CROSS SHELF EXCHANGE IN THE ROSS SEA AND WEST ANTARCTIC PENINSULA FROM MODELS OF THE CIRCULATION AND BIOCHEMISTRY

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Abstract

Exchange of warm, nutrient-rich Circumpolar Deep Water (CDW) onto Antarctic continental shelves and coastal seas has important effects on physical and biological processes. This water mass moderates the ice cover through heat flux, provides a relatively warm subsurface environment for some animals and provides nutrients to stimulate primary production. CDW exchange is known to be episodic, but persistent, and is thought to occur at specific locations due to bottom topography. The present study uses a high resolution 3D numerical model to investigate locations and dynamics of this exchange on the Ross Sea and west Antarctic Peninsula continental shelves.

Calculations of the advective transport across the shelf break and budgets on the shelf of heat, salt and nutrients show that the cross shelf break transport of CDW is very important to the total budgets on both shelves. Horizontal curvature of the shelf break and the transport across the shelf break are significantly correlated. A momentum term balance shows that momentum advection forces flow across the shelf break in locations where the isobaths curve in front of the flow. For the model to create a strong intrusion of CDW onto the shelf, two mechanisms are necessary. First, CDW is driven onto the shelf at least partially by momentum advection and the curvature of the shelf break; then, the general circulation on the shelf pulls CDW into the interior.

Purpose

Circumpolar Deep Water (CDW) is a relatively warm, salty and nutrient rich water mass which flows across the shelf break in the western Antarctic Peninsula and Ross Sea shelves (Fig. 1). This water mass moderates the ice cover through heat flux, provides a relatively warm subsurface environment for some animals and provides nutrients to stimulate primary production. CDW exchange is known to be episodic, but persistent, and is thought to occur at specific locations due to bottom topography. This study analyzes the amount and dynamics of the exchange of CDW on these two shelves.

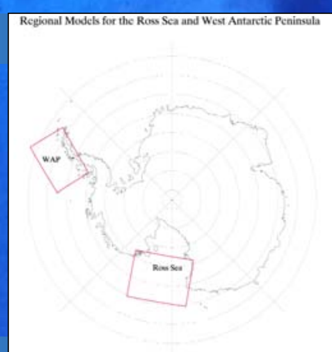

Figure 1. Domains for the two circulation models.

Model Configuration

Rutgers/UCLA Regional Ocean Model System (ROMS):
Parallel primitive equation model derived from the S-Coordinate Rutgers University Model (SCRUM). Model characteristics include

- Free surface and vertical terrain-following coordinate
- General surface fluxes
- Open boundary conditions

Bathymetry:
Model domains for both the western Antarctic Peninsula (WAP-Fig. 2) and the Ross Sea (Fig. 3) have a grid resolution of 5000 m horizontally and 24 levels vertically. Gridded bathymetry for the Ross Sea is derived from ETOPO5 while that for the WAP is derived from Smith and Sandwell ETOPO2 (2 min resolution) with modifications around Marguerite Bay.

Dissipation:
Laplacian horizontal mixing and K profile parameterization (KPP) vertical mixing scheme (including surface mixed layer).

Initial water properties:
Temperature and Salinity for both models were taken from the World Ocean Atlas 98 (WOA98). The non-linear equation of state is used. Nitrate, Silicate and Chlorophyll initial values for the Ross Sea are from our own gridded climatology while those for the WAP are taken from WOA98.

Forcing:
An annual cycle of daily wind stress is created from a blend of NSCAT and ERS 2 scatterometer data with NCEP analyses for August 1996 through July 1997. Surface heat and salt flux are calculated with the COARE bulk flux algorithm modified by ice concentrations from SSM/I climatology. Inputs to the buoyancy fluxes include: daily wind speed, NCEP monthly reanalysis air pressure, humidity and temperature, ISCCP cloud climatology and Xie and Arkin precipitation climatology.

Nutrient Uptake:
The model nutrient values were initialized with the November climatology and then were allowed to advect, diffuse and be subject to uptake after November 15. A chlorophyll climatology for November through February is used to estimate phytoplankton concentrations which then absorb nitrate based on Monod kinetics. Silicate uptake is computed as a ratio with respect to nitrate.

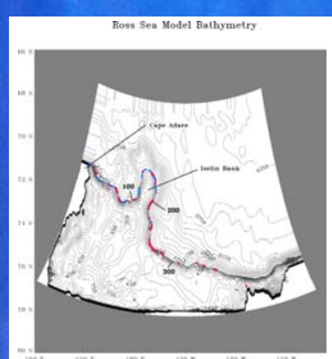

Figure 2. Bathymetry for the Ross Sea Model. The contour interval for the bathymetry is 50 m up to 1000 m depth and 250 m below 1000 m. Red (blue) lines along the shelf break represent sections where the total cross shelf break transport averaged over a year is largely onto (off) the shelf. The numbers are indices for a line defined along the shelf break.

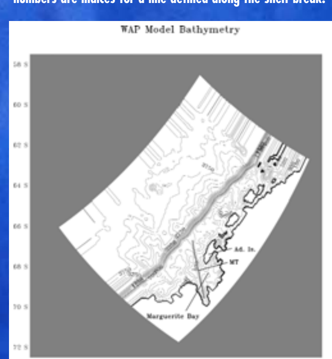

Figure 3. Bathymetry for the WAP Model. The contour interval for the bathymetry is the same as in Figure 2. 'Ad. Is.' is Adelaide Island and the line in Marguerite Bay labeled 'MT' shows the location of the Marguerite Trough.

Results

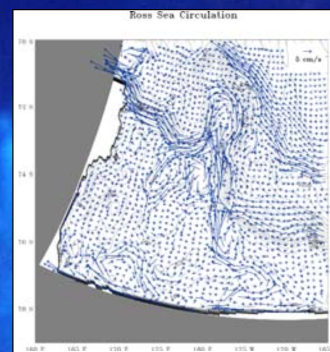

Figure 4. Total flow at 300 m averaged over a year for the western Ross Sea. The contour interval for the bathymetry is the same as for Figure 2. Every fourth model vector is plotted.

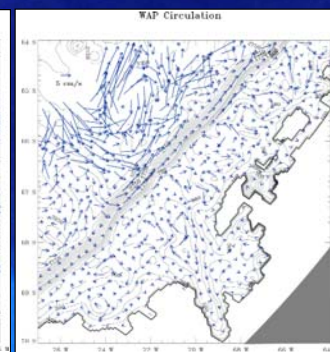

Figure 5. Total flow at 300 m averaged over mid-April to mid-Sept. of model year 2 for the area around Marguerite Bay. The contour interval for the bathymetry is the same as for Figure 2. Every fourth model vector is plotted.

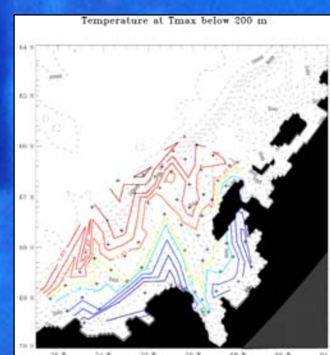

Figure 6. Distribution of the temperature maximum below 200 m from CTD observations during May, 2001. The crosses represent station locations. The contour interval is 0.2 °C except between 1.2 and 1.6 °C where it is 0.1. The thin dotted lines in the background are model bottom topography.

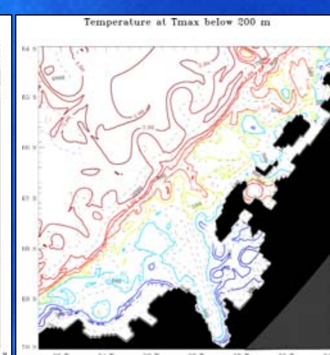

Figure 7. WAP Model maximum temperature below 200 m at model day 710 (late August). The contour interval is the same as for Figure 6.

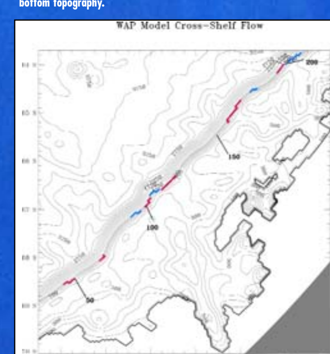

Figure 8. Magnified view of the model domain and bathymetry around Marguerite Bay. The bathymetry contours are the same as for Figure 3. Red (blue) lines along the shelf break represent sections where the total cross shelf break transport averaged over a year is largely onto (off) the shelf. The numbers are indices for a line defined along the shelf break.

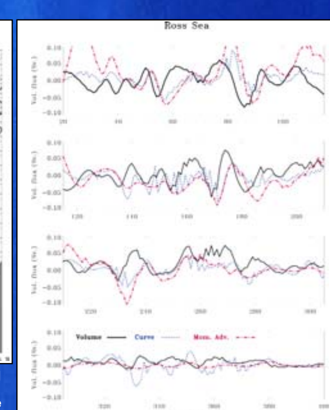

Figure 9. Cross shelf break volume flux (Sv.), shelf break curvature (normalized units * 0.25) and cross shelf break momentum advection term for the entire grid cell volume of water ($10^5 m^4 s^{-2}$) for the Ross Sea. These are averaged values over an entire model year. The x-axis is grid number along the defined shelf break.

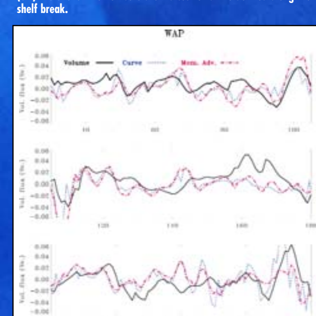

Figure 10. Same as Figure 7 except for the WAP model.

Model simulations are started in the late winter (September 15) and have been run for two years. In both regions, the circulation has very small vertical shear below the mixed layer primarily due to the weak stratification. The annual average model circulation in the western shelf region of the Ross Sea (Fig. 4) has the flow following topography, similar to estimates of the true mean circulation. The semi-annual average WAP circulation (Fig. 5) is also along isobaths, similar to estimates from ADCP measurements.

Intrusion of CDW onto the west Antarctic Peninsula continental shelf is consistently observed at specific locations. For example, warm CDW intrudes along the north side of Marguerite Trough across from Adelaide Island (Fig. 6). Episodic intrusions of CDW can be seen in the model in the same location (Fig. 7).

An enclosed shelf volume is defined for each model along the 1000 m isobath to calculate budgets. The total volume flux onto the shelf is small, as expected. The total heat flux of CDW into the enclosed regions, converted to an equivalent vertical flux by dividing by the surface area, is 14 W m^{-2} (Ross Sea) or 22 W m^{-2} (WAP). The equivalent salt flux is 30 mg salt m^{-2} s^{-1} (Ross Sea) or 41 mg salt m^{-2} s^{-1} (WAP). These fluxes are significant compared to annual average surface fluxes, indicating the importance of exchange across the shelf break. Since CDW is also rich in nutrients, salt flux implies an equivalently large nutrient flux due to this exchange.

The cross shelf break velocity at each individual grid point along the shelf break is calculated along the depth gradient. There are several locations with relatively large and variable transport consistently on or off the shelf, which appear to be related to the curvature of the shelf break (Figs. 2 and 8). There is an obvious lagged correlation of the annual mean cross shelf break volume flux to the curvature over much of the shelf break (Figs. 9 and 10). For the Ross Sea, the correlation is at a maximum at a lag of either 2.5 (r=0.52) or 3.5 (r=0.50) gridpoints (12.5 to 17.5 km). Similarly, the maximum correlation for the WAP is at a lag of either 1.5 (r=0.48) or 2.5 (r=0.45) gridpoints. Note that the direction of the lag is different between the two models due to the different direction of the flow along the shelf break. The large-lag standard error in both cases is 0.11, so these correlations are easily statistically significant at the 99% level (2.6σ). Physically, this indicates that circulation crosses the shelf break in places where the flow would cross the shelf break if it went straight. No significant lagged correlation was found between the cross shelf break flux and either the magnitude of the bottom slope or the depth.

The dominant terms in the annual average across shelf break momentum balance are the Coriolis, the pressure gradient force and the horizontal momentum advection terms, with the surface wind stress contributing but less important. The momentum advection term is greater than, or at least comparable to, the residual (sum of Coriolis, pressure gradient force, horizontal momentum advection and surface wind stress) over the entire shelf break. Momentum advection (Figs. 9 and 10) is very strongly correlated with the shelf break curvature (r=0.68 (Ross) or 0.76 (WAP)) and is significantly (better than 99%) correlated with the cross shelf break transport with a lag of either 3 (r=0.41) or 4 (r=0.42) grid points for the Ross Sea and 0 (r=0.42) or 1 (r=0.42) for the WAP.

However, strong on-shore flow of CDW onto the shelf requires more than just flow across the shelf break. Warm CDW intrudes onto the shelf along the northern side of Marguerite Trough in the WAP model (grid indices 115-125) which is then carried into the interior of the shelf by the general circulation. Conversely, the on-shelf flux around indices 85 or 100 of the WAP model does not intrude very far because of the mean circulation on the shelf. For the model to create a strong intrusion of CDW onto the shelf, it appears two mechanisms are necessary. Much of the CDW first appears on the shelf due to momentum advection and the curvature of the shelf break. Then, the general circulation on the shelf, which in this case is strongly influenced by bathymetric variations, pulls the CDW into the interior or back off the shelf.

Conclusions

The circulation in both models compares favorably to general schematics of the flow based on dynamic topography, water properties from recent hydrography and ADCP measurements. Calculations of the advective transport of heat and salt onto the shelf show that the cross shelf break transport of CDW is very important to heat and salinity budgets on the shelf. There is a significant correlation between the curvature of the shelf break and the volume transport across the shelf break, indicating that circulation crosses the shelf break in places where the tendency of the flow to maintain a given direction would have it cross a curving bathymetric contour. A momentum equation term balance shows that momentum advection helps to force flow across the shelf break at specific locations due to the curvature of the bathymetry. In the model, a strong intrusion of CDW onto the shelf requires two mechanisms. CDW must be driven onto the shelf due to momentum advection and the curvature of the shelf break. Then, the general circulation on the shelf must pull the CDW into the interior.

Acknowledgments

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