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Research papers

Evidence of atmosphere–sea ice–ocean coupling in the Terra Nova Bay polynya (Ross Sea—Antarctica)

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ABSTRACT

A rare long time series of hydrographic profiles and moored current meter data, collected from 1995 to 2008 in Terra Nova Bay polynya, are used in combination with meteorological data, acquired by an Automatic Weather Station, and remote sensing data from a Special Sensor Microwave/Imager. The behaviour of Terra Nova Bay coastal polynya in terms of air–ice–sea interactions and the consequent High Salinity Shelf Water production are detailed. The katabatic regime that characterizes Terra Nova Bay polynya is investigated and different types of events are distinguished on the bases of their duration and intensity. The more frequent katabatic events take place during the winter season from April to October, blowing on average 1–7 h, with speed between 25 and 56 m s⁻¹ and they abruptly end in just a few hours. The link between the persistence of the wind and the opening of the polynya is showed. In particular, an increase of the open water percentage in correspondence with each katabatic event of long duration is detected. Terra Nova Bay polynya appears characterized by two different periods of activity during the winter season. A period characterized by a considerable sea-ice free area and by an increase in salinity along the water column (from July to November), which is preceded (from March to June) and followed (from December to February) by a period in which the polynya is still open but the salinity of the water column decreases. While the period between July and November appears related to a maximum efficiency of Terra Nova Bay polynya in the sea-ice production, the period from March to June marks a “partial” functioning of the polynya. During March–June, the polynya is partially free of ice and consequently the brine is released but, at this time of year, it is merely increasing the salinity of the upper layer of the ocean, reducing the stratification, but not causing High Salinity Shelf Water to be formed.

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1. Introduction

Polynyas are persistent and durable ice-free areas in otherwise ice-covered waters. Polynyas are formed and maintained by off-shore winds, tides and currents advecting the ice away from the coast (latent heat polynya) or by upwelling warm water, melting the ice cover (sensible heat polynya).

Terra Nova Bay (TNB) polynya is a coastal latent heat polynya located in the western sector of the Ross Sea, delimited south by the Drygalski Ice Tongue (DIT) and north by the Campbell Ice Tongue. The katabatic winds are thought to be wholly or partly responsible for the formation of this polynya (Bromwich and Kurtz, 1984; Kurtz and Bromwich, 1985). More precisely, TNB polynya, oriented in a west–east direction, is formed and maintained by the combined influence of the persistent katabatic winds, which advect newly formed bay ice eastward, and by the

DIT which prevents northward drifting pack ice from entering TNB (Bromwich and Kurtz, 1984; Kurtz and Bromwich, 1983, 1985; Parish and Bromwich, 1989; Bromwich and Geer, 1991). Existence of anomalously strong katabatic drainage along TNB coast is predicted by Parish's (1982) simulation of wintertime airflow, which reveals a pronounced confluence of surface winds upslope from the Reeves Glacier (see Fig. 1 in Bromwich and Kurtz (1984), for the Reeves Glacier location), where the winds are further focused by local topography. The blocking effect of the DIT is a consequence of its orientation with regard to western Ross Sea ice drift patterns; ice tongue length controls polynya width. Absence of such blocking along other coasts experiencing strong katabatic outflow partly explains why similar polynyas do not form there (Bromwich and Kurtz, 1984).

In latent heat polynyas, the intense heat loss from the open water (sea water free by the sea ice) to the atmosphere leads to rapid and persistent ice growth. Brine rejected from growing sea ice forms dense brine-enriched shelf waters that, accumulate near the bottom of basins and eventually spill toward the deep sea as dense plumes. Thanks to this process, TNB polynya plays an

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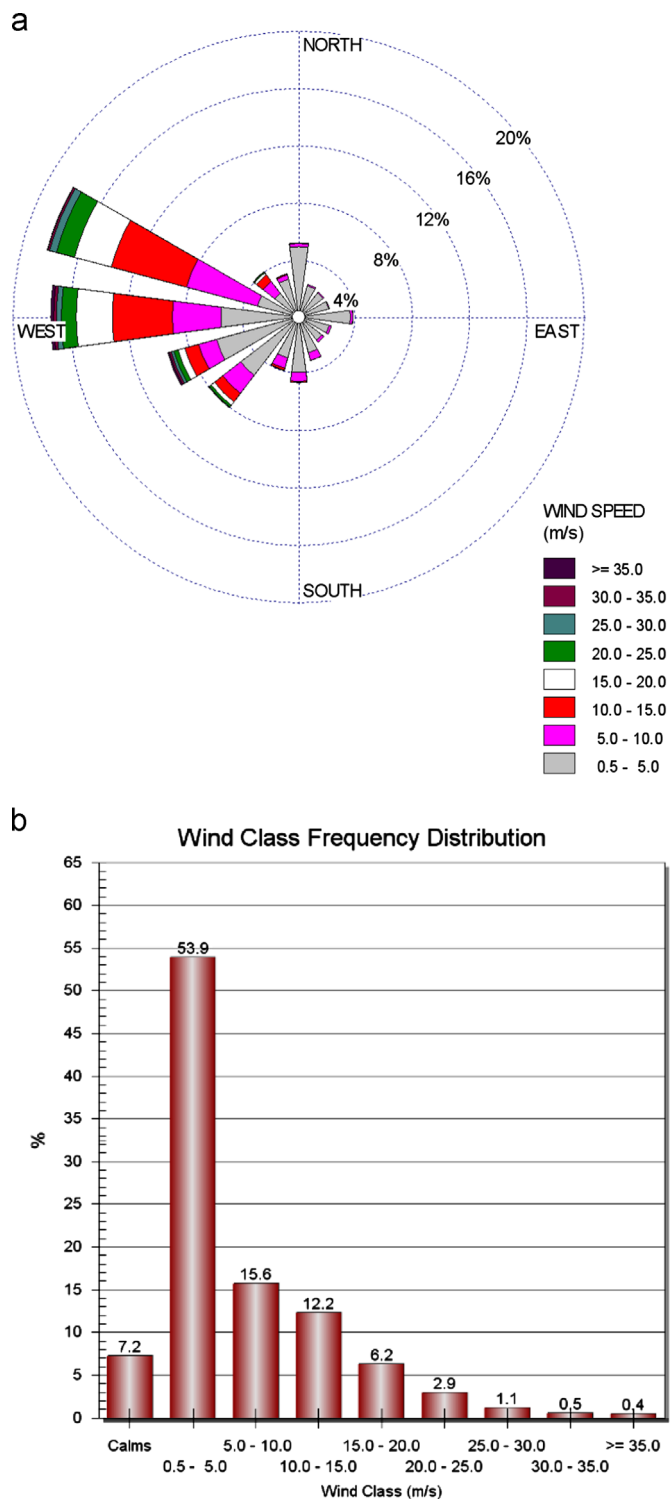


Fig. 1. (a) Wind rose and (b) class frequency distribution from AWS Eneide data in the period 1995–2006.

important role in the formation of salty shelf water in the western Ross Sea; brine released during sea ice formation increases the salinity of the subsurface waters, resulting in the formation of High Salinity Shelf Water (HSSW), the densest water mass of the Southern Ocean (Kurtz and Bromwich, 1983, 1985; Jacobs et al., 1985; Van Woert, 1999a, b; Budillon and Spezie, 2000; Budillon et al., 2003; Fusco et al., 2009). The dense HSSW represents a key element in the formation of the Antarctic Bottom Water (AABW) (Jacobs and Comiso, 1989; Kurtz and Bromwich, 1985; Van Woert,

1999a), the cold and dense water mass that occupies the deep layers of the oceans and contributes to the lower limb of the Meridional Overturning Circulation (Jacobs, 2004). Although the extent of TNB polynya is relatively small, it is involved in intense heat exchange between air and ocean (e.g.: Fusco et al. 2002, 2009), in primary and secondary production and in the formation of sea ice. Estimated cumulative ice production over the winter is around 40–60 m of ice (50–80 km³), which represents about 10% of the annual ice production over the Ross Sea continental shelf (Kurtz and Bromwich, 1985; Van Woert, 1999b).

The polynya is important for the modification of HSSW, as brine plumes produced during ice formation salinize about 1 Sv of HSSW exported from the polynya (Kurtz and Bromwich, 1985; Van Woert, 1999b; Budillon and Spezie, 2000). Increased benthic-layer salinity over the western Ross Sea continental slope reflects the greater access of HSSW to that region. The most saline and densest HSSW layers are trapped within the topographic depression formed by sills at the shelf break. The trapped components of HSSW water may flow northward along the western sector of the Ross Sea as far as the continental shelf break (Budillon et al., 1999), where it takes part in the formation of the AABW by mixing with the Circumpolar Deep Water (CDW) (Bergamasco et al. 2004; Gordon et al., 2008). Another branch flows southward under the Ross Ice Shelf, where the cooling and melting at different depths forms the Ice Shelf Water (ISW), characterized by a temperature lower than the freezing point at the surface pressure. ISW is primarily found on the central continental shelf of the Ross Sea (Budillon et al., 2002; Jacobs et al., 1985), from where it moves northward toward the shelf break to give a further contribution to the AABW formation (Jacobs et al., 1985). In this sector of the Ross Sea, the AABW is slightly different, being fresher and colder (Budillon et al., 2011), than the AABW formed by the HSSW at the western shelf break.

Recent observations along the Antarctic shelves, although discontinuous and sparse, show that AABW has declined in salinity in recent decades highlighting the importance to continuously monitor this area, and emphasizing its key role in the global climate system (Robertson et al., 2002; Jacobs, 2004; Smedsrud, 2005; Rintoul, 2007; Ozaki et al., 2009). Variations in the occurrence and size of polynyas might be suitable indicators of any on-going climatic alteration. Elucidate the interactions between polynyas and their environment is important to determine the role of high latitudes in global climate, especially with regard to deep ocean ventilation, and is without doubt one of the major challenges of present-day polar research (Morales Maqueda et al., 2004).

The observational results showed that, during the second half of the 20th century, bottom water formed in the Ross Sea and offshore of Adélie Land has gradually freshened and a similar behaviour was observed also for the AABW in the Australian Antarctic basin (Whitworth, 2002; Jacobs et al., 2002; Jacobs, 2004, 2006; Aoki et al., 2005; Rintoul, 2007). The Adélie Land Bottom Water (ALBW), which is formed by both the dense shelf water in the Mertz Glacier Polynya and the inflowing high salinity of the Ross Sea Bottom Water (RSBW) (Rintoul, 1998), has also freshened from the mid-1990s to the early 2000s (Aoki et al., 2005). Further the AABW in the Australian Antarctic Basin freshened rapidly from the mid-1990s to the mid-2000s (Rintoul, 2007). The causes of the freshening are considered to be glacial ice melting, an increase in precipitation, or a decrease in sea-ice formation (Jacobs, 2004; Rintoul, 2007). According to Tamura et al. (2008) the ice production in the Mertz Glacier Polynya has not decreased, but they propose that the decrease in ice production, in the Ross Ice Shelf Polynya, is responsible for the recent freshening of RSBW, ALBW, and AABW in the Australian Antarctic Basin. In-situ observations showed the salinity of the RSBW significantly

decreased from 1997 to 2001 (Bergamasco et al., 2004). A similar trend was detected by Budillon and Spezie (2000) and, more recently, by Fusco et al. (2009) in TNB polynya at the end of the 1990s. Jacobs et al. (2002) report a general freshening by 0.1 of Ross Sea HSSW, observed along the front of the Ross Ice Shelf, from the 1960s to 2000. If this salinity change extends throughout the HSSW volume, then it may be expected that bottom water over the continental slope would have been similarly reduced in volume over the same period (Gordon et al., 2008).

Our study shows the seasonal and interannual variability in the water column stratification and details the variability of HSSW production as consequence of the polynya activity. This evaluation has been achieved by conducting an extensive analysis of the hydrographic mooring and CTD (Conductivity-Temperature-Depth) profile data, collected during almost 13 years (February 1995–January 2008) in the framework of the CLIMA (Climatic Long-term Interactions for the Mass-balance in Antarctica) project of the Italian National Research Antarctic Program (PNRA). Meteorological observations, acquired by an Automatic Weather Station (AWS) within the Meteo-Climatological Observatory of the PNRA, and the sea ice concentration, obtained by Special Sensor Microwave/Imager (SSM/I) data set, were also analysed. In Section 2, we present more details on the data used in our analyses. In Section 3, we describe the characteristics of the different water masses circulating in the polynya area and the seasonal variability of the thermohaline properties of these water masses. We examine the katabatic regime that dominates the bay in Section 4 and the sea ice coverage in Section 5. In Section 6, we discuss the interactions between the katabatic winds and the open water percentage in the polynya area with the thermohaline features of the water column. In Section 7, we provide a summary along with some concluding remarks.

2. The data

Long time series of temperature and salinity from CTD and moored current meters, and meteorological data acquired by an AWS, are used in combination with remote sensing data from SSM/I, to derive the dynamics of TNB polynya. In the following, details on each data set used are reported.

2.1. Meteorological data

Meteorological data are acquired by the AWS Eneide installed on TNB (74°41'S–164°05'E) in 1987, providing data with 1 h time resolution. Data and information were obtained from 'Meteo-Climatological Observatory' of PNRA. The AWS Eneide is equipped with sensors to measure: temperature, relative humidity, atmospheric pressure, wind direction, wind speed, solar radiation and snow depth. In this study, we analyse temperature, wind direction, wind speed and relative humidity data set (data available on the web page: www.climantartide.it), acquired between January 1995 and October 2006, in order to characterize the katabatic wind regime in TNB area. In Fig. 1 wind rose (a) and class frequency distribution (b) between 1995 and 2006 are shown. The greater percentage of the winds comes from the W-WNW sectors and the winds that blow with speed over 20 m s^{-1} come only from the western sector (Fig. 1).

2.2. Hydrographic data

CTD profiles and water samplings were performed in TNB polynya (Fig. 2), during 1995 and 2006 in the summer period, using an SBE 9/11 Plus CTD equipped with different sensors (double temperature and conductivity sensors, oxygen, light

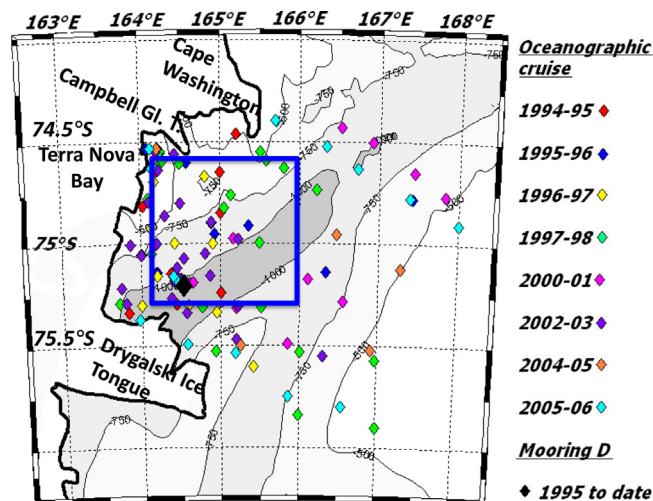


Fig. 2. Coloured diamonds indicate the position of the hydrographic casts collected between 1995 and 2006 in the Terra Nova Bay polynya during the summer period. The black diamond indicates the position of the mooring "D". The blue quadrant indicates the area over which we looked for sea ice concentration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

transmission, fluorescence, pH) coupled with an SBE 32 Carousel sampler, carrying 24 bottles of 12 l each. Temperature and conductivity sensors were calibrated before and after the cruise at the SAACLANT CENTRE of La Spezia (Italy). During the cruise, the CTD temperature was controlled by means of two SIS RTM4200 digital reversing platinum thermometers and with a Guildline Autosol 8400b model Salinometer. At every station, several replicate samples were collected at all depths and analysed on board. Hydrographic data were then corrected and processed according to international procedures (UNESCO, 1988). Standard algorithms (UNESCO, 1983) were used to compute quantities such as potential temperature, salinity, and potential density anomaly.

2.3. Mooring data

A mooring was deployed in TNB polynya (75°06.10'S 164°13.04'E) in 1995 (see Fig. 2 for mooring location) by the CLIMA Project in the framework of the PNRA. The mooring was equipped with sediment traps, turbidity meters, Aanderaa RCM7/9 current meters and SBE16 temperature/conductivity recorder at different depths. The mooring was deployed on 17 February and successively was recovered and re-deployed approximately each year providing up to 2008, a unique time series of 13 years which represents an exceptional opportunity for oceanographer in polar areas. The subsurface data set ended in 2002 since the surface instruments were damaged by a mega-iceberg. After that, only data acquired from instruments below 800 m depth are available (Fig. 3). In this work, we analyse only the salinity and temperature data collected by the SBE SeaCat instruments due to the higher accuracy of these sensors compared to those used by Aanderaa instruments. The accuracy of the temperature sensor (SBE SeaCat) is $\pm 0.002 \text{ }^\circ\text{C}$ with an interval of measure between -5 and $+35 \text{ }^\circ\text{C}$; the accuracy of the conductivity sensor (SBE SeaCat) is $\pm 0.0003 \text{ S m}^{-1}$ ($0.003 \text{ mmho cm}^{-1}$) with an interval of measure between 0 and 7 S m^{-1} . The temperature and salinity data recorded in the deep layers (from year 2000 to 2005) were validated and corrected with CTD measurements, performed in the TNB area during the recovering and deploying of the mooring.

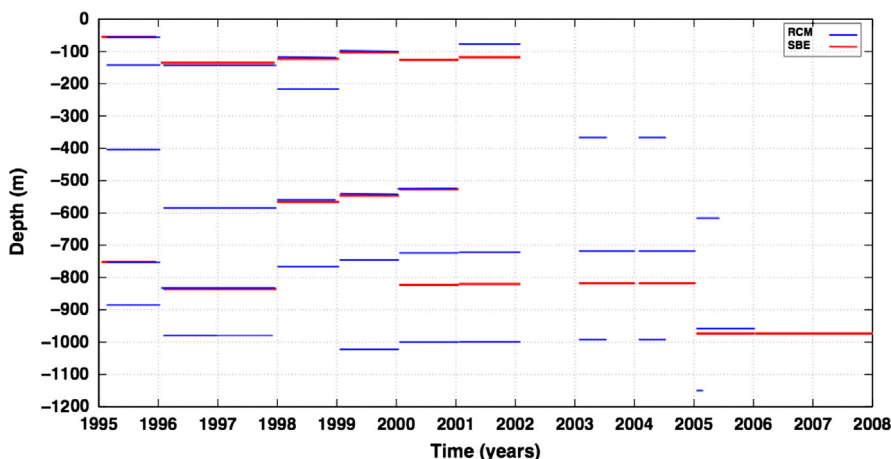


Fig. 3. Details of data set acquired by mooring with Aanderaa RCM7/9 current meters and SeaCat SBE16.

2.4. Remote sensing data

During winter, heat loss over thin ice is one or two orders of magnitude larger than the heat loss over thick ice. For this reason, coastal polynyas are regarded as the ice production factories. Active and passive satellite microwave data are very strong tools to detect polynya areas as thin ice regions (Markus and Burns, 1995; Martin et al., 2004; Wakabayashi et al., 2004; Kwok et al., 2007).

The sea ice concentrations, located in a quadrant at 74.7°S 75.2°S–164.1°E 166°E (Fig. 2), between 1995 and 2005, are used to study the polynya opening. The study area does not cover the coastal band along the DIT and the TNB to avoid the error related to the land contamination due to the data spatial resolution. Concentration values were computed from the brightness temperatures data by the National Snow Ice Data Center (NSIDC) using the NASA Team Sea Ice Algorithm (Swift and Cavalieri, 1985). The brightness temperature was detected by the Special Sensor Microwave Imager (SSM/I). The data set of the sea ice concentration is available on the NSIDC web page and is provided in the polar stereographic projection at a grid cell size of 25 × 25 km, (for more information look to the NSIDC web site reported in bibliography).

3. Thermohaline characteristics and seasonal variability in TNB polynya

3.1. Water masses circulating in TNB polynya

The vertical structure of the water column in TNB polynya appears relatively simple (Fig. 4). The greatest thermohaline variability is observed in the surface layer, from the surface to 50–150 m depth (Fig. 4a and b). Below this layer, the water column is nearly isothermal and the vertical stability is preserved by the increasing salinity. During the summer period (November to March), the vertical profile of the water column may, therefore, be considered composed by two layers. The Antarctic Surface Water (AASW) occupies the upper layer that, during the summer, becomes fresh and warm because it is influenced by the sea-ice melting and by the heat gained from the solar radiation. The solar radiation heating represents the main constituent of the surface heat balance in this region, during the summer period (Budillon et al., 2000). Below this upper layer, the water column is characterized by the presence of HSSW with a potential temperature close to the surface freezing point and $S > 34.7$.

At intermediate depths, of the quasi-isothermal HSSW layer, the Terra Nova Bay Ice Shelf Water (TISW), characterized by temperatures lower than the surface freezing point, is found (Budillon and Spezie, 2000). This water mass is formed by the interaction of the salty HSSW with the base of the glacial ice. TISW has an origin similar to the Deep Ice Shelf Water (Jacobs et al., 1985), which is found in the southern sector of the Ross Sea, emerging beneath the Ross Ice Shelf, spreading to the shelf break and playing an important role in deep water formation (Bergamasco et al., 2002; Budillon et al., 2002; Rubino et al., 2003).

The presence of the water masses described above is also evident in the potential temperature–salinity (θ – S) diagram (Fig. 4c) of the CTD profiles acquired in TNB polynya.

3.2. Seasonal variability of temperature and salinity

Fig. 5 shows the time series of temperature and salinity, acquired by SeaCat SBE16 from February 1996 to December 2000 in the shallow layer (100–150 m). The temperature is close to the surface freezing point during the winter period, from May to October, and it warms slightly in November. The salinity increases between May and early November in response to the brine rejection by sea ice and it decreases between November and April (Fig. 5). During March–April (1995–2000) in the shallow layer (103–142 m), a particular behaviour of the seawater properties is observed. Large temperature and salinity fluctuations occur during this period and small fluctuations continue until July, when the water temperature reaches the freezing point. During the end of summer (March–April) a pulse of warm and fresh water was monitored in TNB. In this period we might have expected the water masses to get salty and cold under the katabatic winds effects, resulting in the consequent HSSW formation. This particular behaviour lasts for about 15–40 days, with the core of the event during March–April. It is characterized by different intensities each year and it appears more prominent during 1998 with temperature range between $-1.7^{\circ}\text{C} \leq T \leq -1.1^{\circ}\text{C}$ and salinity range between $34.1 \leq S \leq 34.42$ (Fig. 5).

The same phenomenon was observed during 1999–2000 in the water properties of McMurdo Sound (Hunt et al., 2003). The data acquired in this area reveal unexpected seasonal temperature changes with large warm temperature excursions during the summer. In year 1999–2000, two prominent episodes of warming are detected, around mid-January and early February, which raised water temperatures above -0.5°C . Maximum water temperatures occurred in mid-January, reaching -0.347°C at the Cape Armitage and -0.436°C at the jetty site (look at Fig. 1 in Hunt et al. (2003) to see the location of Cape Armitage and the jetty site). During the

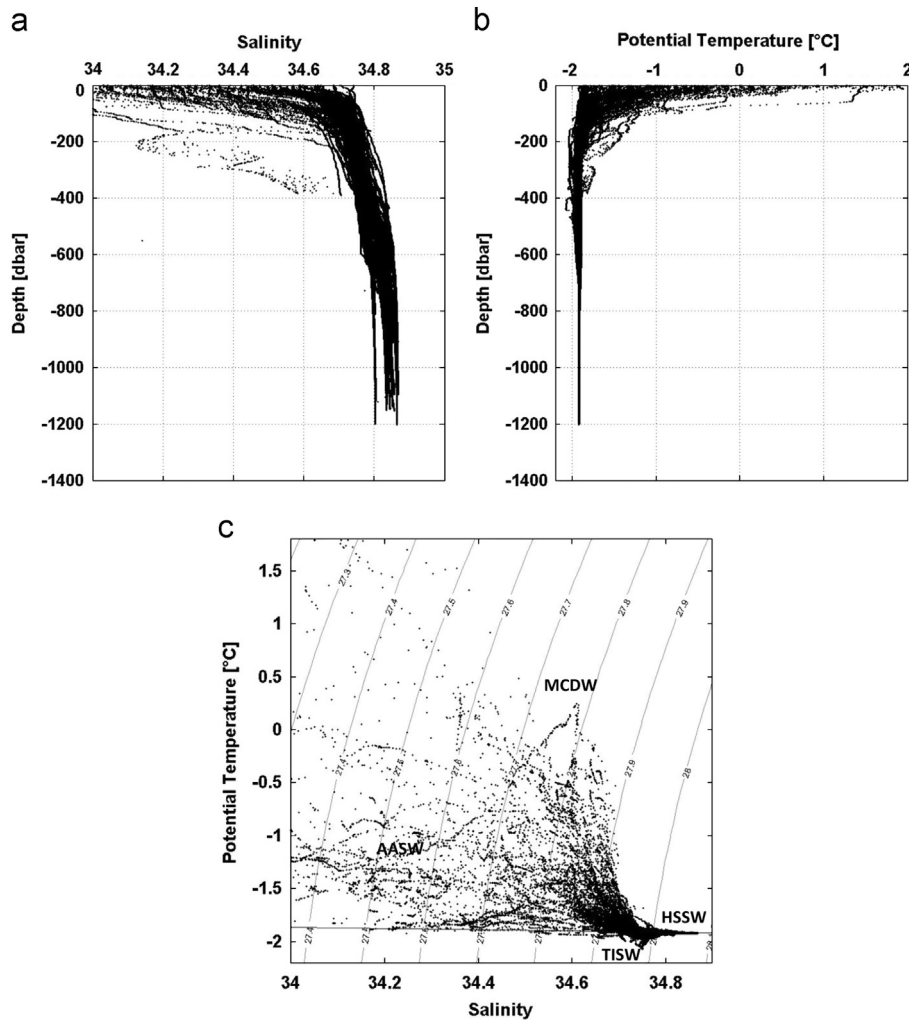


Fig. 4. Vertical profile of (a) salinity, (b) potential temperature and (c) potential temperature versus salinity diagram of the hydrographic casts collected in the Terra Nova Bay polynya.

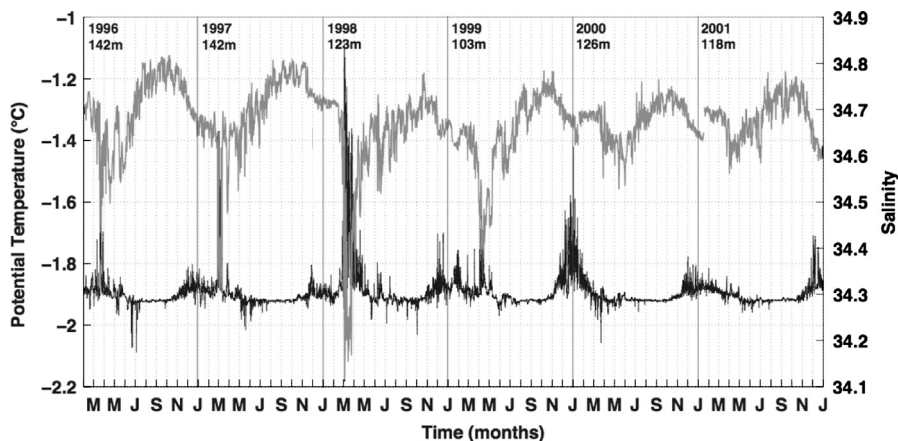


Fig. 5. Time series of temperature and salinity acquired by SeaCat SBE16 from February 1996 to December 2000. Instruments depths and acquisition year are shown.

second year (2000–2001) maximum temperature at the jetty site was $-0.648\text{ }^{\circ}\text{C}$, cooler than prior year's maximum, and occurred in February (Hunt et al., 2003). The fact that the warming episodes observed in McMurdo Sound show temperature fluctuations greater than those observed in TNB (temperatures in McMurdo are warmer of about $0.7\text{ }^{\circ}\text{C}$) is quite certainly due to the fact that the data set acquired in McMurdo are relative to the shallow water

(9 m and 40 m depth) and to a different environment. Despite some differences between the phenomenon observed in TNB and McMurdo Sound, these warming episodes were completely unexpected and contrary to the existing expectation of the thermal stability of these two areas.

About the episodes observed in TNB, different speculations were made to explain the presence of the warm and fresh water

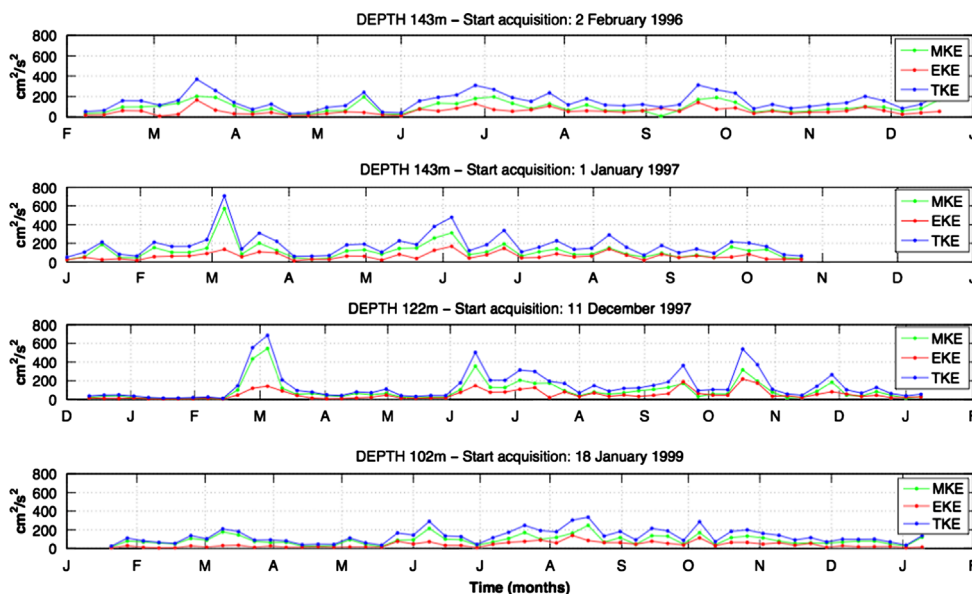


Fig. 6. Time series of mean kinetic energy (green lines), eddy kinetic energy (red lines) and total kinetic energy (blue lines) for all surface current meters (instruments depths and start acquisition are written on the top of each figure). The units are energy per unit mass. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mass monitored during March–April in the polynya area. For us, the most accredited hypothesis is linked to the presence of the coastal AASW and the presence of a cyclonic gyre in TNB. The AASW is formed in summer, after pack ice and glacier melting. This coastal water, warm and fresh, at the end of summer (February to April) can be found at 100–200 m depth (Fig. 5), probably advected in the mooring location from a nearby area. Indeed the position of the mooring is marginal to the area where Van Woert et al. (2001), using satellite data, show a cyclonically rotating gyre in the bay. This gyre might produce an up-welling phenomenon in the central area of TNB and the fresh and warm AASW is thus, advected and accumulated in the outer part of the gyre. In turn, this process will produce, causing of the blocking effect of the DIT, a down-welling phenomenon in the area where the mooring is located. Once removed the AASW, produced during the summer period, it is necessary to wait for the next year so that the cycle will be repeated. In the other months of the year, the gyre will draw only waters now homogeneous with the surrounding sea, covered by ice.

To more speculate about this phenomenon the mean, eddy and total kinetic energy are calculated using the data acquired by the sub-surface current meters. The total kinetic energy is given by:

$$TKE = \frac{1}{2} |\vec{V}|^2 \quad (\text{energy per unit mass})$$

where $|\vec{V}|$ represents the magnitude of the total velocity vector of the current.

$$MKE = \frac{1}{2} (\bar{u}^2 + \bar{v}^2)$$

where u and v represent, respectively, the zonal and vertical component of the mean field of the velocity averaged in the time.

$$EKE = \frac{1}{2} (\bar{u}'^2 + \bar{v}'^2)$$

where u' and v' represent the fluctuation in relation to mean zonal and meridional component of the velocity vector.

The distribution of the mean and eddy kinetic energy is computed on the weekly average of the velocity current.

In Fig. 6 the spikes in energy associated with the warm and fresh events are mainly observed in the mean kinetic energy, especially in March 1997 and February–March 1998 to suggest that

mean currents or larger eddies are causing the phenomenon observed in the sub-surface layer. This particular phenomenon was not yet observed in others polynyas of the Southern Ocean because of its specific preconditions (the presence of coastal, warm, fresh and surface water and of a cyclonically rotating gyre in the central part of the polynya). Unfortunately, the lack of a high-resolution model that reproduces the TNB polynya behaviour, all year long, does not allow validate this speculation.

The intermediate and deep layers show, as expected, a lower seasonal variability. In Fig. 7 are shown the time series acquired, respectively at 566, 546 and 526 m depth, during the years 1998, 1999 and 2000. The temperature and salinity values at intermediate depth are more stable than the sub-surface values but we can observe a consistent interseasonal and interannual variability at this depth. In 1998, the temperature is characterized by values lower than the surface freezing point with some unexpected peaks of about -1.98 °C during the end of March, due to the presence of TISW, and some peaks at -2 °C during June and July (typically the winter season). These low temperature values are also detected during the year 1999, but the shift from summer temperature values to winter values is observed one month earlier (May and June). During the year 2000, only small temperature oscillations are visible during the end of March and the end of May. The salinity values are more similar to those acquired at the sub-surface layer and the salinity increases to values higher than 34.8, during the winter season (due to the brine releasing during the polynya activity).

4. Katabatic regime

In order to study the polynya response to the wind forcing, the katabatic regime that dominates TNB was analysed. As shown before (Fig. 1), the greater percentage of the winds measured by the AWS Eneide comes from the W-WNW sectors and the winds that blow with speeds over 20 m s^{-1} come only from the western sector. These fields are those where katabatic winds coming down from the Antarctic Plateau invest the polynya. After having seen the seasonal trend of this wind with its mean speed and direction, we established some objective criteria to distinguish a katabatic

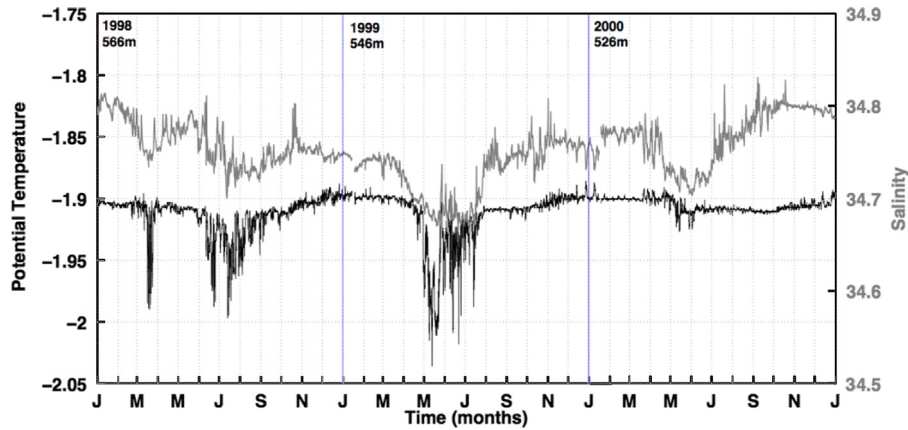


Fig. 7. Time series of temperature (black) and salinity (grey) at the intermediate layer from mooring D. Instruments depths and acquisition year are also shown.

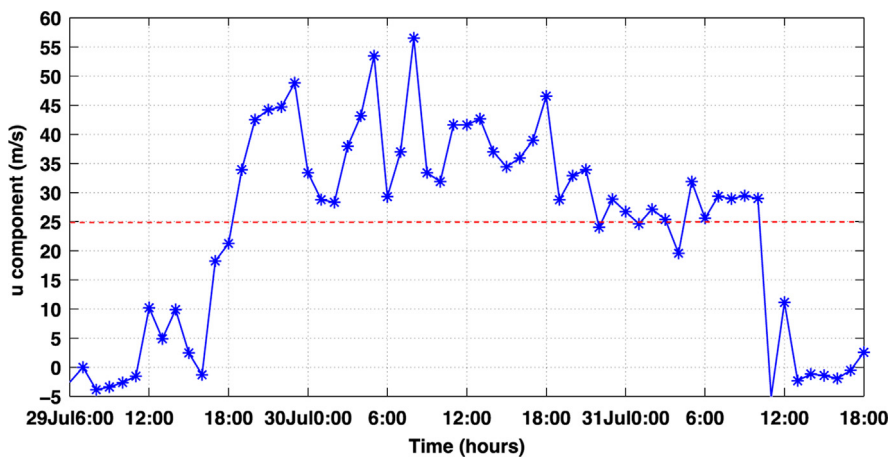


Fig. 8. Example of uninterruptedly katabatic event detected during 2005.

event from the normal wind intensification. The criteria, applied to the zonal component of wind speed (u) and wind direction (D), are:

$$u \geq 25 \text{ ms}^{-1}$$

$$270^\circ \leq D \leq 360^\circ$$

It was not possible to define a further condition based on the humidity of the air, as it has been observed that, in this area, the katabatic winds (typically dry as originated on the Antarctic Plateau) may sometimes raise enormous amount of sleet, which increases the artificially humidity value.

Using our criteria, we distinguished different types of events on the bases of their duration and intensity. As an example, in Fig. 8, a katabatic event lasting about 40 h almost uninterruptedly is showed. We noted that the more frequent events blow with speed between 25 and 56 m s^{-1} and they drastically interrupt in just a few hours.

Lastly, we characterized all the katabatic events occurred during the investigated period in the polynya area. Each circle in Fig. 9 represents a katabatic event that occurred a specific day and its colour indicates the duration of the event in hours. The more frequent katabatic events take place during the austral winter (April to October) and they last a few hours, between 1 and 3 h. The longer events occur between June and September and they last more than 7 h. A long event, lasting 33 h continuously, is observed in June.

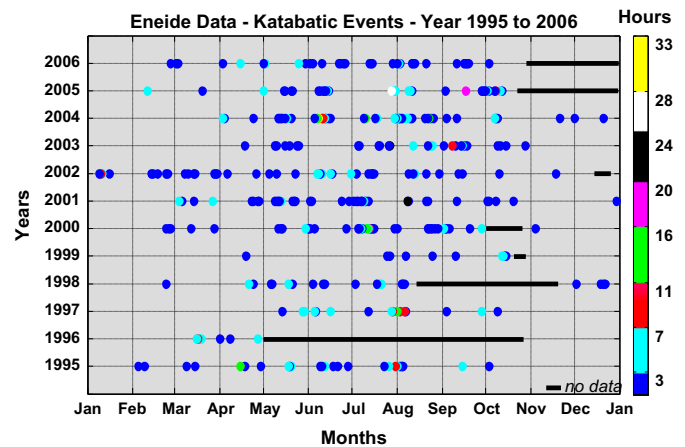


Fig. 9. Katabatic event in Terra Nova Bay from 1995 to 2006. Each circle represents a single katabatic event, the colour indicates the duration in hour. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Sea ice and open water

The presence of sea ice in the polynya is strictly linked to the major or minor activity of the polynya itself. In order to investigate this link and to identify the period of major polynya activity, we analysed the time series of the sea ice concentration between 1995 and 2005, obtained by the SSM/I brightness temperature. The sea ice concentration is an average concentration from a $60 \times 70 \text{ km}$

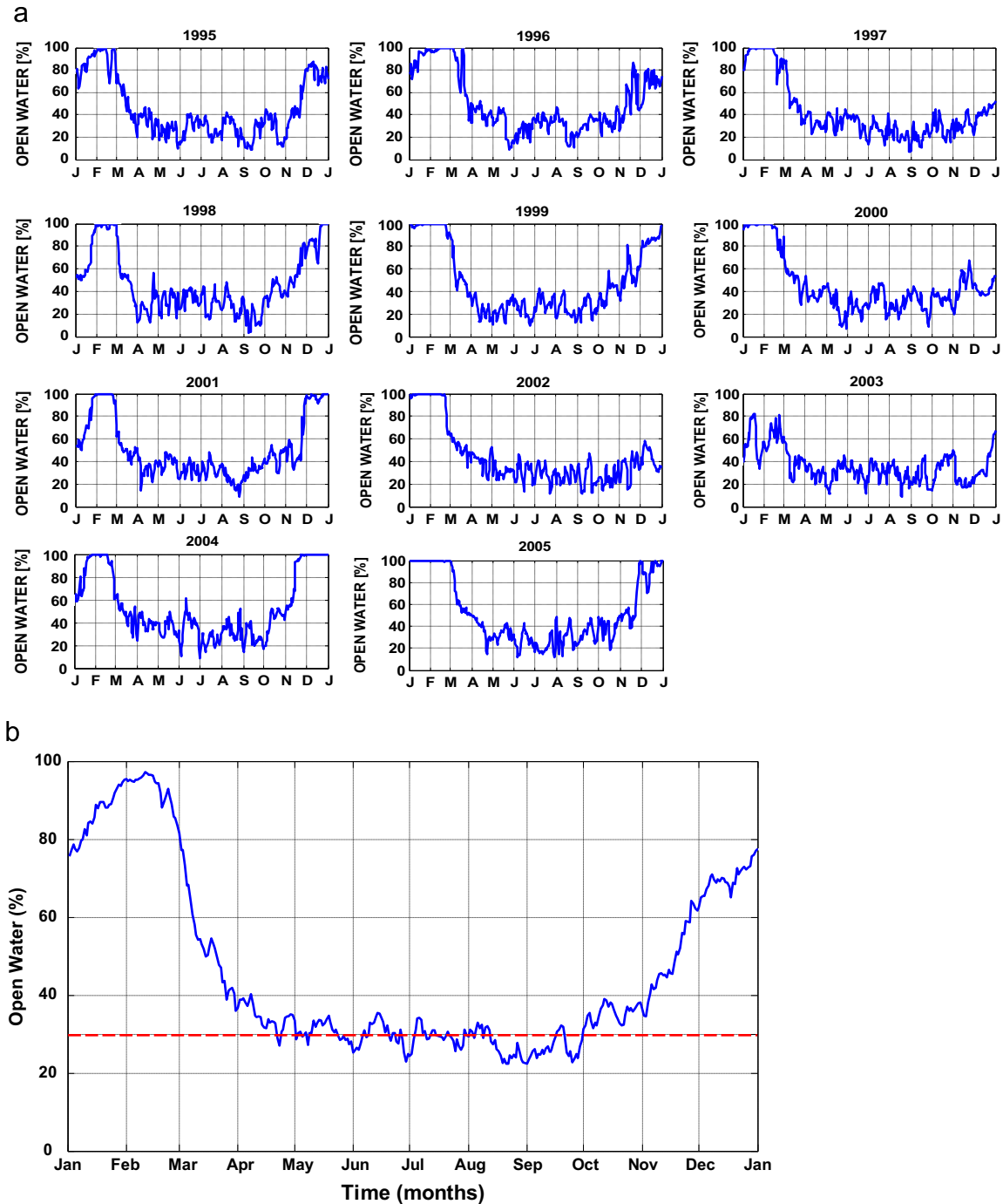


Fig. 10. One-month running mean values of open water (percentage) during the examined period (a) and monthly mean during the period 1995 to 2005 (b).

grid cell (the boundaries used when analysing the SSM/I data are indicated in Fig. 2).

It is evident that TNB is never completely covered with ice during the winter season. The end of the austral summer (identified by a rapid growth of the sea ice concentration) is more evident than the end of the winter (because the melting of the sea ice may occurs in November or two months later). It is important to note that 2003 was a particular year, because it was characterized by a great coverage of sea ice throughout the year due to a low presence of katabatic winds and the presence of the mega iceberg C-19 in the Ross Sea. The presence of the iceberg associated with the atmospheric circulation that has characterized the central-western Ross Sea (Harangozo and Connolley, 2006) has

subsequently blocked the pack in the Ross Sea and, as a consequence, TNB was covered of ice during all the year.

The open water parameter (ice-free fraction at a single grid point), expressed as percentage, was calculated from the values of the sea ice concentration.

The results of the open water estimations (Fig. 10a) show a large interannual variability during the 11 years examined, although, we can observe every year, from early April to late October, the opening of the polynya in winter. The open water never reaches values close to zero even if the rest of the Southern Ocean is frozen. This behaviour is clearly due to the action of katabatic winds that, between April and October, are very intense. In this period, the mean value of open water is around 30% (Fig. 10b). For this reason in the next part of the work, all

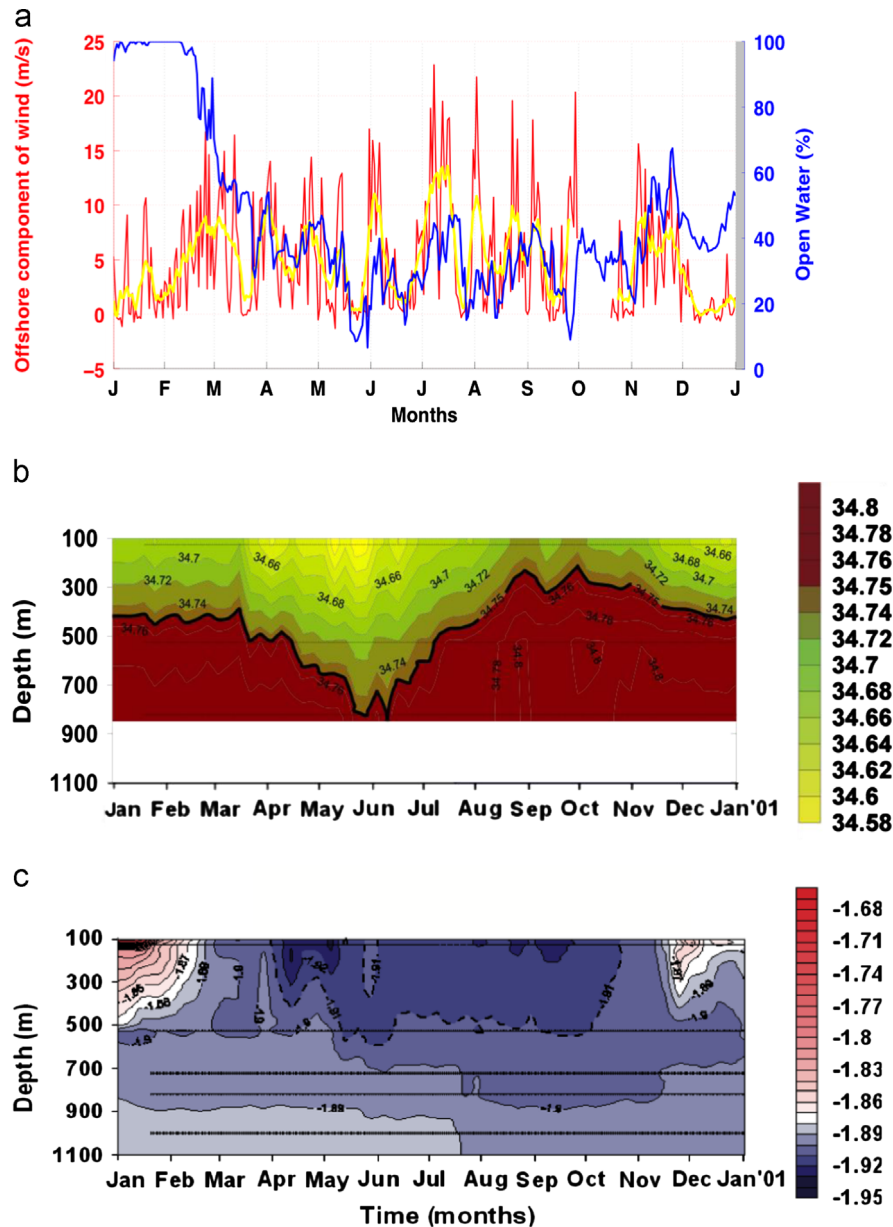


Fig. 11. Terra Nova Bay polynya, year 2000; panel (a) open water percentage (blue line), offshore wind component measured by the AWS Eneide, daily (red line) and low-pass filtered (yellow line) offshore wind component data; vertical distribution of (b) salinity and (c) potential temperature along the water column. Salinity data acquired by SBE SeaCat instruments between 120 and 800 m. Temperature data acquired by SBE SeaCat and Aanderaa instruments between 120 and 1000 m (see Fig. 3 for more details about instruments used and data acquisition depth). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the considerations on the polynya processes are made only during the winter season (April–October) since during the summer, all the Ross Sea is affected by ice melting processes.

6. Atmosphere–sea ice–ocean coupling

Fig. 11 shows for the year 2000, considered representative of the “typical” behaviour of the polynya, the relationship between the periods with more frequent (and longer) katabatic events (Fig. 11a, yellow line) and the percentage of the open water (blue line), and the thermohaline changes in the water column (Fig. 11b and c), measured at different depths by the mooring located approximately in the middle of TNB. At the end of February, the open sea rapidly decreases due to the formation of the sea-ice. Between March and June, the salinity decreases along the water

column, then it shows a sharp increase between July and October (Fig. 11b). Our data show that the increase in the offshore wind speed, regularly detected in June/July, is strongly related with the increase in salinity, which appears in the shallow layer (about 120 m depth) and along the water column (Fig. 11a and b).

Based on these observations, we speculate about the different role of the polynya during the winter season. We distinguished a period characterized by a considerably sea-ice free area and the salinity increasing along the water column (from July to November), which is preceded (from March to June) and followed (from December to February) by a period in which the polynya is still open but the salinity of the water column decreases. While the former appears related with a maximum efficiency of TNB polynya in the sea-ice production, the latter marks a “partial” functioning of the polynya. The polynya may still be open, by the presence of relatively intense offshore winds, but the production of sea-ice

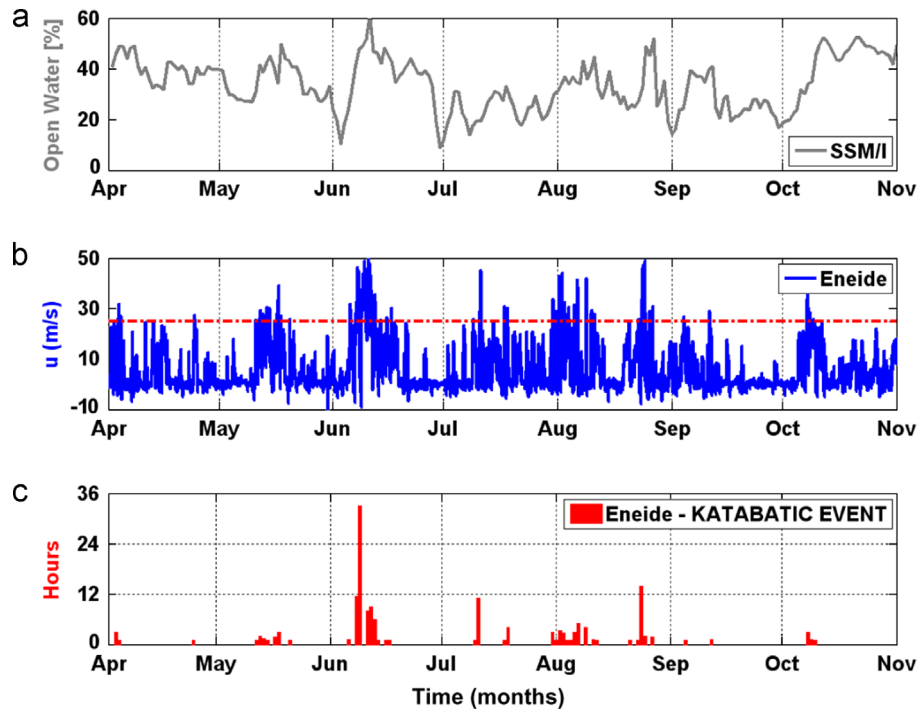


Fig. 12. Years 2004: (a) open water percentage of the polynya, (b) zonal component of the wind, (c) period of the katabatic event.

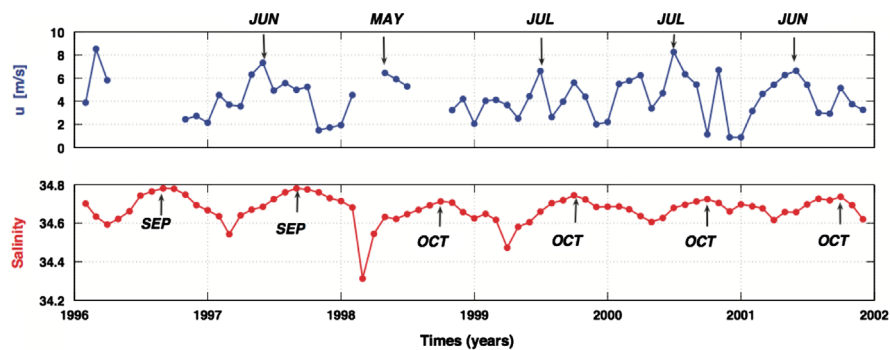


Fig. 13. Monthly means of u-component of wind speed from AWS Eneide and salinity averages (salinity data were acquired by mooring D at 126 m).

(and the associate release of brine) is not really evident, due to the shortness or to the infrequency of the katabatic wind regime. During March–June the polynya is partially free of ice and consequently the brine is released but, at this time of year, it is merely increasing the salinity of the upper layer of the ocean, reducing the stratification, but not causing HSSW to be formed. This is confirmed also by the vertical thermal signature of the water column in TNB. A relatively warm surface layer of about 150 m appears in November producing a thermocline between 150 and 500 m depth. The thermocline persists during the austral summer (December–February) and rapidly disappears at the beginning of the winter conditions (March), due to the increase of the vertical turbulent mixing provided by the katabatic events (Fig. 11c).

Fig. 12a shows the percentage of the open water, the zonal component of the wind speed (Fig. 12b) and the duration of the katabatic events (Fig. 12c), during the austral winter 2004. We noted that an increase of open water corresponds to each katabatic event and in particular manner the polynya is more ice free with more frequent and longer events (peak of open water of about 60%, showed on Fig. 12a, between June and July), while the open water is less (peak of about 40% between August and September) with frequent but shorter events. In August, in fact, the winds recorded have durations of less than 10 h, while the events

recorded during the month of June are much longer, up to an event of maximum duration of 33 h uninterrupted. This difference, in the duration of the katabatic wind, is a key factor in promoting the greater or lesser percentage of the open water. The polynya activity is more influenced by the duration of the katabatic events than by the frequency and by the intensity of the wind. In Fig. 12, we can also observe that the most of the increase in open water in June appears to take place before the main katabatic events. This increase of the open water percentage before the katabatic events may imply that persistent winds, with a westerly component, occurring before (and perhaps causing) the katabatic events may be an important precursor to these cooling events themselves. This observation was also found in other years (not shown here). In the investigated years, we have generally observed intense katabatic events of long duration (some days) at the end of July that promote the opening of the polynya. Katabatic events measured during the month of September, although characterized by high intensity, have short duration that imply an immediate opening of the polynya but the opening is limited to a much shorter period.

In this last part, the wind forcing and the salinity of the water column were compared to study the atmosphere–ocean coupling. The wind speed and the surface salinity data, during the period 1995–2001, were monthly averaged (Fig. 13). The monthly

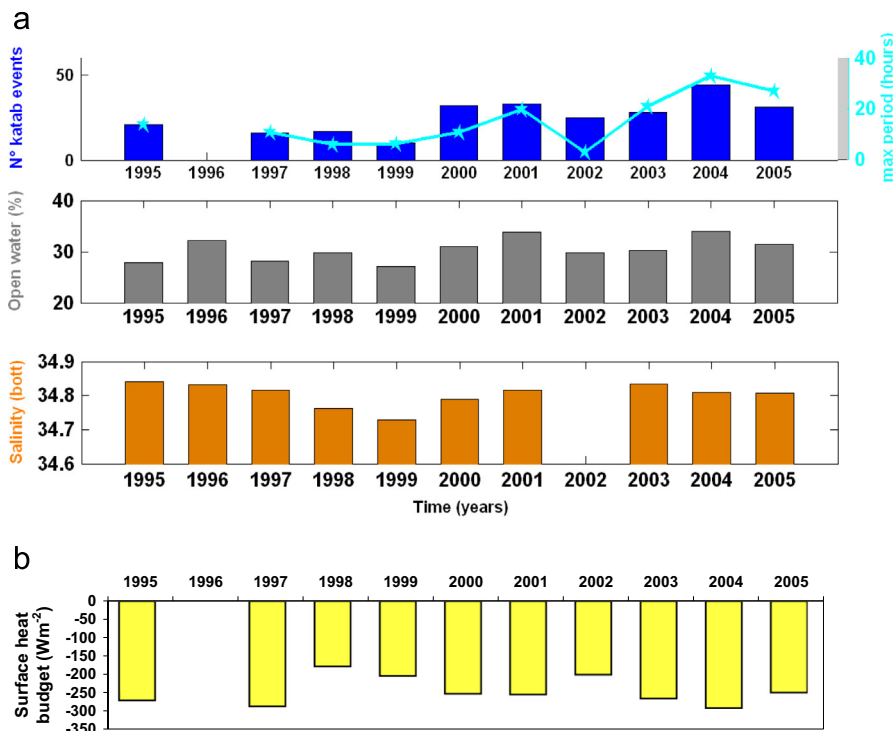


Fig. 14. (a) Interannual variability of katabatic events, open water, salinity acquired by mooring D at deep level (about 820 m depth) and (b) surface heat budget estimated in the period 1995–2005.

averages show that the maximum in surface salinity is reached three months later than the maximum of the atmospheric forcing. In particular, each year, between June and July, is measured a maximum wind speed with a corresponding increase in surface salinity values, between September and October. The effects due to a general intensification of wind regime, between June and July, become evident, with an overall salinity increase in the surface layer, after about three months. Finally, observing the open water behaviour and the salinity measured at the deep level (Fig. 14a), we noted in correspondence of a lower number of katabatic events (of short duration), as measured in 1999, a smaller percentage of open water and a lower salinity of HSSW. On the contrary, a greater number of katabatic events (e.g. 2001, 2004), of long duration, corresponds to an increase of the other parameters influenced by it, during the same year. In Fig. 14a we cannot observe a good correspondence between data sets during 2003, since high salinity values were found although a low number of katabatic events and low percentage of open water were measured during this year.

In order to assess and to support the results obtained, the analyses of the surface heat budget was performed. The surface heat flux in TNB is estimated on an hourly basis for the period 1995–2005 by combining air temperature, wind speed, relative humidity, mean sea level pressure, provided by the AWS Eneide, and total cloud cover, provided by the European Centre for Medium-range Weather Forecasts (ECMWF). To homogenise the two data sets, the linear temporal interpolation of the total cloud cover was computed. A temporal budget was used to derive hourly estimates of the surface heat flux using the relation:

$$Q_T = Q_S + Q_B + Q_H + Q_E$$

where Q_S is the shortwave radiation flux, Q_B is the net longwave radiation flux, Q_H and Q_E are the sensible and latent heat fluxes, respectively. The heat flux parameterisations are adapted for polar regions (Budillon et al., 2000; Fusco et al., 2002, 2009). The yearly averages of the net heat loss from the ocean to the atmosphere

were computed in TNB polynya, for the period 1995–2005. The surface heat budget, showed in Fig. 14b, evidences an interannual variability during the investigated period. The heat loss reaches maximum value in 2004 ($-291 W m^{-2}$) and minimum value ($-178 W m^{-2}$) in 1998. The mean value for the entire period is $-245 W m^{-2}$ with a standard deviation of about $33 W m^{-2}$. Fusco et al. (2009) estimated that the cooling of a water layer 100 m deep, from $-1.5 ^\circ C$ to its freezing point, can be achieved by only around 10 h of $400 W m^{-2}$ surface cooling. This result allows us to appreciate the estimated heat flux and to speculate on the relevance of the katabatic winds in TNB polynya. Indeed, the katabatic winds represent the most important factor for fostering the heat loss at the sea surface, in this region. Comparing the surface heat fluxes (Fig. 14b), the duration of the katabatic events (cyan line in Fig. 14a) and the salinity, acquired in the bottom layer of TNB polynya (Fig. 14a), a similar behaviour is found. When the duration of the katabatic events and the related heat losses reach high values, high salinity is observed. These correspondences are not observed during 1997 and 2003. This behaviour could be due to the presence of the Modified Circumpolar Deep Water (MCDW) in the Ross Sea continental shelf and consequently in TNB polynya. Jacobs et al. (2002) asserted the freshening observed during the late 20th century in the Ross Sea appears to have resulted from a combination of different factors including increased precipitation, reduced sea ice production, and increased melting of the West Antarctic Ice Sheet. The only other important sources of freshening for the Ross Sea continental shelf are waters imported by the coastal current and waters along the southern edge of the Ross Gyre (Jacobs et al., 2002). Their results, based on database for the interior Ross Gyre, show that the Ross Sea continental shelf has recently been importing fresher and/or more surface water relative to the inflow of MCDW. Dinniman et al. (2003), in a modelling study, show the strength of the CDW intrusion onto the shelf appears to depend on two mechanisms. First, CDW is driven onto the shelf at least partially 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, pushes the CDW into the interior or back off the shelf (Dinniman et al., 2003). Fusco et al. (2009) justify the behaviour of the observed salinity values at 900 m depth (CTD data provided in the framework of the multidisciplinary campaigns conducted by the Italian CLIMA project) by a combination of factors suggest by Jacobs et al. (2002) and Dinniman et al. (2003) and by a different contribution of CDW transport and HSSW production. Consequently, the salinity values observed in Fig. 14a could be explained by the combination of the katabatic events of long duration and the related heat losses, and, by the different contribution of the CDW transport and HSSW production, to the salt content within the water column.

7. Conclusions

The purpose of our study was to investigate the dynamics of TNB polynya focusing on the characterization of the katabatic wind regime, the response of the sea-ice to the wind forcing and the HSSW production. As has been largely documented in previous studies, the katabatic winds are responsible for the formation of TNB polynya. Our results highlight some key aspects of the functioning of this latent heat polynya. For the first time, the greater or lesser production of HSSW is showed to be related not only to the intensity of the katabatic winds but above all to the duration and the number of the katabatic events which invest the bay. Intense but short katabatic events do not trigger the HSSW production in the same way as the katabatic winds, characterized by lesser intensity, that blow for longer periods (more than 3 h). This observation allows us to individuate two different behaviours of the polynya. A first period corresponds to the beginning of winter, from March to June. During this period the polynya is partially free of ice and consequently the brine is released but, at this time of year, it is merely increasing the salinity of the upper layer of the ocean, reducing the stratification, but not causing HSSW to be formed. The second period of the polynya activity is detected between July and October characterized by the production of HSSW along the water column.

In this work, we have also estimated the ocean time response to the atmospheric forcing using salinity as major parameter. The sum of the effects due to a general intensification of katabatic events during the period June/July becomes evident with an overall increase in surface salinity after about three months. Considering the annual variability, during the year 1999, a decreased activity of the polynya and a consequent lower salinity of the HSSW were observed. During that year, a lower number of katabatic events of short duration and a lower percentage of open water are detected in the analyses. On the contrary, in 2001, the polynya has been much more active. During this year a greater number of katabatic events of long duration promoted an increase of the sea ice production and therefore an increase in the salinity of the HSSW. However the behaviour observed in 1997 and in 2003 probably could be justified by a different contribution of CDW transport and HSSW production to the salt content within the water column.

This study underlines once again the important role of the TNB area as production site of the densest water of the Antarctic continent, the HSSW, and its fundamental role in the global thermohaline circulation. Improving our understanding of the TNB polynya dynamics and variability certainly requires knowledge of the sea ice export that should be estimated from sea ice extension and thickness. Unfortunately the data set, used in this study, does not allow us to investigate on the sea ice export; this could be an outlook for further studies using in situ data and high resolution satellite data.

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