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Simulation of Southern Indian Ocean Currents with σ and z Coordinate Ocean Models

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Abstract—The Southern Indian Ocean (SIO) is dynamically important because it connects three major world oceans. Observations in the SIO are few so modeling is most appropriate to study the region. Simulation of SIO is performed with two Ocean General Circulation Models (OGCMs): σ coordinate Ocean model POM and z - coordinate model MOM3.0 and their results are compared. It is shown that the σ coordinate model is better in simulating coastal currents. It is also shown that wind stress is the major forcing for this part of Indian Ocean.

INTRODUCTION

The Southern Ocean is the only ocean which is connected to the Pacific, Indian and Atlantic Oceans with a zonally uninterrupted current flow throughout the year. The Antarctic Circumpolar Current (ACC) is one of these currents; it is the strongest of the world ocean currents and is dynamically important. This current extends from 45°S to 55°S (Trenberth *et al.*, 1990; Orsi *et al.*, 1995) and the transport in the Drake Passage is estimated at 130 Sv (1Sv = 10^6 m^3 s^{-1}) (Nowlin & Klinck, 1986). Eastward wind stress is the major accelerator of this current, however, it has been shown that thermohaline processes are also responsible (Olbers & Wubber 1991).

The circulation in the Southern Ocean is not restricted to the upper few hundred meters of the ocean, but extends to great depths so the topography of the ocean floor has more impact on the currents and on the hydrology than in any other ocean. The bottom topography of the Southern Ocean shows that this region consists of different basins (depth greater than 4000 m) and ridges that effect ACC transport.

Only satellite-based data is available and observational stations are sparse in the Southern Ocean region, and for the region south of 45°S high quality data is still unavailable. Unlike the tropics, the dynamics of this important region are still not fully understood and the only way to study them and the circulation in this region is by modeling. In the present work we have attempted to discuss circulation features for the region 0°E to 150°E and 25°S to 70°S in order to include the Southern Indian Ocean (SIO) and adjoining portions of the Atlantic and Pacific Oceans. A sensitivity experiment has also been performed with variable model resolution on a sigma coordinate Ocean General Circulation Model (OGCM).

The sigma coordinate ocean is better in simulating flow over sills, continental shelves and bottom boundary layers, so it is widely used for coastal regions and estuaries. The bottom layers are well represented in the model by a single layer but the sloping bottom can not be modeled by z-

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coordinate ocean models by a single layer and a multi layer structure produces a step like structure, which is not a better representation (Ezer & Mellor, 1997). Baroclinicity and bottom relief jointly drive the circulation (Ezer & Mellor, 1994) so the effect of bottom topography cannot be ignored and there is need of a comparative study of circulation produced by the σ and z coordinate models. These comparative studies were done earlier for large-scale processes (Gerdes, 1993), Gulf Stream dynamics (Willems *et.al.,* 1994) and coastal processes (Haidvogel & Beckman, 1999). This is the first time that Princeton Ocean Model (POM) is configured for the entire SIO and run for a sufficiently longer time.

MODEL SETTING AND DATA

The POM used here was developed by Blumberg & Mellor (1987) and Mellor (1996) and is a primitive equation, sigma coordinate, free surface, which uses a turbulent closure mixing scheme (Mellor & Yamada, 1982). Model bottom topography is shown in the figure (1), bottom topography of 5' resolution of terrain base is used and interpolated to a model grid. The sigma coordinate has 14 vertical layers (σ = 0.0, -0.002, -0.004, -0.009, -0.018, -0.036, -0.071, -0.143, -0.286, -0.429, -0.571, -0.714, -0.857, -1.0) the resolution is fine for the upper 8 layers and coarse for the lower 5 layers and $\sigma = (z-\eta)/(H+\eta)$ where $\eta(x,y)$ and $H(x,y)$ are the surface elevation and water depth respectively. The model has a split time step: a two dimensional external time step of 25 s and a three dimensional internal mode time step of 750 s. The model grid extends from the deep ocean to 10 m depth on the coastal region to shallow region in the model simulation. The maximum grid between two adjacent grid points is $\Delta H/H < 0.2$.

The model was initialized with the yearly climatology from the Levitus (1994) atlas for temperature and salinity and forced with monthly climatology wind stress of 1°x1° of the Comprehensive Ocean-Atmosphere Data Set (COADS) analyzed by da Silva *et al.* (1994). A Smagorinsky-type horizontal diffusion (Smagorinsky *et al.*, 1965) is used here such that the diffusion coefficient is calculated according to

$$A_M = C\Delta x\Delta y\left[\left(\frac{\partial u}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right]^{1/2}$$

where u and v are the horizontal velocity component and C is a coefficient taken here as 0.2.

Model domain extends from Antarctic continent to northern boundary that includes major subtropical gyres of Southern Ocean; area extending from 0°E to 360°E and 70°S to 25°S. The model is run for 15 years for proper spin up but circulation pattern of SIO is discussed only. The

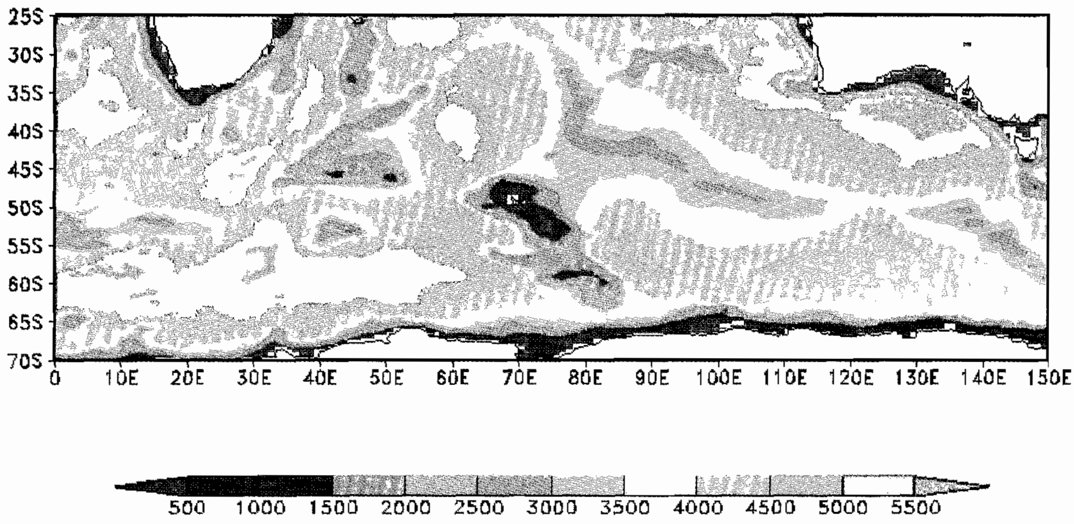

Fig. 1. Bottom topography of the model domain (contour interval is 500 meters)

northern region is chosen such that it includes most of the gyres of Southern Ocean hence insulating ACC from the effect of northern boundary. This enables the influences of only wind stress forcing and bottom topography instead of boundary effects of northern hemisphere. This domain not only includes the southern part of Southern America, but South Africa, southern Australia and New Zealand as well.

The results of POM are compared with a z-coordinated OGCM (MOM3.0) configured globally and run for 25 years. This enables us to show the ability of the sigma coordinate model for better simulation of coastal regions. MOM3.0 is a version of the GFDL Modular Ocean Model (Pacanowski *et al.*, 1993; Huang & Schneider, 1995; Schneider *et al.*, 1999). Its domain is that of the world oceans between 74.25°S and 65°N. The zonal resolution is 1.5°and the meridional resolution is 0.5° between 10°N and 10°S, gradually increasing to 1.5° at 20°N and 20°S and there are 25 levels in the vertical. The original surface reanalysis is on an irregular grid with a zonal resolution of 1.875° and Gaussian latitudes of grid spacing less than 2°, which is linearly interpolated to the OGCM grids. The model surface salinity is relaxed to Levitus (1982) monthly climatology. Surface heat flux is also relaxed to Levitus (1982) climatology and relaxation time is 100 days.

Another experiment is also performed with POM with same initial condition, boundary conditions, but with finer resolution of 1° x 0.25°. Here the source of wind stress forcing is from da Silva *et al.*, (1994) climatology of 0.5° x 0.5° and interpolated to model grid.

RESULTS AND DISCUSSION

Figure (2) shows the long term mean surface current of Southern Indian Ocean (SIO). The model is simulating almost all major currents of this part of Indian Ocean. The major uninterrupted ACC is well seen between 40°S to 60°S and its velocity is between 20 cm/sec to 40 cm/sec, which is in agreement with observational and modeling studies (Klinck & Nowlin, 2001). The second important current system simulated by the model is the

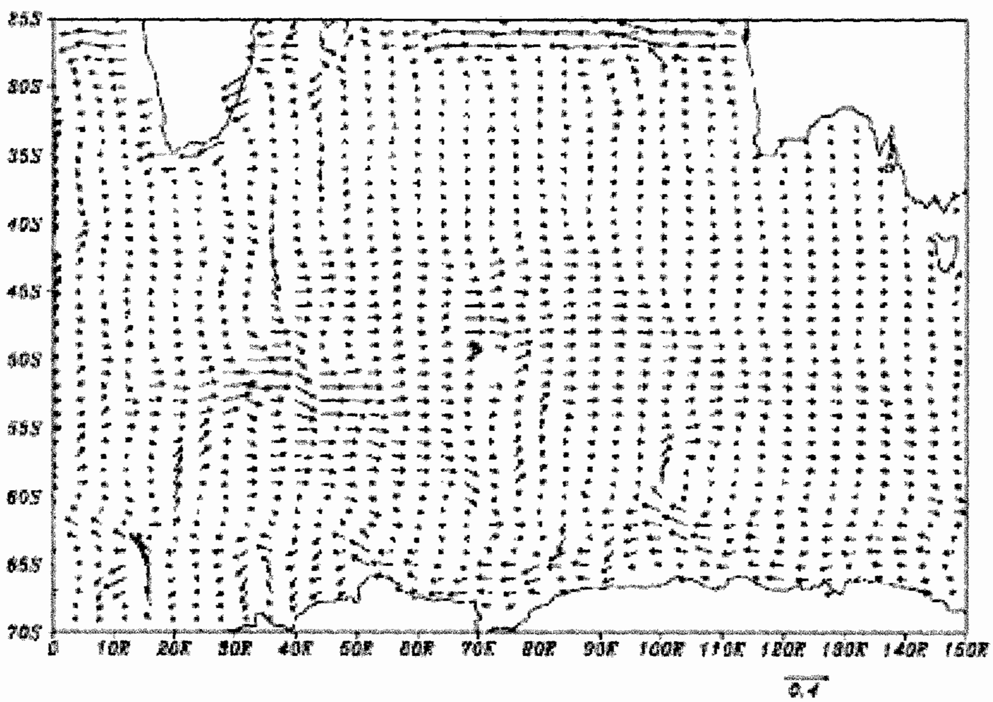

Fig. 2. Long-term mean of surface current in the Southern Indian Ocean simulated by POM with spatial resolution of 1° X 1° (arrow length of 0.5 cm represents current speed of 40cm/sec)

Agulhas current, which is the major western boundary current of Southern Ocean. The retroflection (Peterson & Stramma, 1991; Stramma & England, 1999) separation of this current from the southern tip of South Africa is seen, which makes a balance between viscosity and inertia in a fluid moving across latitudinal lines. Some parts retroflect and meet the west wind drift current system and some parts meet in the Benguella current system, which is clearly seen in the model simulation. The South Equatorial Current (SEC) is seen meeting the ACC from the western coast of Madagascar. These features (figure 3) are compared with a z-coordinate ocean model which is able to partially simulate these features. The retroflection of the Agulhas is also seen here at 22°E and 32°E but at 12°E the bending is not seen which is a part of Agulhas Retroflection system. This may be due to the coarse resolution of MOM3.0 which is about 1.5°x1.5° and other reason may be its inability to simulate coastal regions. The third important current is the west wind drift current flowing westward along the coasts of Antarctica continent driven by west flowing wind stress. As the eastern boundary is closed so this current turns in a circular arc and meets with ACC. The speed of this current system is in the range of 20 cm/sec to 30 cm/sec, which is comparable to ACC. This current is not well simulated by MOM3.0 and although some of its signatures are seen its strength and spatial coverage is not comparable with observations. The fastest current in the region is Agulhas current, which has been simulated, and its speed is in the range of 40 cm/sec to 50 cm/sec which is in agreement with the observational studies and simulation results of MOM3.0. The current along the coast of Australia is not seen in MOM3.0, but it is well recognized and simulated with the POM, and flows east along the southern coast of Australia before it turns around the eastern coast meeting in the SEC.

The experiment was repeated with similar constants but with a finer resolution of 0.25° in the vertical and finer resolution wind stress data

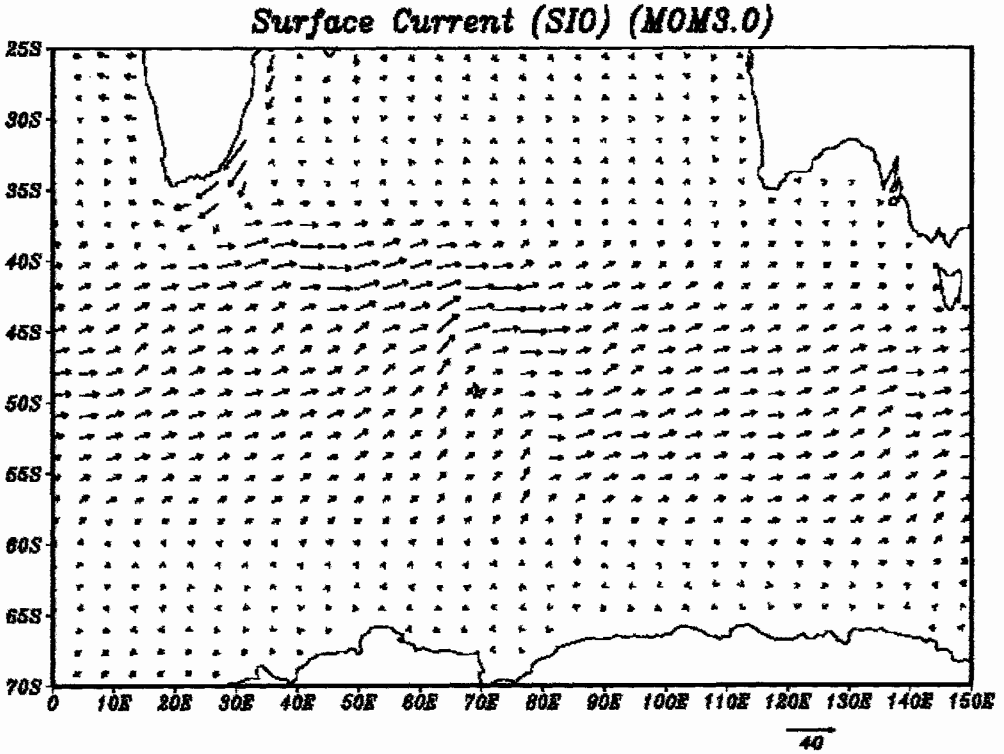

Fig. 3. Long-term mean of surface current the Southern Indian Ocean simulated by MOM3.0 (arrow length of 0.5 cm represents current speed of 40cm/sec)

as explained in the section Model settings and data. The results (figure 4) are analogous with the 1° X 1° resolution but the strength of these currents are slightly increased especially in the coastal areas of Africa, Australia and the Antarctic, but the pattern is similar. This region is influenced by mesoscale fronts and eddies (Kostianoy et.al., 2003) and the model partially captures these features.

are small since MOM3.0 includes heat flux and salt flux forcing.

In recent years much attention has been drawn to the effect of topography and stratification on the transport of the ACC but their affects remain unclear. There is a need to perform sensitivity experiments by changing wind stress in this part of the Ocean, because it is unclear how the ACC responds to changes in the Southern Hemisphere

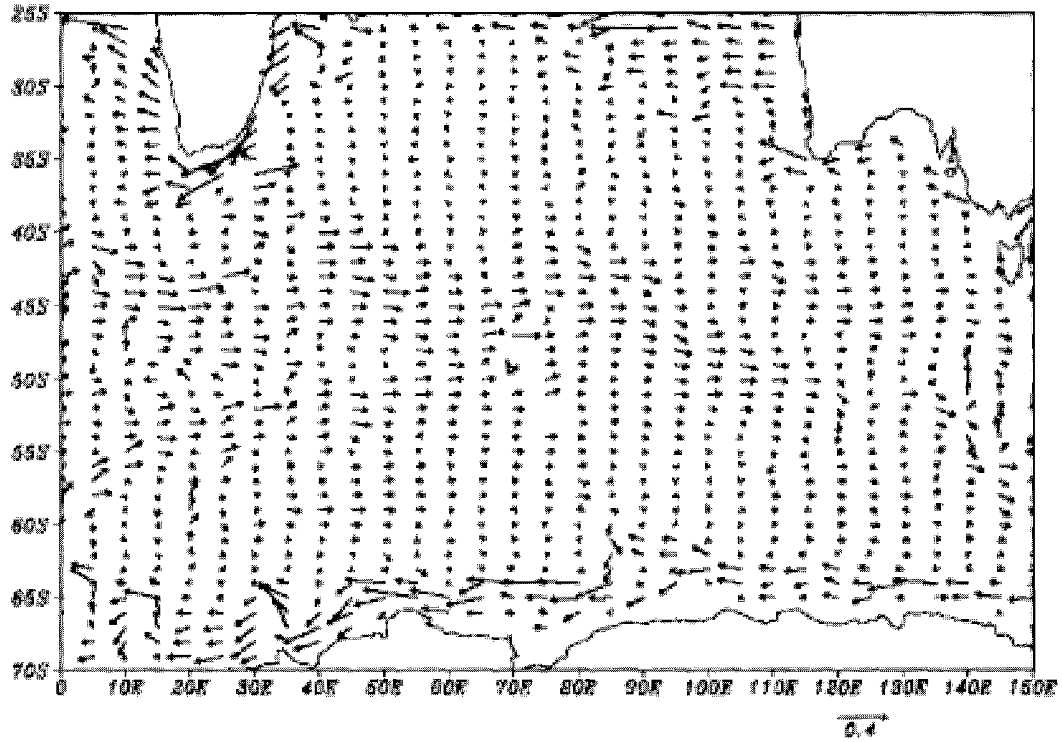

Fig. 4. Long-term mean of surface current in Southern Indian Ocean simulated by POM with spatial resolution of 1° X 0.25° (*arrow length of 0.5 cm represents current speed of 40cm/sec*)

CONCLUSION

The simulation was done with two different OGCMs MOM3.0 and POM. The coordinate system, mixing schemes, model resolution and surface forcing are different. MOM3.0 is globally configured but POM is configured for the Southern Ocean region. Forcing in POM includes only wind stress and it captures all the major current systems in SIO confirming that the wind is the main driving force for ACC region. Although some buoyancy forces also drive these currents yet these effects

winds and how the momentum input by the surface wind stress can be transferred down to the Ocean floor. In the present work the POM has been used to simulate the SIO region and it has been shown that wind is the main driving force.

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