Currents variability in Terra Nova Bay polynya (Ross Sea, Antarctica)

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Abstract

Long time series of current measurements have been collected in Terra Nova Bay polynya since 1995. Until 2001 the measurements covered the entire water column, from a minimum depth of 55 m to the bottom. This unique data set is here described and results from time-frequency analysis and variability at different time scales presented. General circulation is mainly northeast along the coast with some differences between the upper layer and the rest of the water column which is strongly barotropic. Seasonal and inter-annual variability is dominated by the thermohaline forcing, in particular by the high sea-ice production in the polynya. Strongest currents occur at the end of winter, in correspondence of the maximum density increase as the results of dense water formation process, while during summer deep layer currents have the minimum energy. The response of the basin to the prevailing tidal components (K_1 and O_1) is mainly barotropic. At sub-daily time scales the contribution of semidiurnal tides is negligible but persistent inertial currents are often observed.

Keywords. Currents measurements, Terra Nova Bay, tidal currents, time series analysis

1. Introduction

Since 1994, oceanographic measurements are regularly performed in the western sector of the Ross Sea in the framework of the Italian National Program of Antarctic Research (PNRA). Measurements include CTD profiles and water samples collection during the austral summer expeditions as well as the deployment of moorings (PNRA, 1995). In particular, in Terra Nova Bay a mooring (indicated as mooring D) equipped with temperature and conductivity sensors, current meters and sedimentary traps was deployed in 1995, with the aim of investigating the processes occurring in the polynya, a well-known, peculiar feature of the region (Fusco et al., 2009, Jacobs and Comiso, 1989, Kurtz and Bromwich, 1985, Parmiggiani, 2006, Van Woert, 1999). Since then, great efforts have been devoted to regularly maintain the mooring which is now part of a permanent marine observatory, providing one of the longest time series of oceanographic data in the Southern Ocean. The configuration of the mooring payload has changed during the time to better meet the needs of the scientific investigations carried out in the area and according to the instruments availability. After 2002, when the all mooring line was lost, probably damaged by the passage of large icebergs calved from the Ross Ice Shelf (Robinson and Williams, 2012), no more instrumentation was located in the upper 300 meters, thus limiting the monitoring of the upper layer to the short summer periods. Moreover, scientific interest turned to focus on the dynamics of deep layers (Budillon et al., 2011, Jacobs, 2004), so that the efforts were concentrated to monitoring the highest depths.

More recently, during the XXVII Antarctic Expedition on December 2011 (PNRA, 2012), a 300 kHz ADCP was added to the mooring line at 100 m depth with the aim of investigating the dynamic of the near-surface layer and the air sea interaction, as well as to collect backscatter data associated to zooplankton variability and strong mixing events. Unfortunately, when the mooring was recovered two years later, the ADCP was not found, so that the data collected until 2001 constitute a unique and precious data-set of the upper layer current in the region.

Despite a huge part of these data were used to support several studies (Buffoni et al., 2002, Picco et al., 2008, Rusciano et al., 2013), thus contributing to the understanding of the dynamics of the area, a comprehensive analysis of the entire data-set is still missing. Twenty years after the first deployment, data have been recovered and analyzed with the aim of presenting the whole data-set and providing general statistics and additional information on its temporal variability as a reference for future investigations and climatological studies.

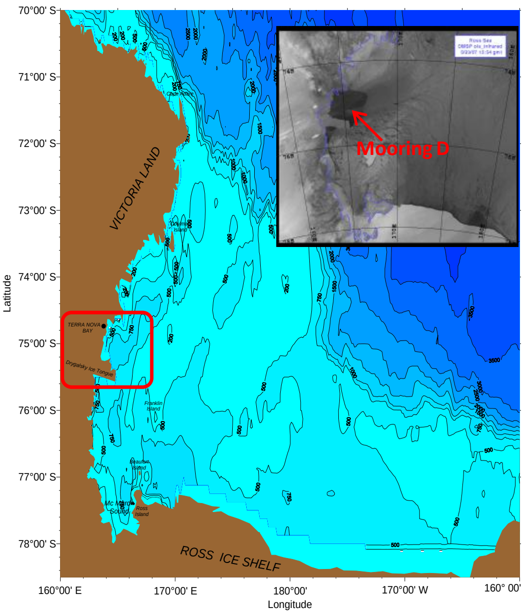

Figure1. The Ross Sea with Terra Nova Bay polynya and mooring D location.

2. Mooring D currents data-set: 1995-2001

The first deployment of mooring D in Terra Nova Bay polynya occurred on 17 February 1995, at a sea depth of 1100 m. During each summer expedition, the mooring was recovered, maintained and redeployed approximately in the same original position (75° 7.35' S; 164°27.16' E). According to the scientific priorities and logistic constraints, the payload differed from one year to the other, as listed in Table 1. Current meters were Aanderaa RCM7 or RCM9; temperature and conductivity sensors were SBE SeaCat3 or Aanderaa. As the CT probes were often redeployed without the possibility of in house calibration, temperature and conductivity data were checked against CTD casts taken at the mooring site during summer campaigns. Sampling interval was set at 30' except from current meters at 144 m, 402 m, and 882 m during 1995, which were set at 1 hour.

The upper layer data (between 55 m and 210 m) cover the period from February 17, 1995 to January 30, 2002. There were data gaps lasting up to several days due to maintenance operations and in some cases the instruments stopped to record before to be recovered because of fails in the batteries. During 2001 a second mooring (D2) with a 150 kHz ADCP was also deployed in Terra Nova Bay not far from mooring D, providing one year of 3-D currents data in the upper 160 m of the water column (Cappelletti et al., 2010).

Depth (m)							
0-100	55			122*	102*	89*	77*
100-200	140*	143*	143*				
200-300				217			
300-450	402						
450-600		585	585	565	545	525	
600-850	748	835	835	766	746	724	722
850-1000	882	979	979		1022	1000	999
Year	1995	1996	1997	1998	1999	2000	2001

Table 1. Vertical coverage of available currents measurements for each deployment. * indicates the presence of temperature and conductivity sensors inside or close to the currentmeter.

Year	Period of measurements	days
1995	17/02/95 – 13/01/96	331
1996	02/02/96 – 31/12/96	333
1997	01/01/97 – 07/12/97	341
1998	11/12/97 – 03/01/99	399
1999	18/01/99 – 15/01/00	363
2000	19/01/00 – 16/01/01	363
2001	18/01/01 – 30/01/02	378

Table 2. Detailed period of measurements of each deployment

Data quality check of currents data aimed at verifying the existence of gross errors such as outliers, flat lines, rate of change. No outliers were found, while in some cases constant data below the minimum detectable value (2 cm/s) -indicating a possible rotor stalling- were found, as well as short period of restricted direction measurements. In these cases, the comparison with data from current meters in the same mooring line to check for consistency allowed to separate low currents velocity data from possible instrument fails.

On the average, only a small percentage of bad data were detected and removed, so the whole data series was not significantly affected. Short gaps and removed bad data were filled by interpolating with non-parametric methods such as splines, to obtain continuous time series when this was necessary for the analysis, while longer periods of removed data were not amended. Additional indication about data set consistency was provided by the exam of progressive vector diagrams. In particular records collected on 1996 and 1997 at a depth of 835 m showed a not coherent pattern of currents in respect to those at 979 m and 585 m, which can be explained only in terms of malfunctioning of the instrument, so that they were not considered for the analysis.

3. General description of currents

Progressive vectors diagrams are a powerful representation which provides a first glance of the general pattern and variability of the currents. Progressive vectors of time series for each deployment were produced from daily mean data (Figure 2).

Dominant direction of currents is Northeast, along the coast, according to the general circulation of the area (Assmann and Timmermann, 2005, Jacobs et al., 2002, Locarnini, 1994) which is supported by the density gradient between the coast and the open sea due to the presence of the Ross Sea and Terra Nova Bay polynyas. Currents in the upper layer have a higher variability and may differ significantly from the layers below, both in terms of speed and pattern, as occurred during 1995 and 2000. In the deeper circulation the vertical structure is strongly barotropic; all the currents time series at the different depths maintain almost the same pattern. Approaching the bottom, due to the effects of the topography, mean currents direction tends to rotate eastward and to increase the velocity. The progressive vector of currents in the upper 160 m measured by the ADCP during 2000, are also reported in Figure 2 as a clear example of the barotropic circulation involving the upper water column.

Basic statistics of each record provided in Table 3 resumes the mean characteristics of the currents on the entire period of each record measurement, about one year.

Complex correlation coefficients among daily mean time series of current measurements on the same mooring line were computed according to Kundu (1976). Complex correlation is appropriate when dealing with 2D components currents as takes into consideration the vector characteristic of the horizontal currents. Results from complex correlation analysis support the observations and, in particular, the barotropic characteristics of the deeper circulation. Complex correlation coefficients between current records at depths below 150 m were higher than 0.8 and the angles lower than 10 degree for all the examined series, while correlation coefficients between the upper layer currents and the deeper data never exceed 0.6.

	Vx *cm s-1*	**σVx**	**Vy**	**σVy**	**Speed**	**σ**	**Dir** *(°N)*
1995							
55	-1.2	10	7.6	11.4	14.5	9.0	351
140	-1	7.1	3.2	7.3	9.5	5.0	343
402	0.6	5.9	2.3	5.8	7.6	4.0	15
748	2.7	5.5	0.9	6.0	7.4	4.4	71
882	5.3	5.7	0.5	6.5	8.9	4.9	84
1996							
143	2.0	8.9	4.3	8.0	11.3	6.0	25
585	2.2	5.7	4.7	5.4	8.0	4.9	25
835	1.2	5.7	3.6	5.5	7.1	5.2	19
979	2.7	6.0	0.7	5.2	7.2	4.5	76
1997							
143	1.5	9.2	4.4	9.6	12.3	6.8	19
585	2.0	5.4	4.6	6.2	8.4	4.6	23
835	1.5	5.3	4.0	5.3	7.2	4.8	20
979	4.2	4.8	2.4	4.0	6.7	4.1	60
1998							
122	1.1	7.8	5.5	8.3	10.4	7.7	11
217	2.5	7.2	4.1	7.1	9.2	6.7	31
565	3.6	5.2	4.6	5.5	8.0	5.6	38
766	5.5	4.7	5.0	4.8	8.7	5.2	48
1999							
102	2.6	7.4	5.6	7.6	11.0	5.5	25
545	4.6	5.6	4.0	5.9	8.6	5.4	49
746	4.4	5.1	4.5	5.7	8.5	5.0	44
1022	6.6	5.5	3.6	4.5	8.5	5.9	62
2000							
89	8.3	6.7	9.0	8.4	14.7	7.0	43
525	4.2	6.2	5.7	6.4	10.1	5.2	36
724	7.2	6.4	6.0	6.0	11.6	5.4	51
1000	8.6	6.4	5.6	6.2	12.3	5.9	57
2001							
77	2.2	7.5	5.4	5.8	11.4	6.3	14
722	5.4	5.8	6.3	6.2	10.5	5.4	43
999	2.9	4.0	8.3	6.2	10.3	5.2	26

Table 3.Statistics of each record of current measurements Vx: E-W component, Vy: N-S component σ: standard deviation

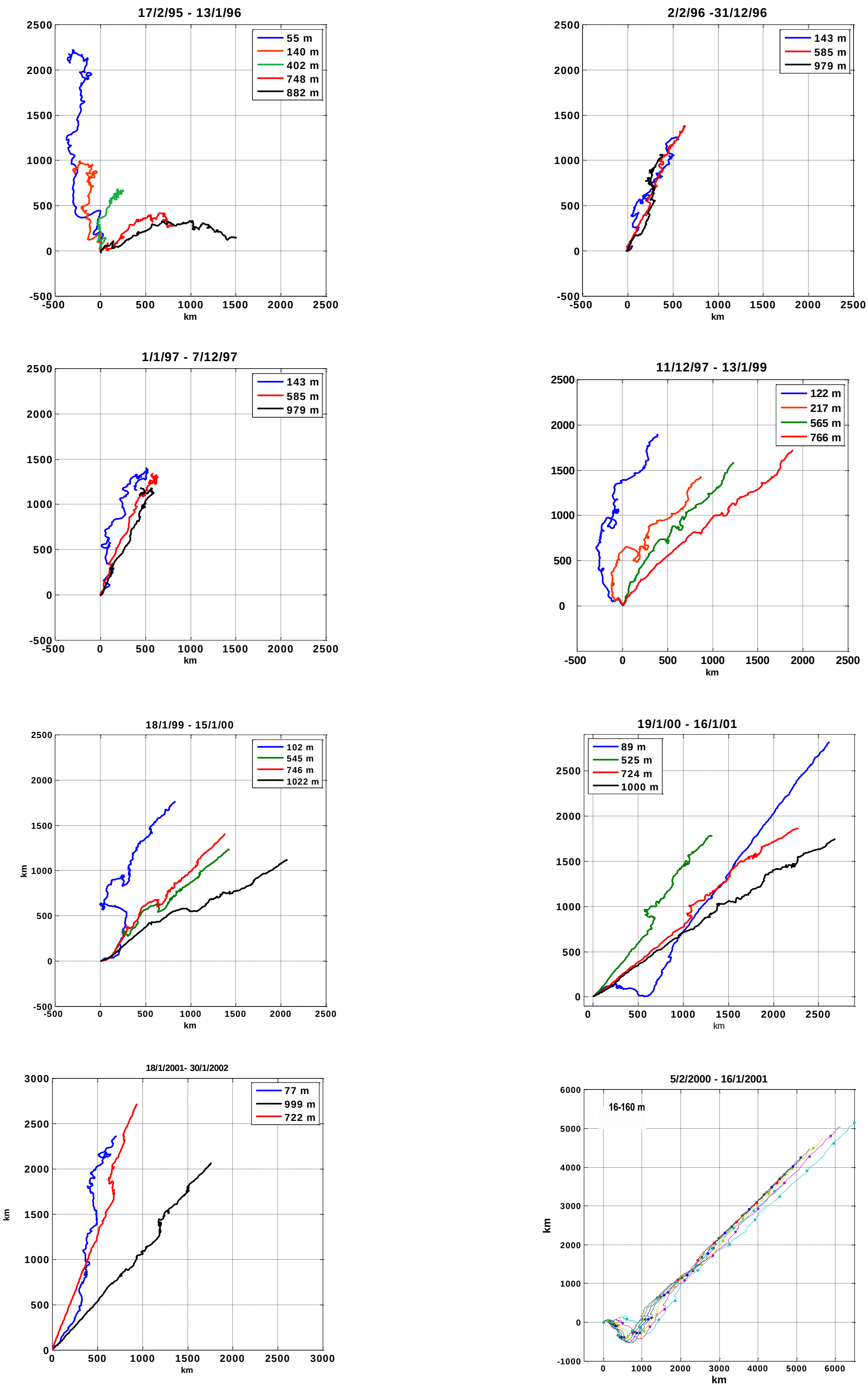

Figure 2. Progressive Vector diagrams of each record. The last is from ADCP data in the upper 160 m.

4. Currents variability

The strong barotropicity of currents observed in the examined time series at deeper layers, as well as in the ADCP data collected in 2000 in the upper 160 m allowed to merge the records, in order to obtain a unique time series to be used for long-term variability analysis. Daily mean data of East/West and North/South components were vertically spline-interpolated starting from the upper available level. The short temporal gaps were filled with spline-interpolated data and the time series at 150 m and 750 m, that were considered representative of the upper and deep layer circulation, were selected for the analysis. To better focus on the alongshore transport, data were rotated according to the main direction (where the maximum energy is found), thus obtaining the along-shore and cross-shore components. Average alongshore velocities on the seven-year period of measurements are 5.4 cm/s (std 7.9 cm/s) for the upper layer and 6.6 cm/s (std 6.7 cm/s) for the deep. It can be noted that cross shore component has an almost null average (0.02 cm/s and -0.1 cm/s), indicating no significant cross shore net transport.

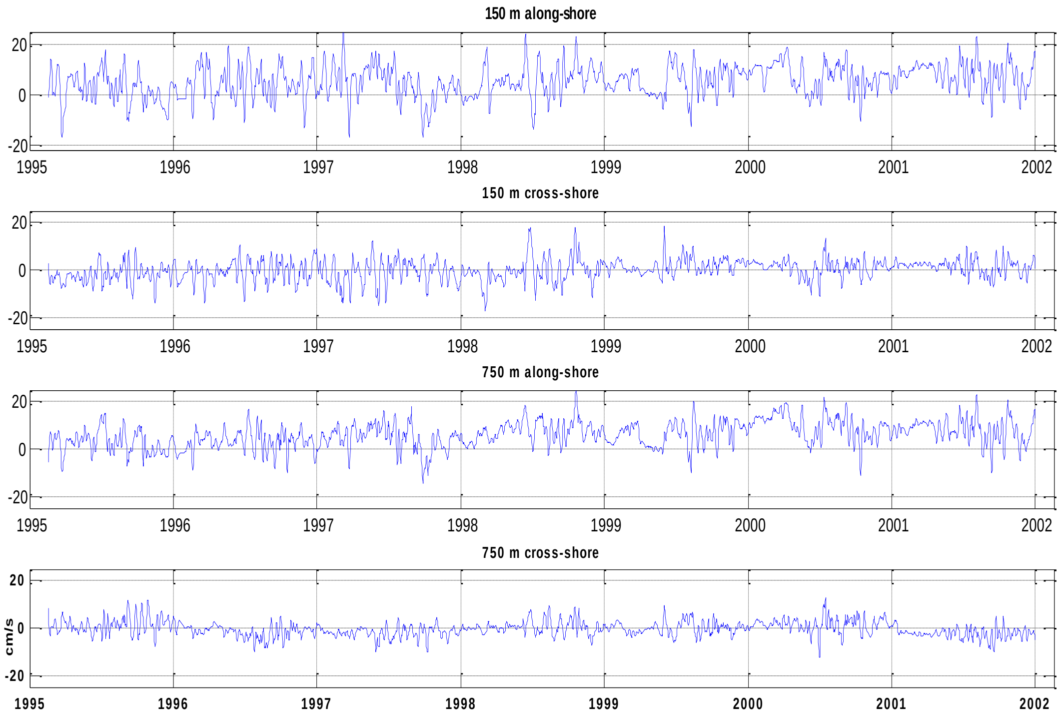

Figure.3 Time series of daily mean along-shore and cross-shore components at 150 m and 750 m smoothed with 5-ponts moving average.

The seasonal variability was evidenced by spectral analysis (Figure 4) which reveals some relevant difference between the two time series. Upper layer seasonal variability is characterized by three components on three, four, and twelve months having about the same amplitude. Currents in the deeper layer have a well defined annual cycle but no other significant peaks occur in the spectrum.

A comparison between kinetic energy and seawater density time series (Figure 5) evidences the importance of thermohaline forcing due to the dense water formation events occurring in the polynya during winter and the summer sea ice melting. A clear correspondence of maxima of kinetic energy with the rapid increase of seawater density can be found in both the upper and deep layers. Minimum kinetic energy is reached during summer months -January and February- in the deep layer while this not happens in the upper layer where an important maximum can be found at the end of the melting season in correspondence of the minimum density. During 2000 and 2001 when the annual cycle of density is smooth, there no significant differences in the kinetic energy between the upper and lower layer.

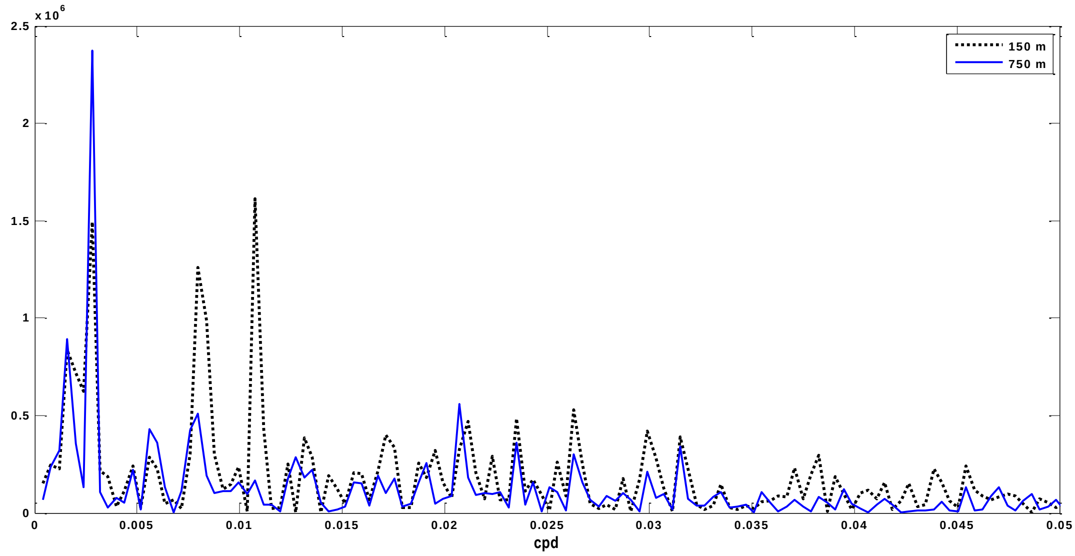

Figure 4. Power spectra of the 7-years daily mean time series: blue line for the deep layer, black dotted for the upper. Annual peak is prevailing in the deep currents spectrum.

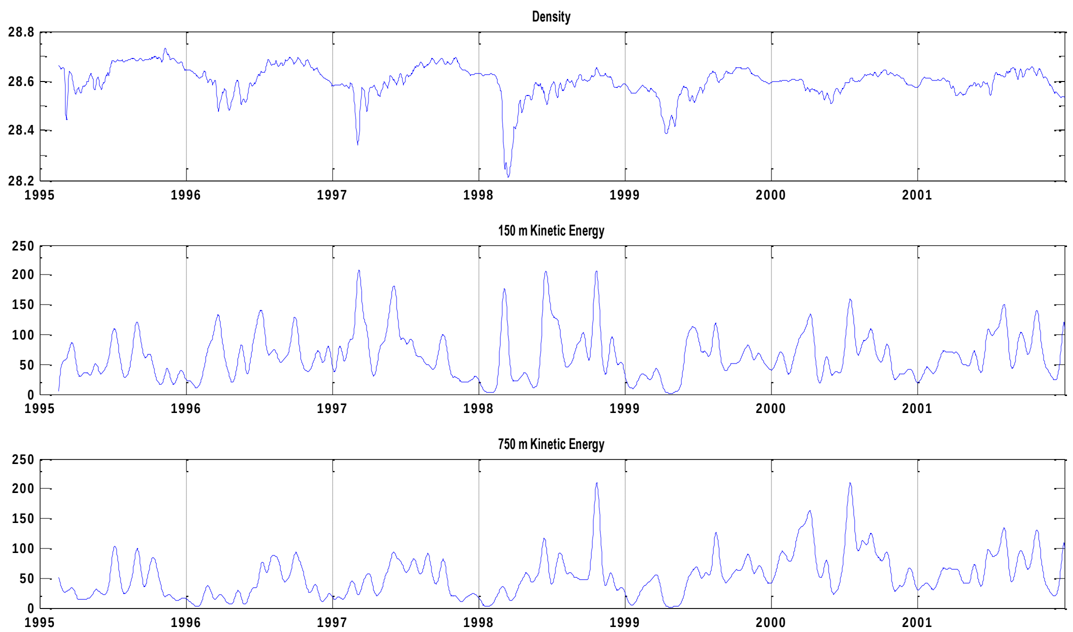

Figure 5. Time series of sea water density, smoothed kinetic energy at 150 m and 750 m.

5. Tidal and inertial currents

Daily and sub-daily variability was investigated by means of time-frequency analysis performed on each year data-set for the records in the upper layer and for the one closest to 750 m. Rotary spectral analysis (Gonella,1972) was considered particularly suited to analyze 2D vector time series such as horizontal currents, as it avoids to separately process the two components. Moreover, it has the advantage that allows identifying inertial currents -which at this latitude have the period of 12.44 h, from the semidiurnal tides, as the peak of inertial currents appears only in one part of the spectrum. To reduce both the contribution of low frequency components and the high frequency noise, data were smoothed with a three-points moving average and linearly de-trended before the analysis. Due to the high temporal resolution (30') and the length of the available time series (about one year each), it was possible to separate quite well all the different tidal components in the diurnal and semidiurnal band. The entire records of each year were firstly analyzed. This reduces the confidence level but provides a high spectral resolution. Diurnal tides strongly dominate, while the spectrum in the semidiurnal band is noisy and no particular component can be identified. The dominant diurnal component is the luni-solar (K_1) which is present in all the analyzed records and accounts for an annual mean velocity of about 3 cm/s. In most of the cases it was also possible to detect the contribution of the principal solar (P_1) component whose frequency is very close to K_1 and the amplitude of the peak is quite smaller, about 1 cm/s. O_1 (principal lunar) is generally lower than K_1, having an amplitude between 1.9 and 2.2 cm/s. Q_1 (lunar elliptic) component peak could be distinguished from the noise in several records, despite its amplitude is about 1cm/s. No relevant differences between upper and deeper layer were found. The amplitude of peaks in the semi-diurnal band -when detectable- is below 1 cm/s and in most of the cases it is better evidenced in the time series of the deeper layers which are less noisy. The relative contribution of diurnal and semi-diurnal tidal currents is also evidenced in the monthly mean complex spectra from the records collected in 1998, the longest available time series (Fig.6). The two main diurnal components peaks are neat, while the contribution in the semidiurnal band is below 1 cm/s and it is mainly concentrated in the positive part of the spectrum. This indicates that inertial currents are responsible for most of the sub-daily variability.

The temporal evolution of the tidal currents was investigated by using time-frequency analysis. A 240-h centered window and a 24-h temporal step was applied to the same records obtaining a temporal series of spectra. From each spectrum the positive and negative signal amplitude in the 24 h and 12 h bands was then extracted. This analysis is less accurate in terms of spectral resolution due to the short length of each sample, but it allows evaluating how the tidal response varies in time. All the records of time series amplitude share common features. The total amplitude (positive plus negative) of diurnal tidal component (Fig.7) is higher during winter months and can reach more than 10 cm/s, but the signal is more irregular, has an higher variability and relevant differences -both positive and negative- between upper and deeper layer are found. From November to May tidal currents are quite barotropic, fortnightly modulation is prevailing and can reduce the amplitude of the diurnal component to less than 1 cm/s in correspondence of the neap tide. Semidiurnal amplitude is by far smaller than the diurnal but the relevant difference between the clockwise and anticlockwise spectra allowed putting into evidence the occurrence of inertial currents. Inertial current have generally higher velocities in the upper layer and can persist for more than three weeks. Such episodes are detected in all the analyzed records; they appear more frequently during March - May but do not seem to show any clear seasonal trend.

year	**Depth** [m]	**K_1** (23.9 h) [cm/s]	**O_1** (25.8 h) [cm/s]	**P_1** (24.07 h) [cm/s]	**Q_1** (26.9 h) [cm/s]
95	140	3	2.2	0.9	x
95	748	3	1.8	1	x
96	143	2.8	1.5	1	1
96	835	2.8	1.4	0.9	x
97	143	2.9	2.1	x	x
97	585	2.4	2	0.9	x
98	123	2.9	2	x	x
98	766	3.3	2.6	1.6	x
99	102	3.3	1.9	1.3	x
99	746	3.2	2.0	1.1	x
00	89	4	2.9	1.9	1.5
00	724	3.7	2.5	1.7	1.1
01	77	3.7	3.2	0.9	1.1
01	722	4.2	3.1	1	1.2

Table.6. Amplitude of tidal current diurnal components for each annual record at two selected depths. x indicates no distinguishable presence of peaks.

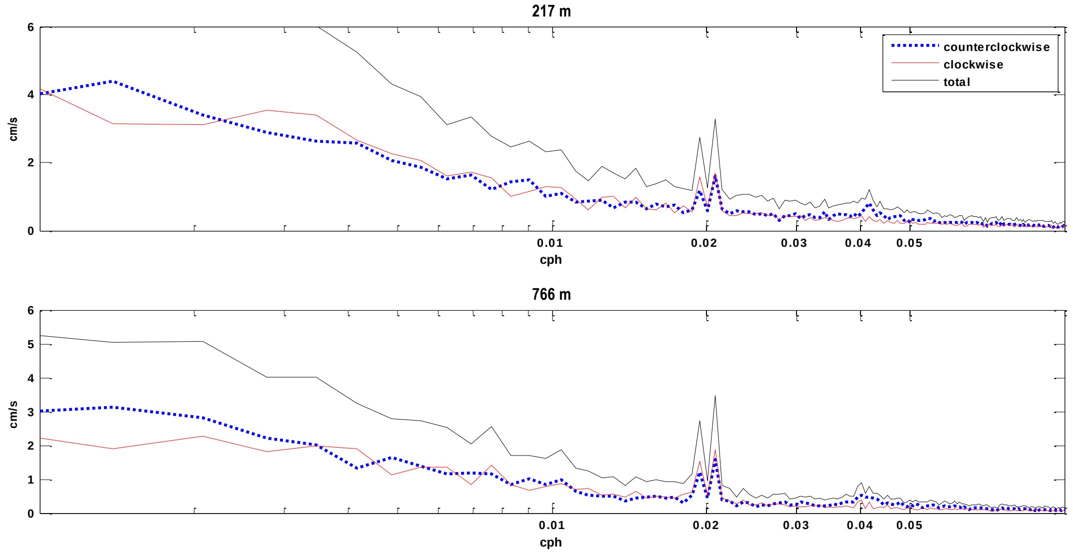

Figure 6. Rotary spectrum averaged from twelve 30-days sub-samples of currents at 217 m and 766 m depth during 1998.

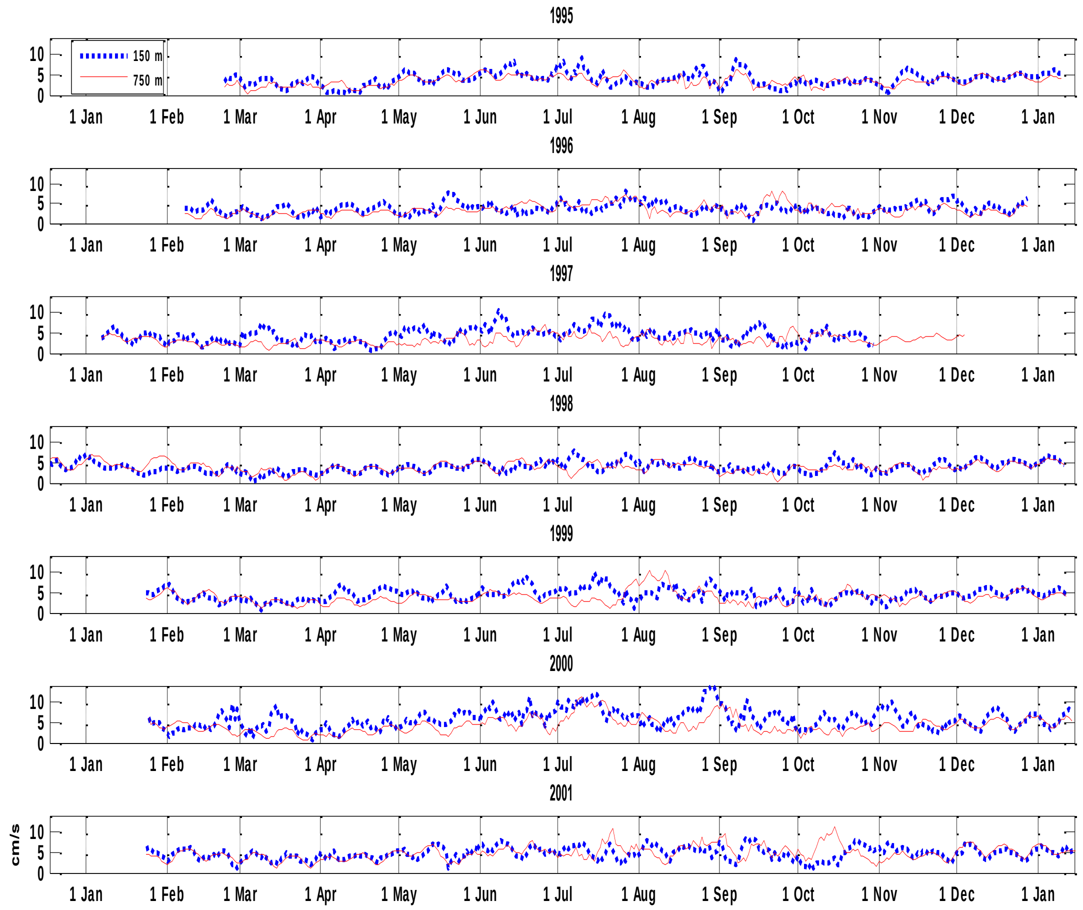

Figure 7. Results from time frequency analysis with 240 h centered window and one day time step: time series of amplitude of 24 h harmonic. Blue dotted line is for the upper layer records and red line is for the deeper as indicated in Table 3**.**

6. Summary and Conclusions

Seven years of current meters data from a fixed mooring deployed in Terra Nova Bay polynya and covering the entire water column constitute a unique and precious data-set as well as an important source of information about the dynamic of this area and its variability.

General pattern and large scale circulation of the area is characterized by a North-western current flowing along the coast. This flow has a quite stable direction but the resulting total transport shows a relevant inter-annual variability.

The vertical structure changes from an almost barotropic to a two-layer circulation: the upper layer, between the surface and 150- 200 m, where the effects of melting process are detectable and able to affect the local circulation, and the rest of the water column up to the bottom.

The strong annual cycle of deeper currents having, the maximum in winter as the results of dense water formation processing occurring in the polynya and minimum during January and February, enlighten the importance of thermohaline forcing in the circulation of the area (Buffoni et al., 2002). Ice production and dense water formation in the polynya is subject to strong inter-annual variability (Assmann and Timmerman, 2005, Budillon and Spezie, 2000) that can explain the observed inter-annual variability in the annual cycle of the deep currents.

The local variability of thermohaline forcing also plays a relevant role in determine the baroclinicity of the currents. This occurs when important density gradient resulting from sea-ice and coastal glaciers melting is able to modify the upper layer circulation.

At shorter time scales, diurnal tidal component is responsible for a good part of currents variability. Tidal currents give a relevant contribution to the general circulation of this area having speed comparable with those of the mean circulation and play an important role in the mixing and spreading of the deep waters formed in the polynya (Padman et al., 2009). The response of the basin to diurnal tidal forcing changes from a complete depth-independent, to a baroclinic, in particular during winter months. The dominance of diurnal tidal constituents in the whole area is consistent with the results of a comprehensive analysis of long-term time series of tidal currents in the Ross Sea (Johnson and van Woert, 2006).

Despite the mooring was deployed not far from the critical latitude (74°28.8'S) -where M_2 period equals the inertial- no significant basin response to semidiurnal tidal forcing was found. Very low semi-diurnal tidal currents in the area of the measurements also resulted from an M_2 forced dynamical model simulation in the Ross Sea (Robertson et al., 2003) which identified an amphidromic node in front of the Ross Ice Shelf at 178°W and higher semi-diurnal currents close to the shelf-break and in the western area of the basin.

On the contrary, persistent inertial currents reaching velocities up to 25 cm/s were often observed, in particular in the upper layer. It cannot be determined whether these oscillations are produced locally or propagate from the shelf break where can be excited by semi-diurnal tides, as suggested by model results (Robertson, 2005).

The obtained results, based on the longest available current-meter time series in the area, can represent a reference for future climatic studies and numerical simulations and put into evidence the importance of long term monitoring and data preservation and dissemination.

Acknowledgment

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