Variability of the Filchner overflow

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1. Introduction

Cold and saline water formed on the relatively large continental shelf in the South-Western Weddell Sea enters the cavity under the Filchner-Ronne Ice-shelf and interacts with the glacial ice. The produced water mass, often referred to as Ice Shelf Water (ISW) is cold and dense, and it has the potential to sink to the bottom of the Weddell Sea. ISW exits the ice-shelf cavity through the Filchner depression, forming a plume of cold dense water on the continental slope (figure 1a). ISW is usually defined as water with a temperature lower than its surface freezingpoint, (i.e. ca $T<-1.9^{o}C$) and has a salinity around 34.6 (Foldvik, Gammelsrød & Tørresen 1985*b*). On the continental slope it encounters Warm Deep Water (WDW), which is characterized by temperatures between 0-0.8^{o}C and salinities between 34.64-34.72.
The ISW plume was first observed by Foldvik, Gammelsrød & Tørresen (1985*a*) and since then a number of mooring arrays have been placed on the slope and in the Filchner Trough proper in order to monitor the flow. Data from all existing records were synthesized by Foldvik, Gammelsrød, Østerhus, Fahrbach, Rohardt, Schrøder, Nicholls, Padman & Woodgate (2004) who estimated the flux of ISW to 1.6±0.5 Sv. They also indicated three main pathways for the plume down the slope and suggested that relatively high frequency processes, e.g. tidal motion and shelf waves, would determine which path was followed by a particular water parcel. The view of the plume as an unsteady flow of cold water is consistent with laboratory work and model efforts as well as with observations from other overflow regions.
This article presents a summary of the observed variability in the Filchner overflow area (1968-1998) and relates it to processes and phenomena occurring on slopes and in dense gravity plumes.

2. Data

The first mooring arrays were placed in the area as early as 1968. This was to monitor a possible flow of dense water directly from the shelf (the ISW plume was not yet discovered) and has been followed by a number of arrays throughout the years 1968-1998. In total 40 currentmeters have been deployed in the area. Possible interannual variation must be kept in mind when comparing records from different deployments.
The position of the moorings are shown in figure 1b. Data were recorded every hour, except for mooring Fr1 and Fr2 where the logging interval was two hours. More detailed information on the moorings and the instrumentation can be found in Foldvik et al. (2004).

The work presented here will to some extent be focused on data from mooring F1-F4,

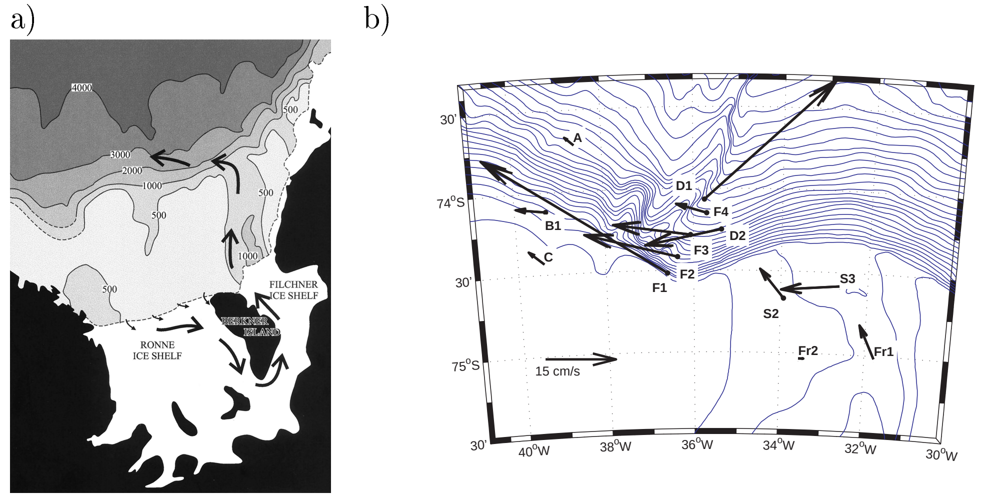

Figure 1: *a) Path of Ice Shelf Water (ISW), formed beneath the Filchner Ronne ice shelf in the southwestern Weddell sea. The cold dense water passes through the Filchner depression in the east, and cascades down the continental slope as a density driven plume. From Foldvik et al 2001. b) Position of moorings in the outflow area. The arrows indicate mean current from the bottommost instrument. The reference arrow to the left represents a velocity of 15 cm/s*

and D1. The F1-4 moorings were deployed in 1998 and they were placed across the slope, covering a depth range from 647 to 1974 meters and thus "catching" the main plume path.

3. Analysis

The data have been analyzed using rotational and ordinary Fourier analysis as well as wavelet analysis (e.g. Torrence & Compo (1997)).
Hanning windows with 50% overlap have been used for the Fourier analysis. The length of the window was allowed to vary as the number of windows used was kept constant at 8. The results from the Fourier analysis are presented in energy preserving diagrams. The data were not de-tided prior to the analysis, but the spectra have been cut off at tidal frequencies. The coordinate system was rotated for several moorings,(B1-B3: -25^o; A,F1-2: -40^o; D1:-140^o and D2: 20^o) in order to align the x-axis with the isobaths, i.e. 'U' is along- and 'V' across-slope.
Through Wavelet analysis an oscillation can be located in time, i.e. it shows when energy is present at a certain frequency. Prior to the wavelet analysis the data was filtered using a 3-hour Hanning-filter and then decimated at intervals of four hours. The series was zero-padded and analyzed using a "Morlet" base.
The slope-aligned coordinate-system described above was used also in the wavelet analysis. The confidence levels are calculated assuming a red noise background with a lag-1 of 0.72.

4. Results

The plume is observed to be highly variable with variations and oscillations occurring on many timescales. To get an impression of the variability the bottom temperature and salinity records from F1-4 are presented in figure 2. The plume seems to be concentrated mainly around mooring F2 and F3 (at 1180 and 1637 meters depth respectively), but is intermittently present also at F1 and F4 (647 and 1984 m depth). It will be shown later that the arrival of ISW at F4 is related to an oscillation of roughly 6 days.

4.1 Oscillations - Fourier Analysis

Results from the Fourier analysis are presented in figure 3. The shown spectra are chosen to be the clearest and statistically most significant (i.e they are derived from sufficiently long time series). We find high energy levels on frequencies corresponding to periods of ca 35h (f=0.7), ca 3 days (f=0.3) and ca 6 days (f=0.17).

- **35 h (O35h)**
  The oscillation with a period of 35 h (O35) is the most energetic and is observed mainly in the time series from D2 (along shelf), F1, F2 (across shelf) and from F3. Although less energetic it can be seen also F4. (Figure 3c-f,h).
  Rotary spectra show that the oscillation is Counter Clockwise (CCW) at F1 and Clockwise (CW) at F2 and F3. At D2 the CCW energy is larger, although the contribution from CW rotation is substantial.
- **3 days (O3)**
  The three-day oscillation (O3) is primarily seen in the across slope series from D2 and F3 but also in F2 and F4 (across/along)(Figure 3 c,f-h) and to some extent in S2 (not shown).
  The oscillation is CW at both D2 and F3 (and F4), but CCW at F2.
- **6 days (O6)**
  The six-day oscillation (O6) is most pronounced in the along slope record from D1 and F3 and will be discussed further in relation to F4 where the oscillation at times occurs along as well as across slope, see section 4.2. Energy is also found at these frequencies in the trough proper, e.g. in Fr1, S3 and S2.(Figure 3 c-d,g-h. S2-3 are not shown).
  A CW rotation is observed at F4.

Interestingly, the periods observed on the slope seem to be multiples of the shortest one: O3=2*O35, O6=2*O3=4*O35. It is however not possible to determine the oscillation frequencies precisely from the Fourier analysis.
The energy levels on mooring A (figure 3a), located relatively far from the Filchner Trough, is notably low compared to other moorings in the plume.

5. Discussion

Greatly simplified, we would expect a dense plume to adjust geostrophically and thus to flow along the isobaths, with the (upslope) Coriolis force balancing the (downslope) pres-

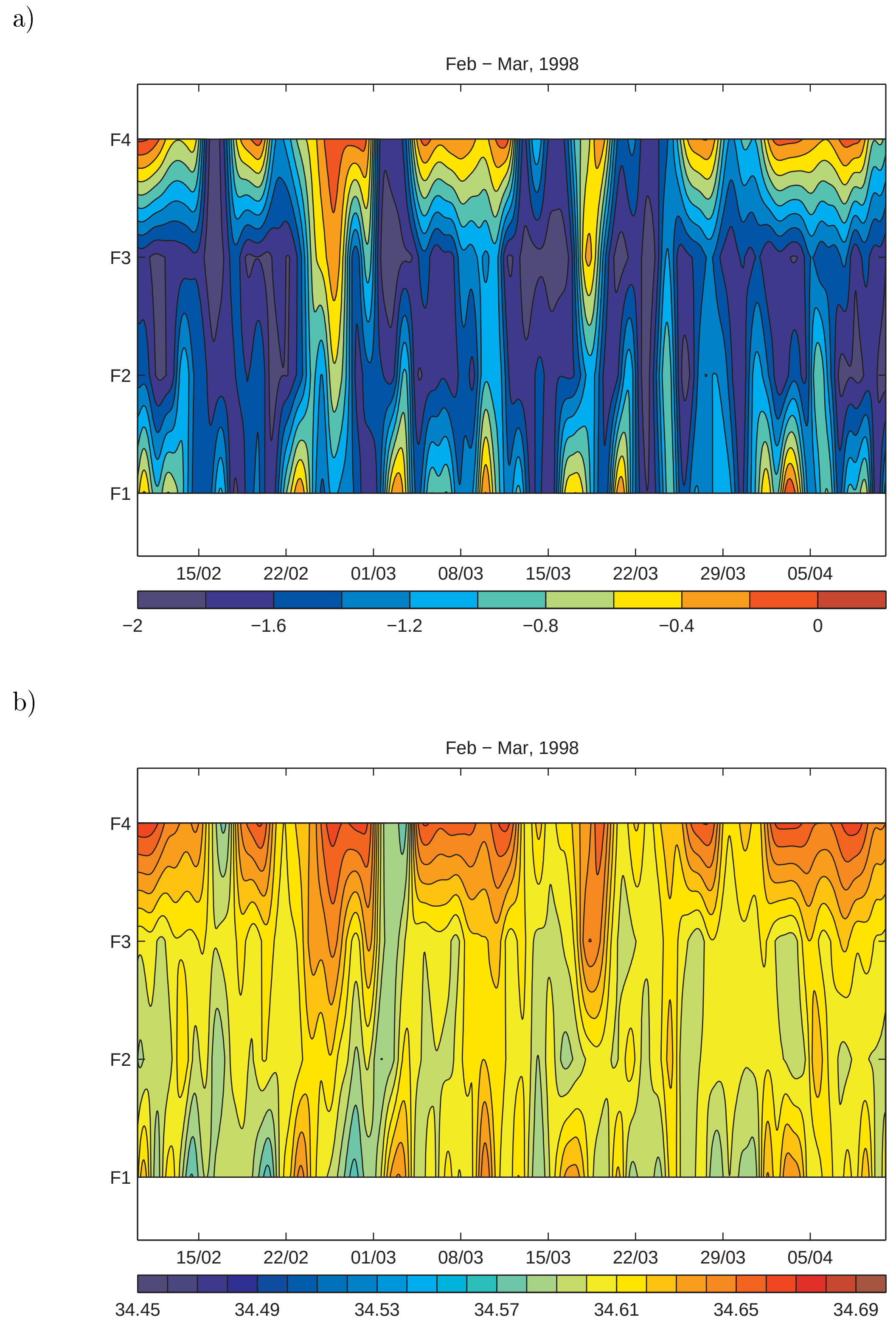

Figure 2: *Bottom (9 mab) a) temperature and b) salinity at F1-F4 in February-March 1998.*

sure force. Friction would slow down the flow, and cause it to deflect slightly downslope. However, many laboratory and model experiments show results that complicates this sim-

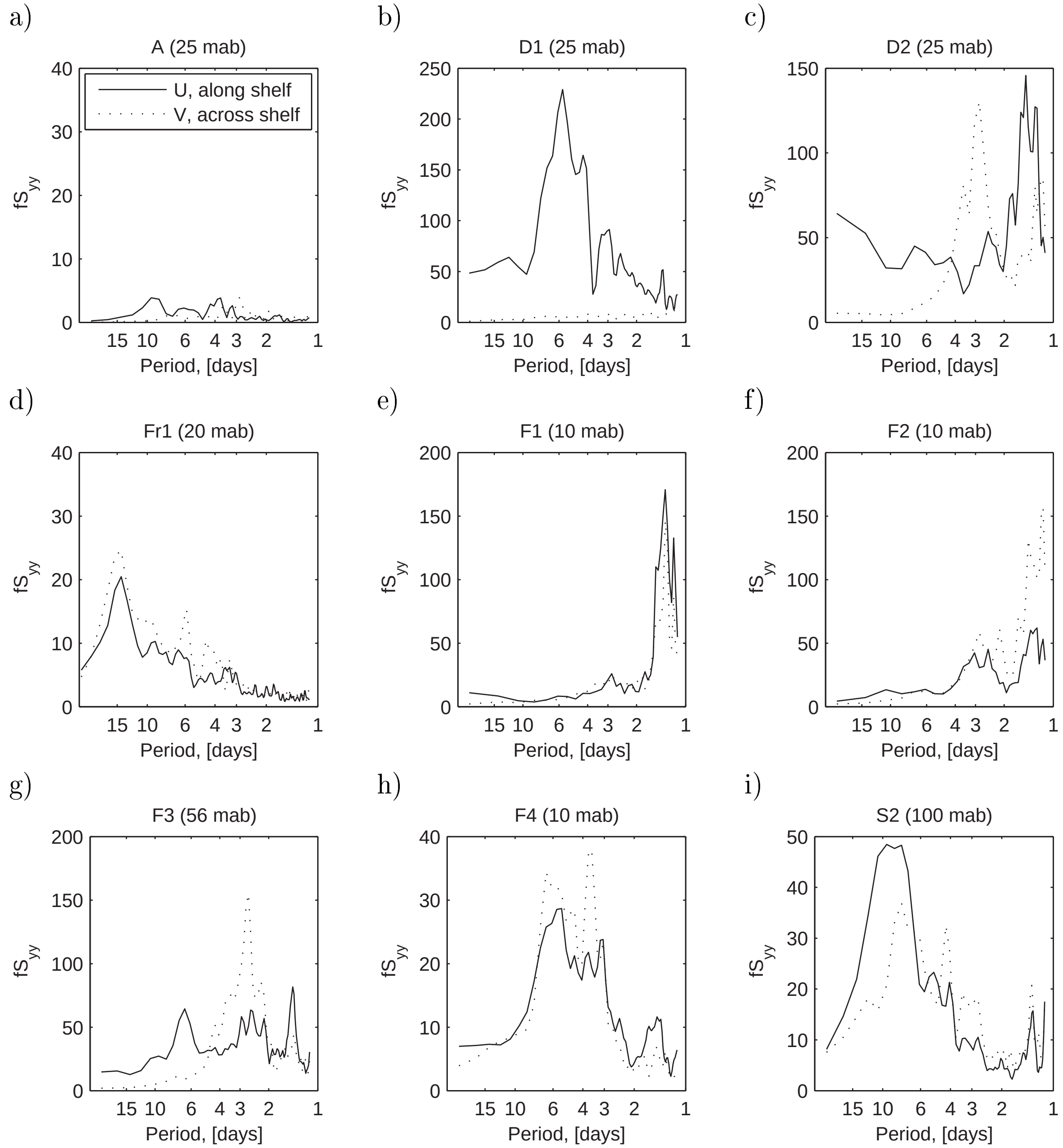

Figure 3: *Results from Fourier analysis - energy preserving spectra.*

ple picture. Eddies and waves develop greatly altering the shape and the velocity patterns of the plume. They increase downslope transport (Tanaka & Akitomo 2001) and enhances mixing (Cenedese, Whitehead, Ascarelli & Ohiwa 2004)(Jiang & Garwood 1996).

Our observations of oscillations within the plume (O35, O3, O6) suggest that eddies and other disturbances is generated also in the Filchner overflow plume. The features might however be generated elsewhere and simply imposed on the plume flow.

The O6 motion at F4 is cyclonic and most likely barotropic, since it is close to homogenous in the vertical (at least over the height of the mooring, which covers 200 meter or 10% of the water column). This is consistent with the eddies observed in the laboratory studies.

The co-occurrence of cold water and oscillations (O6) at mooring F4 and D1 (at 1984 and 2075 m depth respectively) could indicate that eddies or periodic subplumes like those observed in the laboratory by Etling, Gelhardt, Schrader, Brennecke, Kuhn, d'Hieres & Didelle (2000) and in models by Jiang & Garwood (1995), transport dense water downslope. The relatively steep ridge just west of D1 certainly influences the flow and steers the water downslope. Wåhlin (2002) showed how a plume can lean on topography, allowing a geostropically balanced flow across isobaths.

Another possible explanation to the observed oscillations on the slope is coastally trapped waves or so called shelf wave. It has been suggested that the observed intensification of the diurnal tidal currents near the shelfbreak in the Weddell Sea is due to the excitation of shelf waves with tidal frequencies (Middleton, Foster & Foldvik 1987). Middleton, Foster & Foldvik (1982) adapted a barotropic shelfwave model (earlier presented by Saint-Guily (1976)) to the southern hemisphere and the continental slope in the Filchner area and based on data from mooring A-C they provide evidence for the existence of shelf waves with frequencies of 3-60 days.

Looking closer at O35 with respect to shelf waves and the Saint-Guily model one sees that the frequency would correspond to a wavelength of about 200 km and that the first mode (S=0) is the only possible mode (figure 10a in Middleton (1982)). The first mode correspond to CCW motion on the upper slope and a CW motion lower down with the transition occurring at roughly 1600 m depth. This value is however relatively dependent on a slope parameter, λ. Now mooring F1 located at 687 m depth show a strong CCW signal at O35, while F2 located at 1180 m depth show a strong CW signal (weak CW signal at F3 and F4), which agrees qualitatively with the theory for shelfwaves. The oscillation is equally strong at all mooring depths, indicating that the motion is barotropic.When concentrating on the F-moorings it seems plausible that O35 is related to propagating shelf waves - but D2 (1800m) show relatively strong CCW motion at O35 (discussed in Foldvik, Gammelsrød, Restad & Østerhus (2003)) and the older moorings B-C, located close to the shelf break, show no O35 at all.

Waves could be generated elsewhere and travel to the plume area along the continental slope, but it is also possible that processes related to the plume is involved in the wave initiation. Whitehead & Chapman (1986) observed that shelfwaves was generated in the laboratory due to the flow of a (light) surface gravity current over a sloping bottom.

The data set is limited by its low spatial resolution and by its temporal patchiness. More observations in combination with a regional numerical model is needed in order to understand the meso scale processes responsible for the variability described in this work and to be able to explore their effects on the plume and the production of deep water.

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