Tidal vertical mixing beneath Filchner-Ronne Ice Shelf

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Introduction

High Salinity Shelf Water (HSSW) flowing into the cavity beneath Filchner-Ronne Ice Shelf (FRIS) occupies the lower portion of the water column. Tidal mixing is likely to be a primary mechanism for mixing HSSW up through the water column, where it is transformed through melting at the underside of the ice shelf into Ice Shelf Water (ISW), a precursor of Antarctic Bottom Water (AABW).

Beneath the ice shelf, frictional stress influences tidal currents not only at the seabed but also at the ice shelf base, inducing vertical mixing. In deep water regions of the ice shelf cavity with slow tidal currents, the frictional boundary layers occupy a small fraction of the water column but in shallow regions they could occupy the entire water column and dominate the tidal dynamics. Furthermore, the northern portion of FRIS lies close to 74°28' S, the critical latitude for the M_2 tidal constituent. At this latitude the inertial or Coriolis frequency (f) equals the M_2 tidal frequency (ω) resulting in a strong depth-dependent tidal current with thick boundary layers that increase as the critical latitude is approached [*Furevik and Foldvik*, 1996]. As boundary layers are usually turbulent, vertical mixing is likely to be enhanced near the critical latitude.

The work presented here is concerned with the influence of polarisation of the tidal current ellipse on vertical mixing in the stratified, sub-ice shelf water column. The polarisation range’s from a purely circular clockwise current, through a flat or degenerate ellipse, to a purely circular anticlockwise current. Properties of a tidal current ellipse can be divided into purely clockwise (R_-) and anticlockwise (R_+) rotary components (Figure 1).

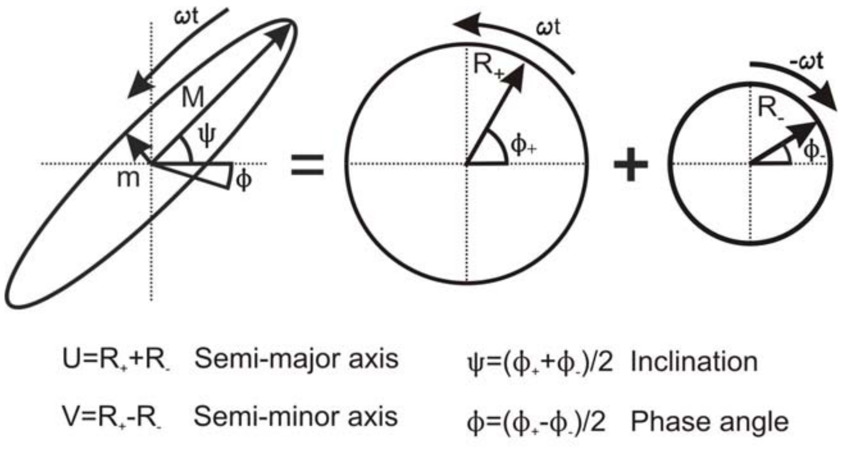

Figure 1. *The basic parameters of a tidal ellipse and its two counter rotating components.*

In the southern hemisphere their frictional boundary layer thickness is approximately proportional to $(\omega - f)^{-1}$ and $(\omega + f)^{-1}$ respectively, giving a marked difference in the vertical structure between the two components (dashed lines in Figure 2). The amplitude of R_- is largely depth independent while the amplitude of R_+ is depth dependent. Varying the current ellipse polarisation allows the investigation of the tidal boundary layer thickness and its influence on vertical mixing and, ultimately, basal melting.

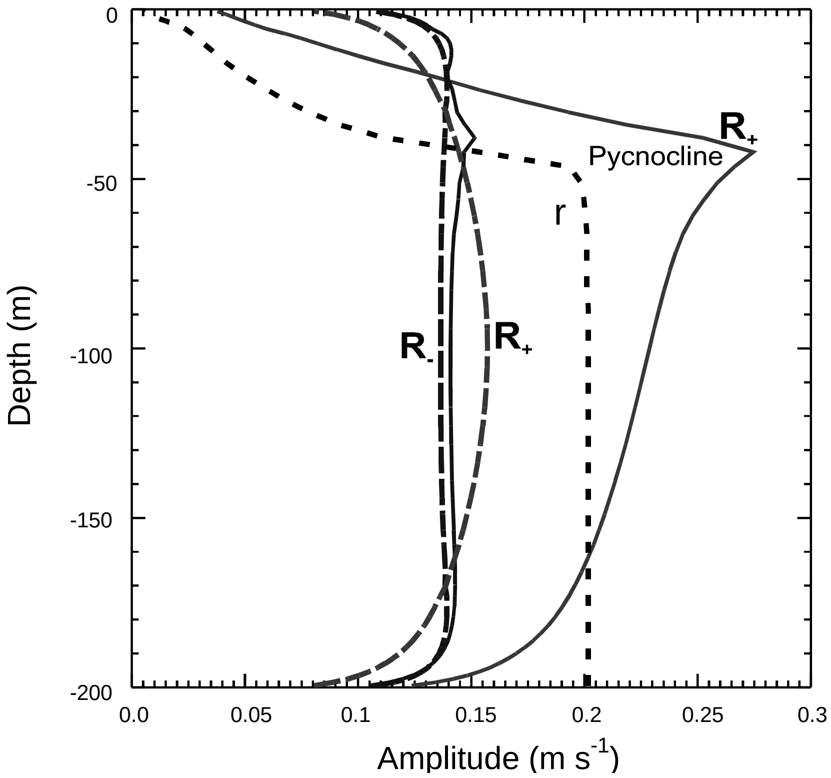

Figure 2. *The vertical structure of the M_2 rotary components beneath an ice shelf with stratification (solid lines) and without stratification (dashed lines). The clockwise component has small boundary layers, while the boundary layers of the anticlockwise component occupy the whole water column. Note that the resulting ellipse would be almost flat with anticlockwise rotation in the mid-water column and clockwise rotation at the boundaries.*

Vertical Mixing Model

A one-dimensional numerical model was constructed that uses an implicit scheme to integrate the horizontal velocity components of the momentum equations. A smoothly graded vertical mesh is used to give the highest resolution at the boundaries, in this case, 1.0 m. At the seabed and ice shelf base a quadratic drag law is applied. Horizontal property gradients are not considered in this study, and consequently only the vertical diffusion of heat, salt and momentum are considered. The model is forced with oscillating M_2 sea surface gradients. These are varied to drive a range of tidal current amplitudes and control the polarisation of the tidal current.

A level 2.5 turbulent closure scheme of *Mellor and Yamada* [1982], incorporating the modifications of *Galperin et al.* [1988], determines the effects of turbulence in transferring momentum and mixing heat and salt. This provides evolving vertical viscosity and diffusivity coefficients, dependent on the interaction of flow and stratification.

At the ice-ocean interface, phase changes during melting or freezing produce heat and fresh water fluxes. As the ice-ocean interface is approached eddies are suppressed and the eddy diffusivity becomes increasingly small to a point where molecular diffusion becomes the principal transfer mechanism for heat and salt. The parameterisation of transfer coefficients for heat and salt follow *Kader and Yaglom* [1972]. Also, during the production of melt water, the model accounts for the heat required to both warm the ice to the in-situ melting point and melt the ice, assuming the salinity of the ice is zero. Away form the ice-ocean interface, both heat and salt are conserved during mixing.

Model Results

The model has been used to determine the extent to which the two rotatory current components and their associated boundary layers for the M_2 tide influence vertical mixing. The results presented here are for a 200 m water column beneath an ice shelf with a draft of 250 m at 77°S, similar to the Ronne Ice Front region. The initial water column temperature and salinity are taken to be -1.9°C and 34.65 psu.

Tidal current profiles in Figure 2 (solid lines) show the vertical variation of the rotary velocity components after a period of melting. The negative clockwise component remains almost unchanged by the presence of the pycnocline, whereas the positive component is strongly depth dependent and reaches a maximum at the depth of the pycnocline, a situation observed in the Canadian Arctic by *Prinsenberg and Bennett* [1989].

Ranges of different forcings of the M_2 tidal constituent were applied to the model with initial conditions as above. The model was spun up and allowed to stabilise before initiating melting. After 8 model days the pycnocline depth was recorded and contoured against the two rotatory components (Figure 3). There is a clear asymmetry in the results, which are dependent on the magnitude and ratio of the two rotary components, with the anticlockwise currents generating the deepest pycnocline. The effect is highlighted for different water column speeds in Figure 4, here increasing polarisation gives a pronounced transition through the range - 0.3 to + 0.3 with pycnocline depths increasing approximately three fold.

The polarisation (*P*) is a measure of the relative contributions of the two rotary components and describes the tidal current ellipse. The polarisation is defined as

$$P = \frac{R_+ - R_-}{R_+ + R_-} = \pm \frac{V}{U}$$

where *U* and *V* are the semi-major and semi-minor axes of the tidal ellipse, with the plus and minus indicating anticlockwise and clockwise rotation, respectively. The effect of increasing polarisation results in the tidal ellipse becoming predominantly anticlockwise with increased boundary layer thickness, leading to increased vertical mixing throughout the water column.

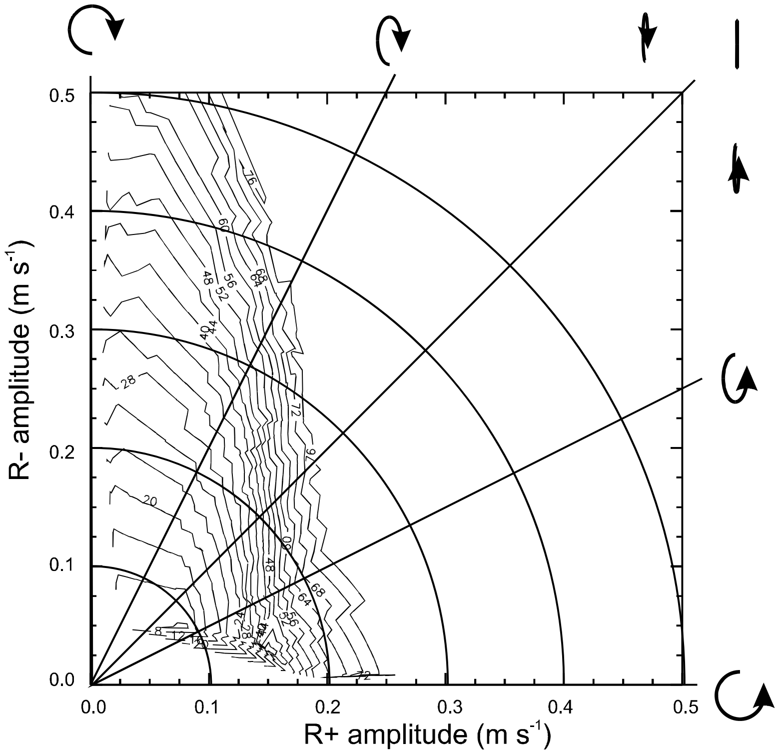

Figure 3. *The dependence of the pycnocline depth after a period of 8 days on the rotary components of the tidal ellipse. The contours are regularly spaced at 4 m intervals. The lines radiating from the origin connect points of equal polarisation with the sense of rotation indicated by the arrows. The arcs connect points of equal average speed.*

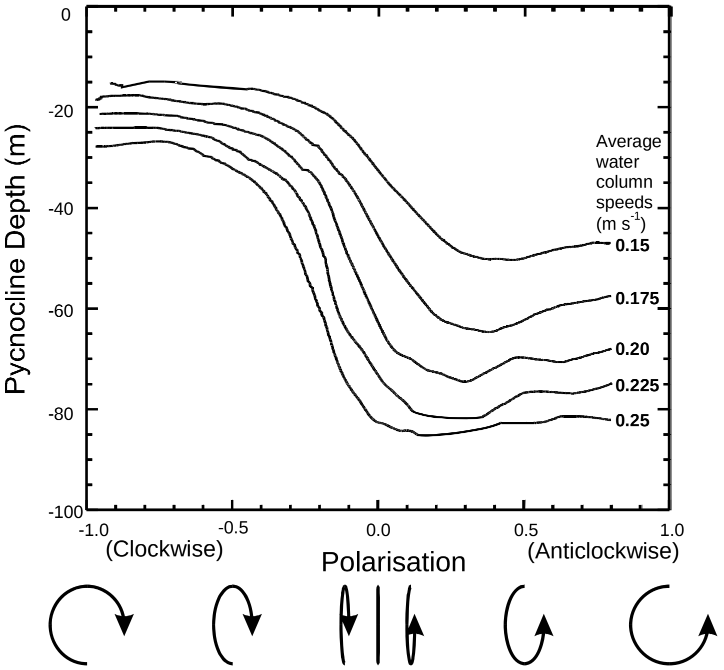

Figure 4. *Pycnocline depth for different average water column speeds verses the polarisation of the tidal current ellipse.*

The tidal model results of *Makinson and Nicholls* [1999] beneath FRIS indicate that in the shallow ice front region $P > 0.5$, whereas in the central ice shelf region $P < -0.5$. This range easily spans the polarisation with the largest changes in pycnocline depth, although the latter region has an increased water column and slower average water speeds. In regions where tidal current average speeds are similar, small shifts in polarisation, either through seasonal changes in stratification or spatial changes could result in significant variations in vertical mixing.

Water masses advected into the ice shelf cavity by residual currents through the ice front region [*Makinson and Nicholls,* 1999] will experience vigorous mixing leading to the formation of a strong pycnocline that is ultimately eroded (Figure 5). Also indicated is the associated melt rate that is initially high, reducing as the water column approaches the in-situ freezing conditions. In the shallower and more energetic ice front regions this process will be accelerated.

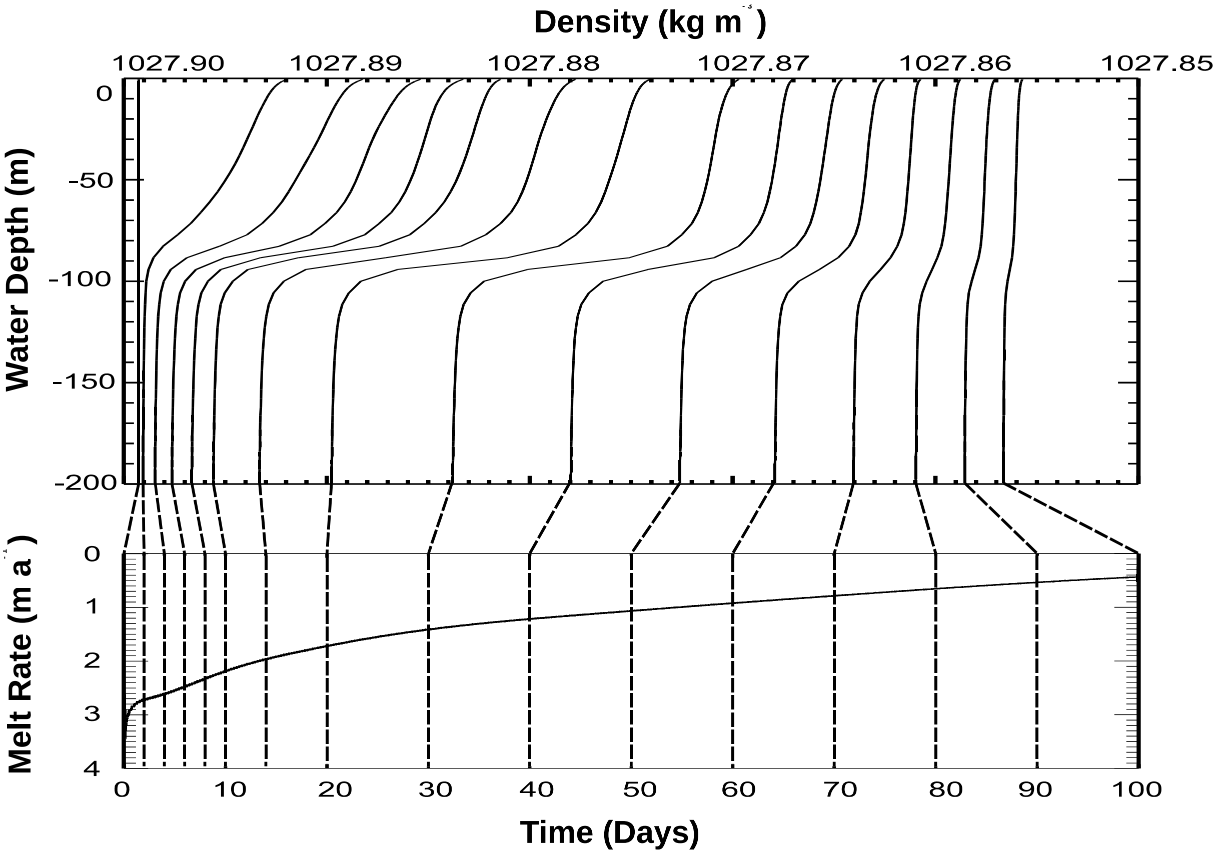

Figure 5. *Pycnocline formation and erosion for conditions similar to those found at the central Ronne Ice Front (Average water speed of 0.3 m s^{-1} and polarisation of +0.5). The development of the density profile with time is shown in the top panel (note the density axis is reversed) and linked to the corresponding melt rate beneath.*

Summary

The application of a 1-D vertical mixing model beneath FRIS has given further insight into the effects of mixing resulting from tidal currents. The influence of the critical latitude is evidently significant with large boundary layers increasing the depth to which the pycnocline can penetrate. Increasing polarisation through the range - 0.3 to + 0.3 marks the most rapid changes in pycnocline depth. For predominantly anticlockwise rotation the model predicts enhanced mixing, and therefore increased melting, for the semi-diurnal M_2 tide. Water masses passing through the Ronne Ice Front region will be exposed to high average water velocities with polarisations above +0.5. This combination will lead to boundary layers occupying the entire water column, a situation leading to efficient vertical mixing.

References

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