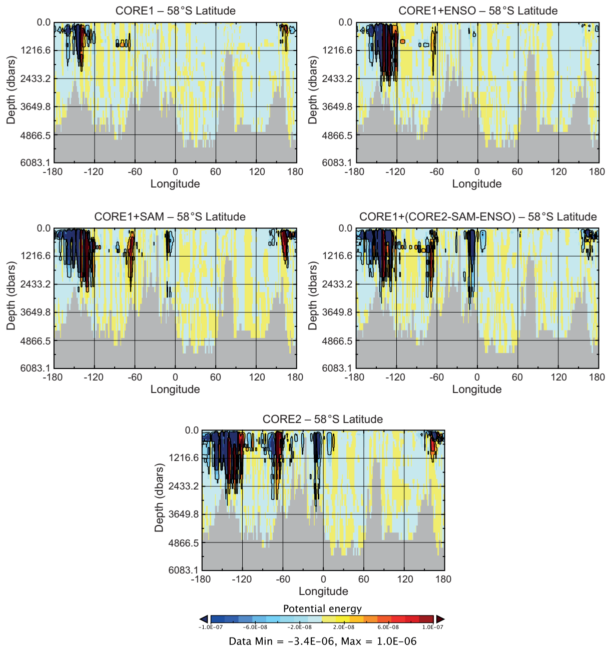

Figure 2: Potential energy transfer along latitude $58°S$ (Eq. 1 scaled by $1/g$). Forcing configurations are (Top row) CORE1 (left), CORE1+ENSO (right). (Middle row) CORE1+SAM (left), CORE1+CORE2-SAM-ENSO (right). (Bottom row) CORE2. Units are $10^3 kg\ m^{-2} s^{-1}$

structures extending from south of Australia $120°E$ to the Atlantic $30°W$. For CORE1 the region in the Pacific at 150°W of the East Pacific Rise, after the ACC passes through Eltanin and Udinstev fracture zones, defines the location where the flow is predisposed to be being intrinsically unstable. At this location, low frequency variability occurs due to unique topography that the ACC encounters steep topography at the rise and a downstream flat abyssal plain. CORE1 intrinsic mode calculations show the Drake's Passage as a choke point for the eastward propagating baroclinic disturbances that were generated/amplified at the East Pacific Rise and resonant with the eastward propagating Rossby waves. These intrinsic baroclinic disturbances are typically an order of magnitude weaker to those found in the CORE2 simulation but are typically of larger scale and more coherent (i.e. less variable) in the ACC with a regular 20 year period.

Sections along $58°S$ (Fig. 2) show the vertical structure of PE for each of the respective forcing experiments. Both CORE1 and ENSO runs show regions of baroclinic processes are localised about the thermocline in the Pacific ($150-130°W$) over and downstream of East Pacific Rise and in a region along the Chilean coast ($60°W$). The enhanced vertical extent of baroclinic processes in the CORE1+ENSO forced case relative to the intrinsic CORE1 clearly demonstrates the role of ENSO in driving baroclinic transfers in the Pacific. The SAM also drives the long timescale disturbancs in the ACC (Fig. (2 middle left) exhibiting an enhanced signal between $150°E$ and $180°W$ relative to the CORE1 and CORE1+ENSO simulations.

The role of the high frequency winds in driving long-lived thermocline disturbances is further illustrated in Fig. 2 (middle right). Here we see an almost equivalent response in the Pacific to the CORE1+SAM case but now with additional significant response in the Atlantic near $0°E$. We also see evidence of a pathway for baroclinic disturbances propagating at depth $\approx$ 800dbars between the East Pacific Rise and Drake Passage ($60°W$). Baroclinic processes in the CORE2 experiment may superficially be regarded as a superposition of the preceding CORE1 experiments but with the significant addition of an anomaly pathway emanating from the Pacific and teleconnecting to the Atlantic. There is no evidence of long timescale baroclinic (or barotropic) processes in the ACC in the greater Indian Ocean between $15-150°E$.

Summary and Conclusions

Our study finds that there exists a nonlinear relationship between model atmospheric forcing, Rossby waves and thermocline disturbances (and although not discussed here sea-ice variability). We have demonstrated that decadal scale intrinsic modes of low frequency variability are present in a non-eddy resolving model with sufficient Southern Ocean resolution to resolve Rossby waves and to enable the development of intrinsic low frequency variability in the Pacific sector. We find that large scale coherent wave-trains of potential energy transfer structures coincident with significant density gradients are generated in the region of the East Pacific Rise, whereas kinetic energy is much more small scale and highly localised with little or no amplitude away from significant topographic peaks at the Rise. Thus we surmise that the intrinsic variability observed in the Pacific arises largely due to baroclinic processes. Further it is shown that the intrinsic mode may be amplified by either or both of the low frequency SAM and ENSO modes of variability present in the CORE2 reanalyses atmospheric forcing dataset. In the Pacific, both SAM and ENSO excite the intrinsic ocean mode with SAM producing a larger amplitude disturbance than ENSO. In the Atlantic ENSO is ineffective at generating significant variability exciting little or no baroclinic disturbances. While the SAM only generates modest largely unstructured variability it is more effective at exciting a baroclinic response. In contrast, year to year changes in the high frequency weather patterns are found to be the dominant mechanism driving subsurface disturbances in the Atlantic. High fre-

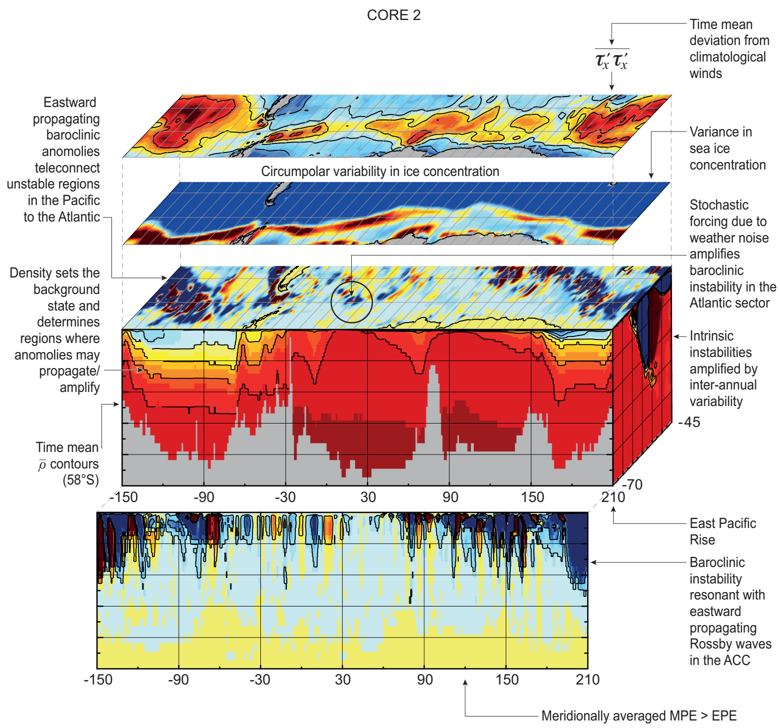

Figure 3: CORE2 schematic of inter-annual variability.

quency winds also act to excite a significant response in the Pacific, although weaker than either of the SAM or ENSO modes.

We summarise the mechanisms driving low frequency variability in the Southern Ocean thus (see Fig. 3):

1. There exists an intrinsic mode in the Pacific centred on 150°W 58°S associated with large density gradients and thermocline anomalies above and east of the East Pacific Rise. The variability of this mode is set by the flow topology and deterministic baroclinic (propagating), and to a lesser extent barotropic (localized), disturbances.

2. The intrinsic mode identifies the most unstable region of the ACC which may be further excited by either of the low frequency atmospheric forcing modes of variability (SAM and ENSO).

3. In order for low frequency variability in the Atlantic sector of the ACC to occur, thermocline anomalies are required to propagate from the Pacific through Drake's Passage to the region between 10°E-10°W where the density structure is such that they may amplify. Baroclinic disturbances resonant with eastward propogating Rossby waves are the mechanism by which this teleconnection is achieved. While variability due to the SAM alone could allow thermocline anomalies to propagate to the Atlantic it was found that stochastic forcing due to the high frequency weather noise was the most efficient mechanism for this to occur. Stochastic forcing was further required as an amplification mechanism of nascent baroclinic disturbances in the Atlantic. Moreover it was shown that stochastic forcing in and of itself was sufficient to induce thermocline variability on timescales longer than the intrinsic mode (> 20 years).

References

[1] Delworth, T., Broccoli, A., Rosati, A., Stouffer, R., Balaji, V., Beesley, J., Cooke, W. and Dixon, K., GFDL's CM2 global coupled climate modelsPart 1: Formulation and simulation characteristics, *J. Climate*, **19**, 2006, 643674.

[2] Dijkstra, H. and Ghil, M., Low-frequency variability of the largescale ocean circulation: A dynamical systems approach, *Rev. Geophys.*, **43**, 2005, RG3002.

[3] Hughes, C., Rossby waves in the Southern Ocean: A comparison of TOPEX/POSEIDON altimetry with model predictions, *J. Geophys. Res.*, **100**, 1995, 15,933–15,950.

[4] Large, W. and Yeager, S., Diurnal to decadal global forcing for ocean and sea-ice models: the datasets and flux climatologies., *NCAR Technical Note:*, **NCAR/TN-460+STR, CGD Division of the National Centre for Atmospheric Research.**

[5] McDougall, T. and McIntosh, P., The temporal-residual-mean velocity. Part I: Derivation and the scalar conservation equations., *J. Phys. Oceanogr.*, **26**, 1996, 2653.

[6] Murray, R., Explicit generation of orthogonal grids for ocean models.., *Journal of Computational Physics*, **126**, 1996, 251–273.

[7] Quattrocchi, G., Pierini, S. and Dijkstra, H. A., Intrinsic low-frequency variability of the gulf stream, *Nonlinear Processes in Geophysics*, **19**, 2012, 155.

[8] Sloyan, B., Talley, L., Chereskin, T., Fine, R. and Holte, J., Antarctic intermediate water and subantarctic mode war. fineter formation in the southeast pacific: The role of turbulent mixing, *J. Phys. Oceanogr.*, **40**, 2010, 1558–1574.

[9] Uotilla, P., O'Farrell, S., Marsland, S. and D.Bi, A sea-ice sensitivity study with a global ocean-ice model, *Ocean Modelling: In Press*, 18 pages.