Seasonal stratification and tidal current profiles along Ronne Ice Front

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Introduction

Throughout much of the year a coastal polynya along Ronne Ice Front in the southern Weddell Sea is maintained by winds blowing from Ronne Ice Shelf and tidal divergence [*Foldvik et al.*, 2001; *Renfrew et al.*, 2002]. In wintertime, the coastal polynya is the focus of intense heat loss, as relatively warm water is exposed to the cold atmosphere, causing the seawater to cool to its surface freezing point, with further heat loss resulting in sea ice production. Sustained sea ice production is maintained as newly formed sea ice is transported northward away from the polynya by offshore winds. Production rates are 1 or 2 orders of magnitude higher than for the surrounding sea ice, with typically 6.1 % of the entire Weddell Sea ice production focused within the polynya that makes up only 0.013 % of the Weddell Seas area [*Renfrew et al.*, 2002]. The associated High Salinity Shelf Water (HSSW) production will be equally intense within the

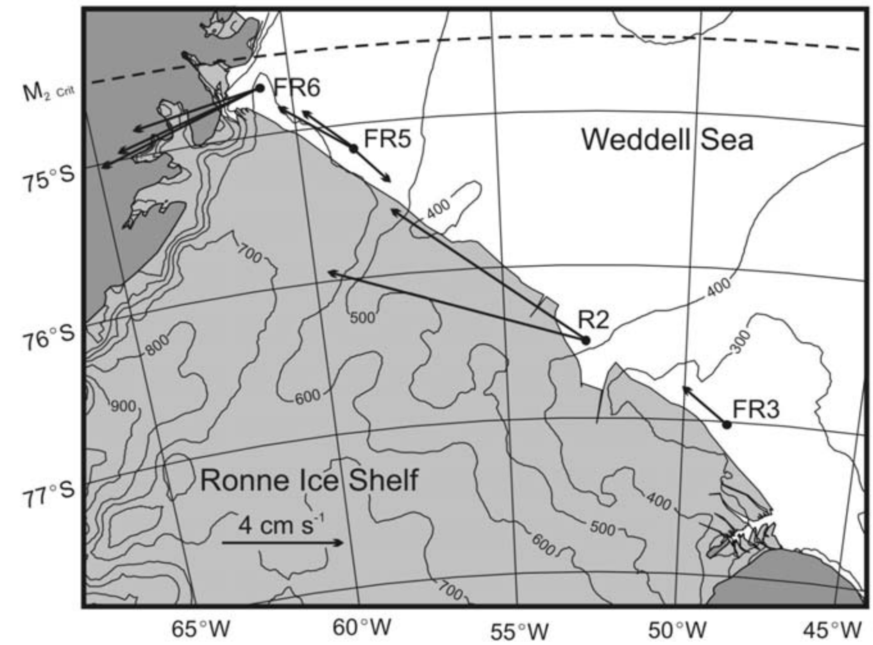

Figure 1. Map showing the ice front region of Ronne Ice Shelf. The contours indicate the bedrock depth below sea level, with a 100-m contour interval [*Vaughan et al.*, 1994] and the M_2 critical latitude is marked by the dashed line at 74° 28' 18"S. The locations of the ice front moorings are indicated together with arrows showing the time-averaged currents for each instrument [*Foldvik et al.*, 2001; *Woodgate et al.*, 1998].

polynya resulting in convective overturning of the entire underlying water column during winter [*Foldvik et al.*, 2001; *Nicholls et al.*, 2003] and a strong seasonal signal in the water column properties.

Any changes in seasonal stratification are likely to significantly affect the tidal current profile in this region [*Makinson*, 2002]. It is the strongly depth dependent semi-diurnal tidal currents, associated with the proximity of the critical latitude [*Foldvik et al.*, 2001; *Foldvik et al.*, 1990], that are sensitive to these changes. The northern most part of the Ronne Ice Front region lies near the M_2 critical latitude (74° 28' 18"S), which can give rise to a thick bottom boundary layer that may occupy the entire water column. Along the ice front, early observations of tidal currents and water column properties were confined to short summer observations and hence no seasonal data was available. However, four moorings with records greater than one year have been successfully recovered from the Ronne Ice Front coastal polynya [*Foldvik et al.*, 2001; *Woodgate et al.*, 1998]. Initial analysis by *Makinson and Schröder* [2004] has shown that during periods of stratification, the tidal current profile is notably different from those during the winter. The data from these moorings forms the basis of the work presented here and their locations are shown in Figure 1.

Data analysis

In total, nine instruments yielded records of between 1.2 and 2.5 years in length between 1993 and 1997 along Ronne Ice Front [*Foldvik et al.*, 2001; *Woodgate et al.*, 1998]. Figure 2 shows the positions of the instruments within the water column and the conductivity-temperature-depth (CTD) measurements taken close to the time of deployment. In addition, the mean flow along the ice front is generally to the northwest parallel to the ice front, with instruments at FR6 and R2 showing a significant component of flow directed beneath the ice shelf (Figure 1).

With recent modelling and observational work showing that semi-diurnal tides, particularly M_2, are likely to exhibit strong seasonal characteristics in this region [*Makinson*, 2002; *Makinson and Schröder*, 2004], the ice front mooring data are analysed and used to describe the tidal current profiles and any seasonal variations. A harmonic analysis of the current meter data yields the

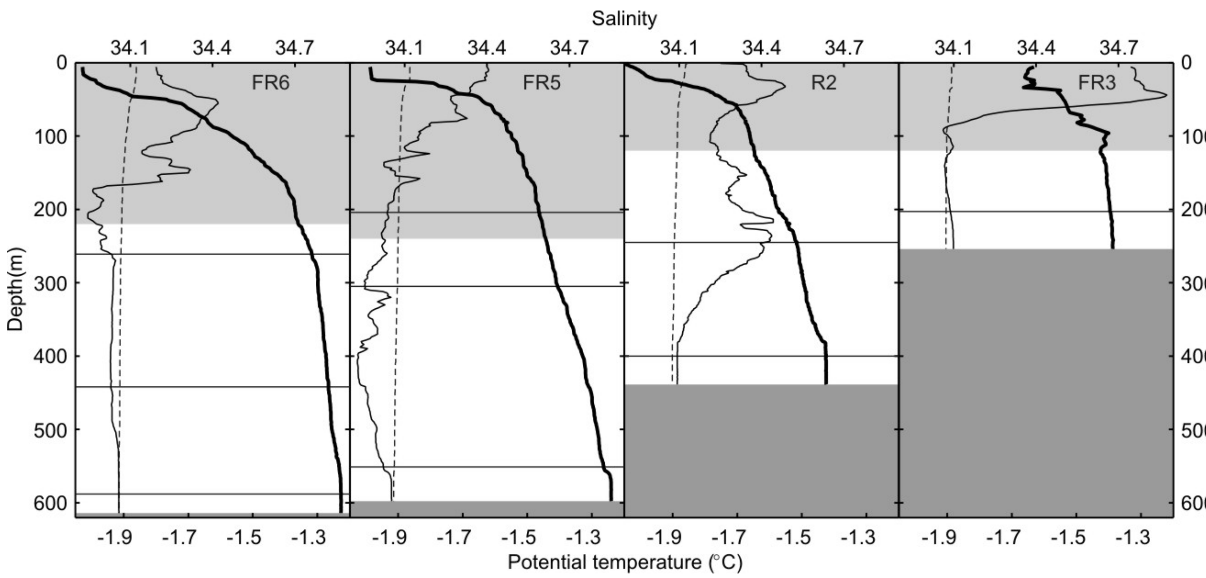

Figure 2. Vertical profiles of potential temperature (thin line), salinity (bold line) and surface freezing point (dashed line) close to each mooring location at the time of deployment. The lightly shaded area shows the part of the water column occupied by the adjacent ice shelf and darkest shading indicates the seabed. The thin horizontal lines show the depth of the moored instruments.

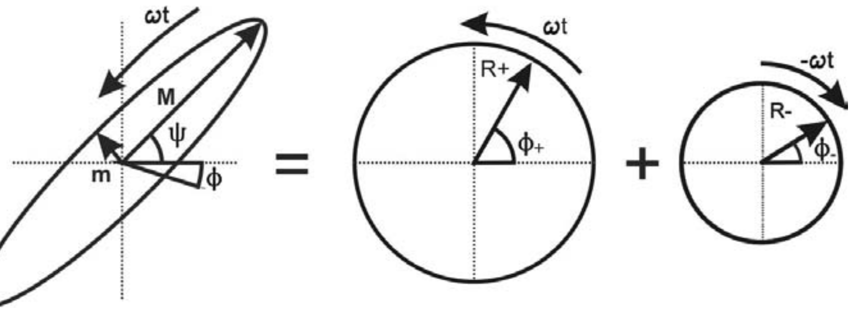

Figure 3. The basic parameters of a tidal ellipse and its two counter rotating vectors

amplitude and phase of the east-west and north-south velocity components for each tidal constituent. These four parameters define the tidal current ellipse that is traced out by the tip of the current vector, in terms of semi-major (*M*) and semi-minor (*m*) axis, angle of the inclination or ellipse orientation (ψ) and Greenwich phase angle (ϕ). Alternatively, the tidal ellipse velocity vector can be represented by the sum of two co-rotating vectors with amplitudes of R_+ and R_- and phases of ϕ_+ and ϕ_- (Figure 3). In order to identify any seasonal changes in the tidal currents it is necessary to analyse short sections of the current meter time series. The M_2 tide is the largest tide in the region and its critical latitude is closest to Ronne Ice Front and therefore of primary interest. A harmonic analysis was applied to the initial 662-hour section of a current meter record separating a total of six tidal constituents (Q_1, O_1, K_1, N_2, M_2, and S_2) [*Foreman*, 1977]. This analysis was repeated by moving the 662-hour window forward in steps of 24 hours until the end of the record was reached. The results of the decomposition of the M_2 tidal currents into rotary components for each instrument at FR6 are shown in Figure 4 together with the temperature, salinity and monthly sea ice production within the ice front polynya.

Tidal currents

The seasonal changes in stratification that result from sea ice production are highlighted in the temperature and salinity data in Figure 4. In addition, the M_2 rotary components, R_+ and ϕ_+, show a strong seasonal signal that coincides with the changes in stratification at FR6, resulting in the amplitude of R_+ at 442 m exhibiting a two-fold increase during summer months with swings of up to 50° in ϕ_+. The changes in ϕ_+ for the other semi-diurnal tides can also change by over 40°, equivalent to 20° in ellipse orientation, which at FR6, is typically around 55° during winter. Conversely, the clockwise tidal components of the semidiurnal tides (R_- and ϕ_-) and all components of the diurnal tides remain unaffected by the seasonal changes in stratification, as predicted by the boundary layer theory.

With three current meters at FR6, vertical profiles of the rotary components can be suggested for various times throughout the year. Based on the analysis of the rotary components at each instrument and profiles modelled by *Makinson* [2002], Figure 5a shows the evolution of the tidal current profile. By late winter, the temperature reaches a plateau as HSSW occupies the entire water column and little or no stratification should be present particularly during 1995 when sea ice production was over 70% higher than in 1996 (Figure 4). During this period of winter, from June to September 1995, the water temperature together with R_+ and ϕ_+ remain relatively stable, suggesting a well-mixed water column. Throughout this time at FR6, the frictional bottom boundary layer can at times extend beyond the instrument at 442 m, over 170 m from the seabed as a result of the proximity to the critical latitude (profile 1, Figure 5a), with R_- having an almost

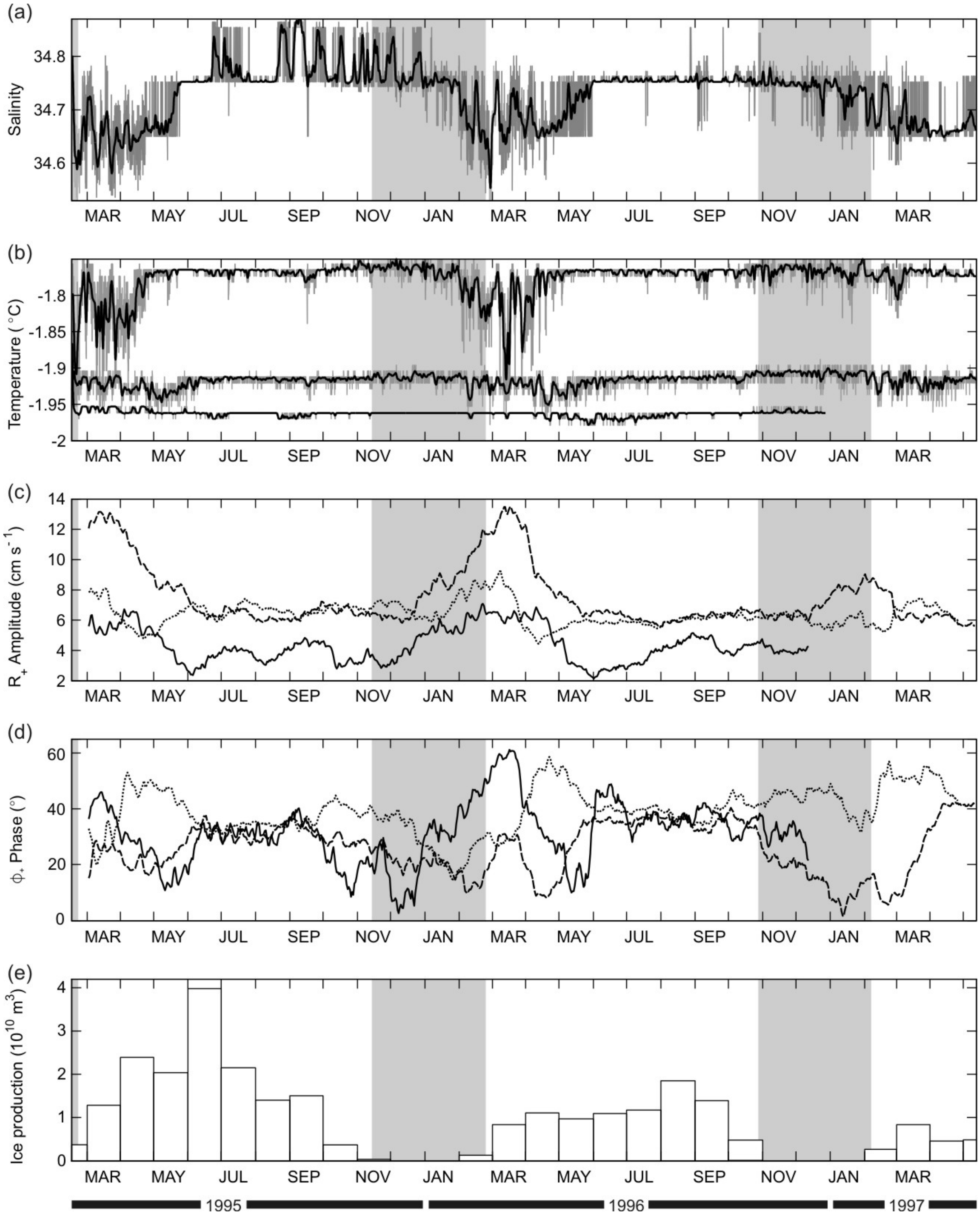

Figure 4. Time series data from mooring FR6. (a) Salinity data from the upper instrument and a smoothed version of the signal has also been plotted. (b) Potential temperature time series and smoothed version from the instruments at 261 m (top), 442 m (middle) and 588 m (bottom). The data from 261 m and 588 m have been offset by 0.15 °C and –0.05 °C respectively to improve clarity. (c) Time series of the anticlockwise rotary component (R_+) for the M_2 tidal constituent for the instruments at 261 m (dotted line), 442 m (dashed line) and 588 m (solid line). (d) Time series of the anticlockwise rotary component phase (ϕ_+) for the M_2 tidal constituent for the instruments at 261 m (dotted line), 442 m (dashed line) and 588 m (solid line) which has also been offset by 60°. (e) Bar chart of sea ice production in the coastal polynya along Ronne Ice Front for each month of the mooring record, with the shaded areas in each plot showing the summer melting season [*Renfrew et al.*, 2002].

uniform profile. After the end of September, the upper water column warms slightly and the earlier peaks in salinity begin to decrease as sea ice formation declines significantly in October, (Figure 4e). There is no obvious response to these changes in the amplitude of R_+, but ϕ_+, which has been stable through the latter half of winter, diverges from its wintertime values during October as the supply of HSSW diminishes and the water column begins to stratify. Through December and January, R_+ increases at each of the instruments. By early February, a reduction in temperature and salinity at the upper instrument indicates the arrival of ISW, with a correspondingly large increase of R_+. However, through this summer period and despite FR6 being offshore, the lower portion of the R_+ profile is similar to modelled [*Makinson,* 2002] and observed [*Prinsenberg and Bennett*, 1989] current profiles found beneath fast ice cover. Clearly, during summer stratification the presence of the ice shelf base influences tidal currents several kilometres offshore, with the amplitude of R_+ decreasing in the upper half of the water column because of a second boundary layer originating from the adjacent ice shelf base. The relatively strong stratification in the upper water column (Figure 2) decouples the water column below the ice shelf draft from that above, allowing the upper boundary layer to be present some distance from the ice front.

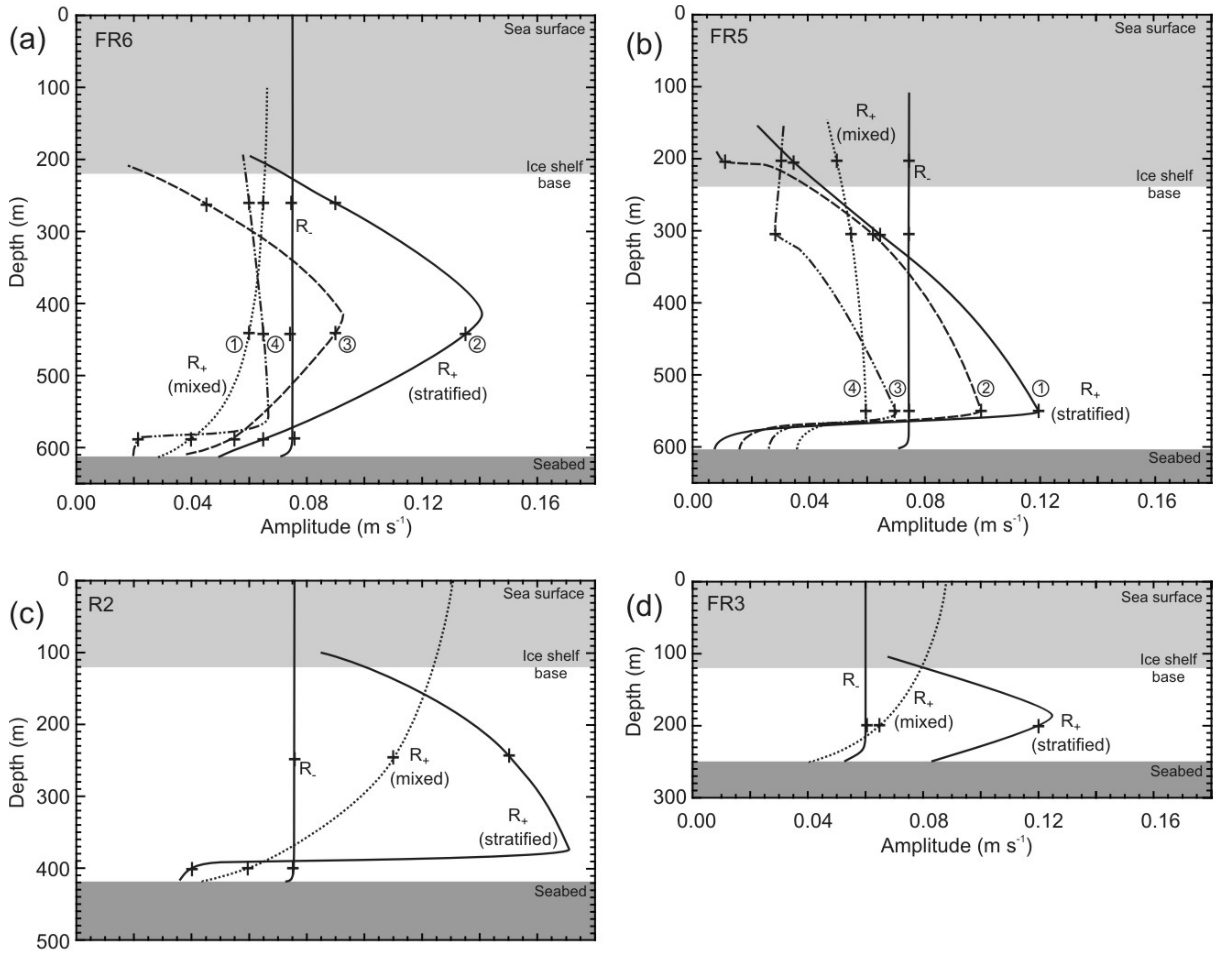

Figure 5. The observed depth variations of the clockwise (R_-) and anticlockwise (R_+) tidal current components for M_2 at the ice front moorings. The light shading indicates the portion of water column occupied by the nearby ice shelf and the darkest shading indicates the seabed. The crosses are the current meter measurements and the lines indicate the suggested vertical current profiles for well-mixed and stratified conditions with R- remaining unaffected.

Through February 1996 and into early March, R_+ continues to increase with increasing stratification, as the two boundary layers develop to occupy the entire water column below the ice shelf draft. The peak in R_+ occurs around mid-March (profile 2, Figure 5a) about 20 days after the onset of the winter freezing season (February 25th) [*Renfrew et al.*, 2002]. The subsequent rapid decline in R_+ signifies the switch from summer to winter conditions in the water column, as HSSW begins to form at the surface and descend into the water column.

The decline in amplitude of R_+ occurs soonest higher in the water column and occurs over a 2-4 week period. At 261 m, R_+ declines after mid-March and continues to a minimum in mid-April. At about the same time, the salinity begins to increase and the temperature plateaus (Figure 4). Temperatures close to the surface freezing point and an increasing salinity signifies the passage of the deepening pycnocline past this instrument. The high shear associated with this pycnocline causes the upper water column to become increasingly decoupled from that below. This decoupling allows the influence of the adjacent ice shelf boundary layer to be intensified, further decreasing the amplitude of R_+ at 261 m and 442 m, and creating a near symmetrical profile (profile 3, Figure 5a). In addition, at the end of March there is a rapid change in ϕ_+ as the pycnocline deepens past the ice shelf base. The arrival of the HSSW is signalled at 261 m by a 30° increase in ϕ_+ and accompanied by a similar decrease at 588 m. At 442 m, the response of ϕ_+ from 30° to 10° follows the response at 588 m, suggesting that these two instruments are within the lower boundary layer.

By mid-May the rapid decline of R_+ at 442m has ceased and ϕ_+ has switched to its wintertime value, coinciding with the arrival of HSSW as the temperature approaches a plateau and the pycnocline passes the instrument. Within seven days, R_+ at 558 m has also reached a minimum, with ϕ_+ increasing by 30° as the pycnocline reaches this instrument, reducing the boundary layer depth and intensifying frictional forces. Based on sub-ice shelf modelling of [*Makinson*, 2002], profile 4 is suggested in Figure 5a with high shear across the pycnocline. At about this time the salinity attains its winter plateau, suggesting that the water column may be fully mixed. At the lowest instrument, however, the temperature does not reach a plateau until late July, when the R_+ and ϕ_+ finally recover to their winter values. Only during August and September do the instrument sensors and tidal parameters suggest that HSSW occupies the entire water column with little or no stratification present.

During the summer period in early1995, very similar changes in water column properties and tidal current response are observed, although absolute values and timings differ slightly from those in 1996. At each instrument, ϕ_+ changes rapidly as the minimum in R_+ is approached, coinciding with the arrival of the HSSW and the deepening pycnocline. During early 1997, however, both the temperature structure and tidal response differed significantly from the previous two years. Only relatively small changes in the amplitude of R_+ are seen at 442 m, although a strong response is observed in ϕ_+ as the water column stratifies, followed by a rapid recovery to the wintertime ϕ_+ phase during March.

Using similar arguments, based on the observations at FR6 and numerical modelling, tidal current profiles at FR5, R2 and FR3 are also suggested for periods when the stratified or mixed conditions are present at a mooring (Figure 5). Transitional profiles are also shown at FR5 as HSSW descends through the water column.

Conclusions

From these ice front data, a clear picture has emerged showing that semi-diurnal tidal currents along the Ronne Ice Front region, and close to the critical latitude, are considerably modified by the presence of seasonal stratification. These changes in the semi-diurnal tidal amplitude can increase the total tidal current amplitude by over 50%. The data also shows considerable seasonal and interannual variability in both semidiurnal tidal current structure and water column stratification. These results are consistent with boundary layer theory, match observations from beneath fixed ice cover in the Arctic [*Prinsenberg and Bennett*, 1989], and have been replicated in a tidally driven vertical mixing model applied to the water column beneath FRIS [*Makinson*, 2002]. One surprising feature of the semi-diurnal tidal current profiles is the presence of a second boundary layer that is associated with the nearby ice shelf base. This additional boundary layer gives the impression of an ice covered water column, despite being several kilometres offshore of the ice front. These two boundary layers occupy the entire water column beneath the draft of the adjacent ice shelf and may extend up to the pycnocline associated with the surface mixed layer. Furthermore, the observed sensitivity of the anticlockwise rotary components to changes in stratification, suggests that it is the best indicator for changes in stratification after direct observations of density variations. Consequently, these observations and their interpretation have provided new insight into how critical latitude, stratification and the nearby ice shelf influence tidal current profiles throughout the year along Ronne Ice Front.

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