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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.

Highlights

►The Terra Nova Bay polynya plays a key role in the formation of salty shelf water in the Ross Sea. ►The formation of salty water is triggered mainly by the persistence of katabatic winds. ►The sea ice and dense water formation is concentrated in the period June–October.

Keywords : Terra Nova Bay polynya ; High Salinity Shelf Water ; Interannual variability ; Katabatic wind ; Air–sea–ice interaction

1. Introduction

Polynyas are persistent and durable ice free areas in otherwise ice-covered waters. Polynyas are formed and maintained by offshore 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).

The Terra Nova Bay (TNB) polynya is a coastal latent heat polynya located in the western sector of the Ross Sea, between the Drygalski Ice Tongue (DIT) on the south and by the Campbell Ice Tongue on the north, which extends in a south-east direction. The TNB polynya is formed and maintained by the combined influence of 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).

Projections of climate models suggest that if global warming occurs, polar regions are likely to experience temperature changes that will be faster and larger than in most other areas of the planet (Everett and Fitzharris, 2001). Variations in the occurrence and size of polynyas might then be suitable indicators of any ongoing climatic alteration. Elucidating the interactions between polynyas and their environment is important for determination 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).

Intense heat loss from the open water (sea water free by the sea ice) to the atmosphere leads to rapid and persistent ice growth in latent heat polynyas. 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.

The TNB polynya plays an 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; Kurtz and Bromwich, 1985; Jacobs *et al*., 1985; Van Woert, 1999a, b; 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). Despite the extension of the TBN polynya is relatively small, it is believed that the HSSW produced contributes to about 10% of the AABW formed in the Ross Sea (Van Woert, 1999a). Moreover, this polynya is involved in intense heat exchange between air and ocean (Fusco et al. 2002, 2009), in primary and secondary production and the formation of sea ice. It is been estimated that in winter the ice produced in this area is about 10% of the total amount of ice produced above the continental shelf of the Ross Sea (Kurtz and Bromwich, 1985; Van Woert, 1999b).

Part of the HSSW formed in the TNB polynya is known to move 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. Another branch flows southward under the Ross Ice Shelf, where the cooling and melting at different depths forms the Deep Ice Shelf Water (DISW), characterised by a temperature lower than the freezing point at the surface pressure. DISW is found primarily 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 formation of AABW (Jacobs et al., 1985) which is slightly different (Budillon et al., 2011) in this sector of the Southern Ocean.

Recent observations along the Antarctic shelves, while 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). In particular, the observational results showed that, during the second half of the 20th century, bottom water which is thought to be 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). According to Tamura et al. (2008) the ice production in the Mertz Glacier Polynya was not decreased, but they propose that the decrease in ice production in the Ross Ice Shelf Polynya is a plausible candidate for causing recent freshening of RSBW, ALBW, and AABW in the Australian Antarctic Basin. 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). In-situ observations showed that 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 the TNB polynya at the end of the 90‟s.

This paper shows the seasonal and interannual variability in the water column stratification and puts in evidence the significant variability of HSSW production as consequence of the polynya activity. This study has been achieved by conducting a deep analysis of the hydrographic mooring and CTD (Conductivity-Temperature-Depth) data, collected for 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 described the characteristics of the different water masses circulating in the polynya area and the seasonal variability of the thermohaline properties of this water masses, and we also report on the katabatic regime that dominates the Bay and the sea ice coverage. In section 4 we discuss the results and in section 5 we provide a summary along with some concluding remarks.

2. The data

In order to perform our analyses data collected from different source were used. 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 hour time resolution. The AWS Eneide is equipped with sensor to measure: temperature, relative humidity, atmospheric pressure, wind direction, wind speed, solar radiation and snow depth. In this study we analyse the dataset available (www.climantartide.it) of temperature, wind direction, wind speed and relative humidity acquired between January 1995 and October 2006 in order to characterize the katabatic wind regime in the TNB area. In Figure 1 wind rose (a) and class frequency distribution (b) between 1995-2006 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 come only from the western sector.

2.2 Hydrological data

Hydrological casts and water samplings were performed in the TNB polynya (Figure 2), during the last 13 years, using an SBE 9/11 Plus CTD equipped with different sensors (double temperature and conductivity sensors, oxygen, light transmission, fluorescence, pH) coupled with an SBE 32 Carousel sampler, carrying 24 bottles of 12 litres each. Temperature and conductivity sensors were calibrated before and after the cruise at the SACLANT 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 an Autosal Guidline 8400b model Salinometer. At every station, several replicate samples were collected at all depths and analyzed on board. All profiles were planned to reach within 4-5 m of the bottom. Hydrological data were then corrected and processed according to international procedures (UNESCO, 1998). 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 Figure 2 for mooring location) by the CLIMA Project in the framework of the PNRA. The mooring was equipped with sedimentary traps, turbid meters, Aanderaa RCM7/9 current meters and SBE16 temperature/conductivity recorder at different depths. For the accuracy of these sensors is possible to consult the cruise reports on the web site http://www.pnra.it. The mooring was deployed on 17 February and successively was recovered and re-deployed approximately each year providing up to date, a unique time series of 13 years, which represent an exceptional opportunity for oceanographer in polar areas. The sub-surface 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, are available (Figure 3). In this work, we analyse only the salinity and temperature data collected by the SBE SeaCat instruments cause the higher accuracy of these sensors compared to those used by Aanderaa instruments. The temperature and salinity data recorded in the deep layers (from 2000 to 2005) were validated and corrected with CTD measurements performed in the TNB area during the recovering and deploying of the mooring.

2.4 Remote sensing data

During winter, heat loss over thin ice is one or two orders of magnitude larger than that over thick ice, and thus 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).

In this work, the sea ice concentration was calculated from the brightness temperatures provided by SSM/I data using the NASA Team Sea Ice Algorithm. This algorithm, used by NSIDC to provide the concentrations from 1995 to 2005, uses the brightness temperatures obtained from the 19.5 GHz channel, vertically and horizontally polarized, and vertically polarized channel 37.0 GHz. This algorithm is a product of 20 years of refinements, improvements, and verifications. In this study the polynya area is calculated using a 0-10 cm SSM/I 37 GHz thin ice algorithm with 25 km of resolution.

3. Results

3.1 Water masses

In this section, we give a description of the hydrological conditions in the TNB polynya. The salinity and potential temperature measurements, obtained from the CTD instruments, were used to describe the thermohaline structure of the water column and to identify the typical water masses circulating in the TNB polynya.

The vertical structure of the water column, showed in Figure 4, appears relatively simple. Looking at the temperature and salinity profiles (Figure 4a and 4b) the greatest variability is observed in the surface layer that extends from the surface to 50-150 m of depth. Below this layer, the water column is nearly isothermal and the vertical stability is preserved by the increasing salinity. The vertical structure of the water column in TNB, during the summer period (November to March), may therefore be considered as composed by two layers. The Antarctic Surface Water (AASW) occupies the upper layer that, during the summer, becomes fresher and warmer 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 during the summer period in this region (Budillon et al., 2000a). Below this upper layer, the water column is characterized by the presence of HSSW with a potential temperature close to the surface freezing point (Tf=-1.914°C for p=0 dbar and S=34.85) and S>34.7.

At intermediate depths of the quasi-isothermal layer of HSSW, 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. The presence of the water masses described is also evident in the Θ-S diagram (Figure 4c) of the hydrological casts.

3.2 Seasonal variability of temperature and salinity

Looking at the time series of temperature and salinity (Figure 5) acquired by SeaCat SBE16 from February 1996 to December 2000, in the upper layer (100-150 m) the temperature is close to the surface freezing point during the winter sea ice growth 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 from sea ice growth and it decreases between November and April (Figure 5). During March-April (1995-2000) in the upper layer (103-142 m), a particular behaviour of seawater properties is noted. Large temperature and salinity fluctuations occurred during this period and smaller fluctuations continued until the water temperature reached freezing again in early July. During the end of summer, a pulse of warm and fresh water was monitored in the TNB, while in this period we might have expected the water masses got saltier and colder 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, characterized by different intensities each year. It appears more prominent during 1998 with temperature range between -1.7°C≤ T ≤-1.1°C and salinity range between 34.1≤ S ≤34.42 (Figure 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 summers. In year 1999–2000, there appeared to be two prominent episodes of warming, around mid-January and early February, that 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. During the second year (2000–01) maximum temperature at the jetty site was -0.648°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 more important than the those observed in TNB (temperatures in McMurdo are warmer of about 0.7°C) is quite certainly due to the fact that the dataset acquired in McMurdo are relative to the shallow water (9m and 40m). 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 this warm and fresh water mass. For us, the most accredited hypothesis is that there is coastal water formed in summer, after pack ice and glacier melting. At the end of summer, water column in TNB presents two layers. The upper one, warm and not very salty, is about 100-200 m deep. On this layer, the wind and/or surface circulation curl originates a coastal cyclonic gyre. This gyre produces a down-welling phenomenon in the central area of TNB where the mooring is placed. So, we measured this T and S surface values at about 150 m of depth. Once removed this surface water, it is necessary to wait for the next year, so that the cycle will be repeated. In the other months, the gyre will draw only the waters now homogeneous with the surrounding sea covered with ice. In order to assess these speculations, for all surface current meters, mean, eddy and total kinetic energy were calculated. The results (Figure 6) show that in correspondence with the particular seawater properties we observed high values of mean, eddy and total kinetic energy that confirm the hypothesis of turbulent activity created by the phenomenon hypothesized in the central area of TNB. It is clear that more investigations have to be done on this particular phenomenon.

The intermediate and deep layers show, as expected, a lower seasonal variability. In Figure 7 are shown the time series acquired respectively at 566, 546 and 526m during 1998, 1999 and 2000. The temperature and salinity values are more stable than the surface values but we can observe a consistent interseasonal and interannual variability. During the 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 changing between the summer and winter temperature values are 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 the subsurface layer and they increase during the winter season (due to the brine release during the polynya activity) to values higher than 34.8.

3.3 Katabatic regime

In order to study the polynya response to the wind forcing, the katabatic regime that dominates the Terra Nova Bay was analyzed. As shown before (Figure 1) the greater percentage of the winds measured by Eneide AWS, comes from the W-WNW sectors and the winds that blow with speeds over 20 m/s 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 objectives criteria to distinguish a katabatic event from a normal wind‟s intensification. The criteria, applied to the zonal component of wind speed (u) and wind direction (D), are:

- $u \geq 25$ m/s
- $270° \leq D \leq 360°$

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 Figure 8 we reported a katabatic event that last about 39 hours almost uninterruptedly. We noted that the more frequent events spread with speed between 25 and 56 m/s and they drastically interrupt in just a few hours.

Lastly, we characterized all the katabatic events that occurred every day during the investigated period in the polynya area. Each circle in Figure 9 represents a katabatic event that occurred a specific day and its color 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 1-2 and 3-7 hours, while longer events occur during the winter months, between June and September, and only few events last more than 7 hours, although there have been long event lasted 33 hours continuously.

In Figure 10 the total number of katabatic events for each year and their maximum period are shown. During 2004 we observe a greater number of katabatic events and also the longer event (approximately 33 hours) in the all-available period. The year 2002, even if it shows many katabatic events, is characterized however by their brevity, breathing for a maximum of 3 hours. In 1999 the lowest number of events is recorded, lasting up to 6 hours, and this low prevalence of events is linked to an overall lower intensity of the wind throughout the year. The 2000 and 2001 present the same number of katabatic events, but in 2001 the duration is greater.

3.4 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 greater activity of the polynya, we analyzed the time series of the sea ice concentration between 1995 and 2005 (Figure 11) obtained by the SSM/I brightness temperature.

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 grow in 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. The presence of the iceberg associated with the atmospheric circulation that has characterized the central-western Ross Sea (Harangozo and Connolley, 2006), subsequently blocked the pack in the Ross Sea and as a consequence TNB was covered of ice during all the year, too.

The open water parameter (area free of sea ice presence), expressed as a percentage, was calculated from the values of sea ice concentration, according to the following relation:

Open water = (1 - C) * 100

with C the daily concentration of sea ice.

The results of open water estimations (Figure 12a) 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 also in the period when, however, the rest of the Southern Ocean is frozen. This behaviour is clearly due to the action of katabatic winds that between April and October, is more intense. In this period the mean value of open water is about 30.5% (Figure 12b).

For this reason in the next part of the work, all 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.

4. Discussion

The Figure 13 qualitatively evidences for the year 2000, considered representative of the "typical" behaviour of the polynya, the relationship between the duration of the katabatic winds and the size of the sea ice free area (open water, Figure 13a), and the thermohaline changes in the water column (Figure 13b and 13c), measured at different depths by the mooring located approximately in the middle of the TNB polynya. At the end of February, the open sea rapidly decreases due to the formation of the sea-ice. Until June the salinity freshen along the water column, then it shows a sharp increase between July and October (Figure 13 b). Our data show that the increase in the offshore wind speed, regularly detected in June/July, is strongly correlated with the increase in salinity, which appears in the surface layer (120 m depth approximately) and along the water column (Figure 13a and 13b).

We speculate on the different role of the polynya during the winter season: the period characterized by a considerably sea-ice free area and a salinity increase along the water column, which is proceeded and followed by a period when the polynya is still open but the salinity of the water column decrease. While the former appears related with a maximum efficiency of the TNB polynya in the sea-ice production, the latter marks a "partial" functioning of the polynya that may still be open, by the presence of relatively intense offshore winds, but the production of sea-ice (and the associate release of brine) is not allowed by the shortness or by the infrequency of the katabatic wind regime.

This is confirmed also by the vertical thermal signature: a relatively surface warm layer 150 m deep appears in November producing a thermocline between 150-500 m which persists during the austral summer (December - February) and rapidly disappears at the beginning of the winter conditions (March) cause the increase of vertical turbulent mixing provided by the katabatic events (Figure 13c).

Figure 14a shows the temporal evolution of the open water calculated during the austral winter 2004, the trend of the zonal component of wind speed (Figure 14b) and the duration of the katabatic events identified (Figure 14c). We observe that an increase of open water corresponds to each katabatic event and in particular manner, between June and August, the polynya appears ice free with more frequent and longer events, while the open water is less with frequent but short events. In August, in fact, the winds recorded have durations of less than 10 hours, while the events recorded during the month of June are much longer, up to an event of maximum duration of 33 hours uninterrupted. This difference is a key factor in promoting the greater or lesser percentage of open water. This observation was also found in other years (not shown).

In the investigated period we observed, in general, intense katabatic event of long duration at the end of July that promotes the opening of the polynya, which lasts for several days. Katabatic events measured during the month of September, although characterized by high intensity, they have short duration that imply an immediate opening of the polynya, however, limited to a much shorter period. This evidence is not always the only necessary condition for the open and activity of the polynya. The analysis of time series on the other years (not shown in this paper) showed, in fact, that sometimes in absence of strong and persistent katabatic winds, the polynya can reach relevant amplitudes. The reason of this behaviour can be justified considering a possible contribution of oceanic sensible heat carried by the intrusion of the relatively warm Modified Circumpolar Deep Water (MCDW), as will be discussed later.

Looking at the wind forcing and salinity time series along the water column, we put in evidence the strong relation between the meteorological forcing and the subsequent release of brine. In particular, we found a clear increase of salinity at different depths in correspondence of strong katabatic events that originates a convective plume, observed for the first time in TNB. Using only our observational data at three main depths: surface, intermediate and deep level, we identify the typical time lag of the phenomenon evolution. The Figure 15a shows a katabatic event recorded on 11 July 2000 at 16:00 lasted almost continuously until 12:00 pm on the 12th July, and the salinity at three levels investigated. This katabatic event characterized by high intensity and long duration in time, about 20 hours, induce a large opening of the polynya and a strong production of sea ice that will establish the processes of dense water formation. As consequence of this atmospheric forcing, the salinity measured at the surface level (126 meters) shows an increase on 11 July at 19.30 (Figure 15b), 3 hours after the start of the katabatic event, while the maximum value of salinity is found after 12 hours. At the intermediate level (526 meters), the salinity shows an increase after about 4.5 hours from the start of katabatic event (Figure 15c), reaching a peak at 6.30 a.m. on 12 July, exactly after about 14 hours. Finally, the salinity measured at the deep level (823 meters) shows an increase on 11 July at 21.00 (Figure 15d), which corresponds to a time lag of 5 hours after the onset of the katabatic winds, reaching a peak at 6.30 a.m. on 12 July as already observed in the subsurface layer. In all three layers is noted, however, a rapid decrease in salinity values soon as the wind begins to blow with intensity lower than 25 m/s. The processes examined on July 2000 show a convection of 700 meters along the water column in about 1.5 hours, this allow us to estimate a vertical speed of about 13 cm/s. These observations show, once again (as already said in the previous paragraph) the importance of the katabatic events duration, rather than its intensity, in the activation of the polynya and the convective plume. Such convection phenomena were in fact found in the signals measured by mooring only in correspondence of katabatic events characterized by long duration.

To identify the atmosphere-ocean coupling, on time scales greater than hours, wind speed and surface salinity for the period 1995 - 2001 were monthly averaged (Figure 16). These monthly 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. Even if the release of brine and the resulting increase of salinity, along the water column, in response to the meteorological forcing is characterized by a rapid time lag (as shown above), we can observe that 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 (Figure 17), it is noted that in correspondence of a lower number of katabatic events (of short duration) as measured in 1999, there is 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 correspond to an increase of the other parameters influenced by it, during the same year. In Figure 17 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. As previously described, the 2003 is a particular year characterized by a low presence of katabatic winds (Figure 10) and the presence of the iceberg C-19 that favoured an unusual ice cover in the polynya. Then the high values of salinity could be due to the presence of the Modified Circumpolar Deep Water (MCDW) in the bay. The MCDW represents the only source of salt (and heat) for the Ross Sea. For this purpose a study on the presence of the MCDW within the bay and about its role in the formation of HSSW in TNB polynya were performed analysing the CTD profiles acquired during summer campaigns between 1995 and 2006.

The MCDW is characterized by a minimum value of dissolved oxygen at a maximum value of sub-surface potential temperature (Budillon et al., 1999; Budillon et al., 2003). In order to identify the presence of MCDW, the potential temperature-salinity-dissolved oxygen (θ-S-O_2) diagrams of all profiles were analysed. The distinctive features of temperature and dissolved oxygen were however much more evident only in the data acquired in the outer area of TNB. The MCDW, in fact, entering the TNB moves closer to the coast, at lower depth, mixing with waters characterized by lower temperatures and higher dissolved oxygen content.

Only the hydrological profiles of maximum temperature and minimum dissolved oxygen including in the neutral density range of $28.27 \leq \gamma_n \leq 28.5$ were analysed (Figure 18). Using this range of neutral density and by imposing a further constraint on the potential temperature (θ> -1.75 ° C), the presence of the MCDW in TNB has been identified allowing us to estimate the interannual thermohaline variability (Figure 18).

In Figure 19 the values of MCDW salinity yearly averaged, acquired by CTD instruments, and the bottom salinity values (HSSW), acquired by mooring D, in the polynya area are shown. A good agreement between these two time series is evident, in fact the minimum and maximum values are in phase with each other. This evidence also occurred in the year 2003. The salinity increase found on the HSSW bottom layer, during 2003, is probably due to the salinity increase in the subsurface layers, rather than to a continuous activity of the polynya. So even if the polynya was not particularly active (as shown before), the few katabatic winds and the relatively saltier waters due to a large presence of the MCDW have implied a considerable increase of salinity. Therefore, the greater or lesser presence of MCDW within the TNB appears to play a key role in the formation of HSSW representing an important factor for pre-conditioning of the water column.

5. Conclusion

The results obtained in this study have highlighted some key aspects of the functioning of the TNB polynya. For the first time, we show that the greater or lesser production of HSSW is related not only to the intensity of the katabatic winds but above all to the persistence of these flows. Intense but short katabatic events do not trigger the HSSW production as well as when the katabatic winds, although of lesser intensity, blow for longer periods. This observation allows us to individuate two different behaviours of the polynya: a first period corresponding to the beginning of winter, from April to June, where despite being partially free of ice, there is no release of brine, and therefore there is no formation of HSSW. In this first period, the polynya is open, or free of ice cover (as detected by remote sensing data) thanks to the activity of the winds. The katabatic regime, however, is still insufficient to produce a considerable production of sea ice that releases significant amount of salt needed to the HSSW formation. This period is followed, between July and October, by the real activities of the polynya with consequent production of HSSW.

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, when a greater number of katabatic events of long duration favoured an increase of the sea ice production and therefore an increase in the salinity of the HSSW.

The importance of the duration of the katabatic phenomenon, rather than its intensity, was also stressed as a key role for the triggering of convective salty plumes along the water column. These convection phenomena were identified, in the time series measured by the moored instruments, only in correspondence with katabatic events of long duration (events of duration greater than the average value of about 3-7 hours). These processes show a convection of 700 meters along the water column, with a vertical speed of about 13 cm/s, reaching the bottom layer in a few hours after the start of the katabatic wind. Although it is noted that the release of brine and the resulting increase of salinity along the water column is characterized by a rapid time lag, the monthly mean of salinity and wind show that, 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. In the end, this study enables us to point out the role played by the MCDW in the polynya area. We can assert that the HSSW formation is assisted by the MCDW intrusions in the TNB and by the presence of polynya area, maintained open by the strong katabatic winds of long duration. This study underline once again the important role of this area as production site of denser water of the Antarctic continent, the HSSW, and its fundamental role played in the global thermohaline circulation.

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Figures caption

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Figure 2. Colored diamonds indicate the position of the hydrological casts collected between 1995 and 2006 in the Terra Nova Bay polynya, the black diamond indicates the position of the mooring "D".

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

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

Figure 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 are written on the top of each figure.

Figure 7. Time series of temperature (left) and salinity (right) at the intermediate layer from mooring D. Instruments depths are also shown.

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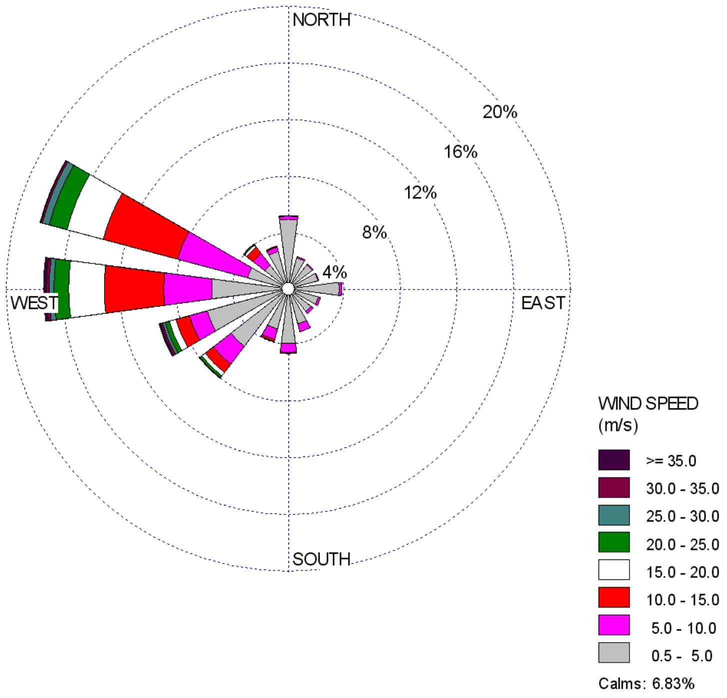

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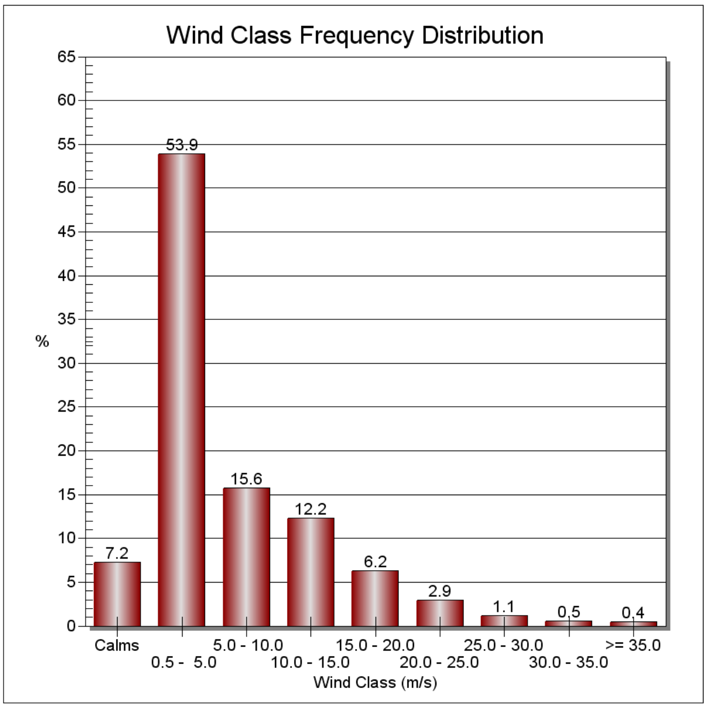

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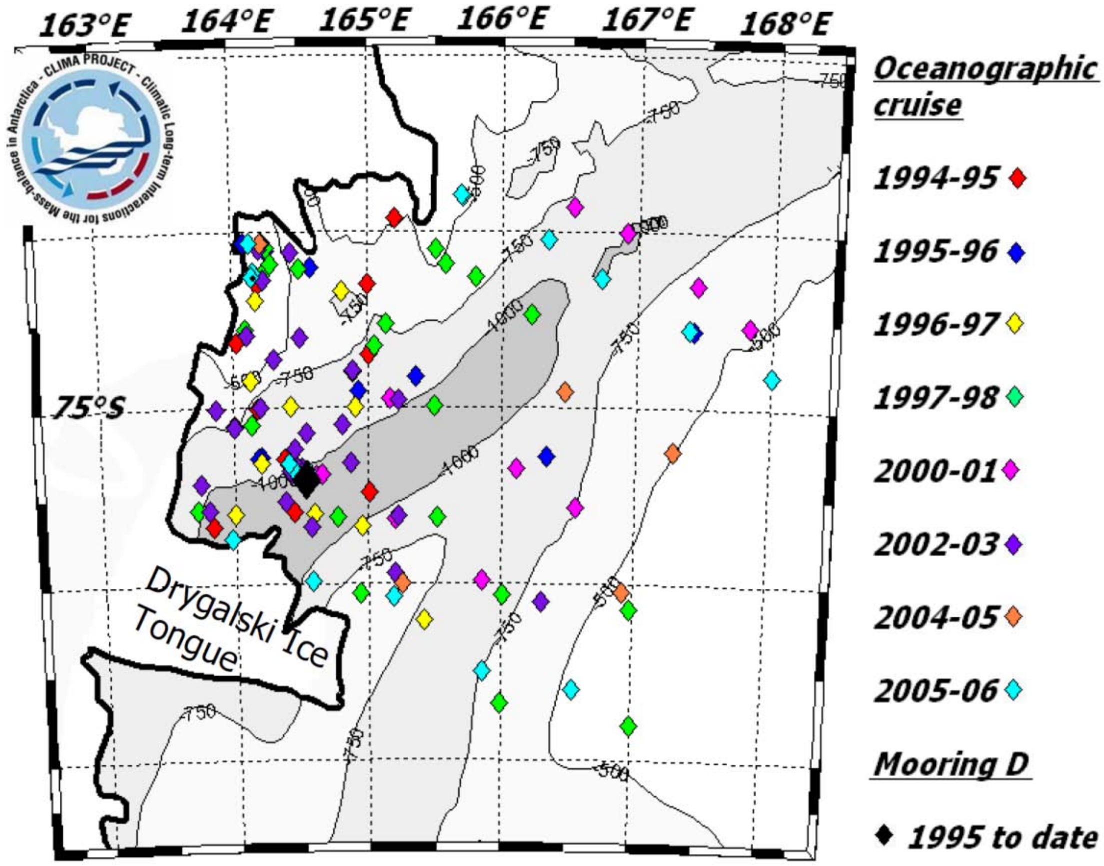

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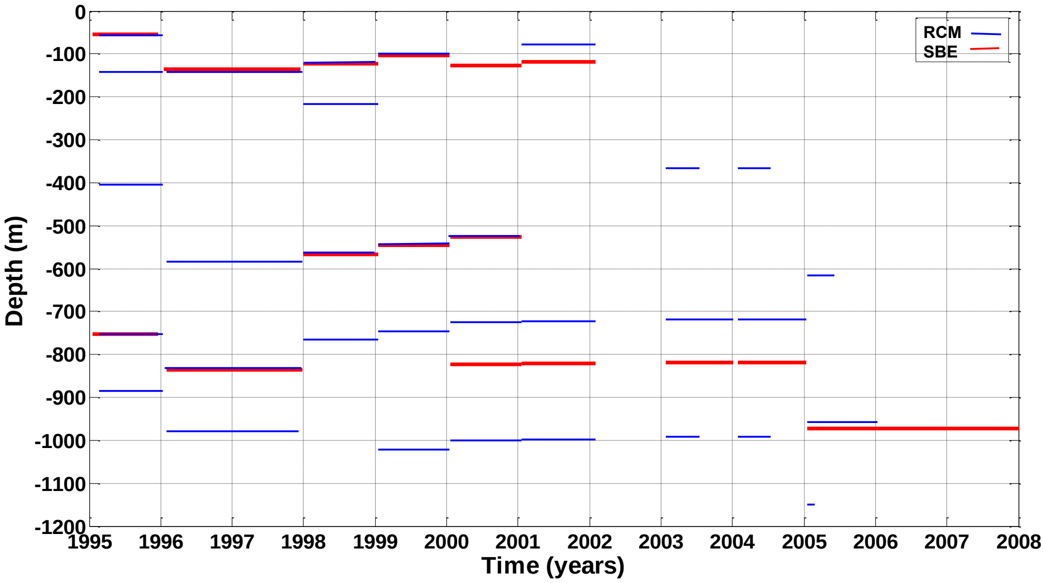

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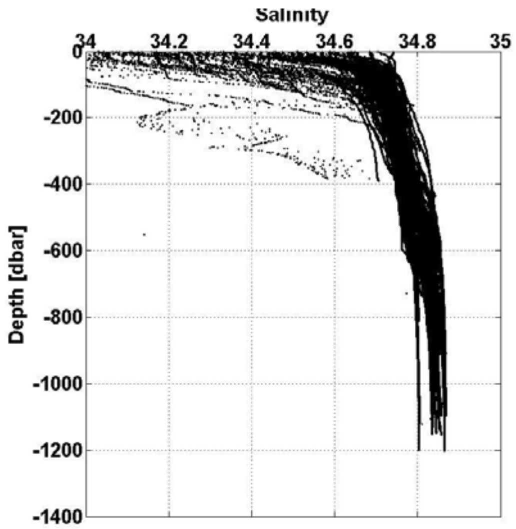

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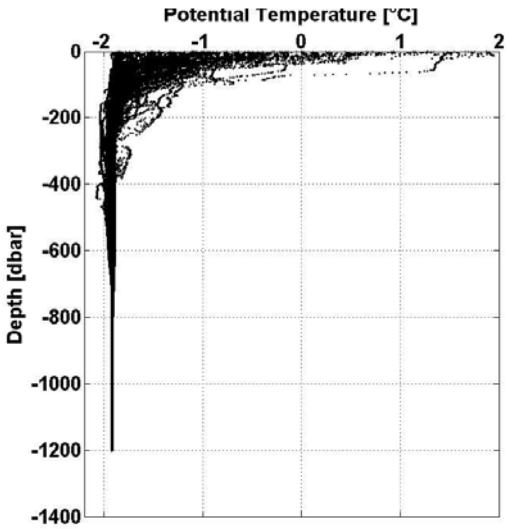

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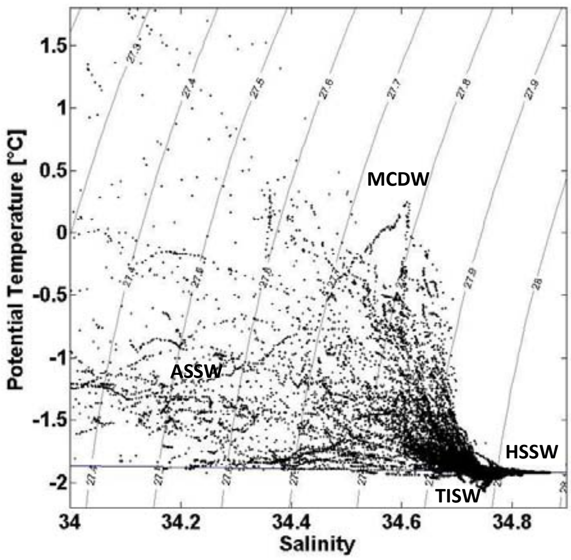

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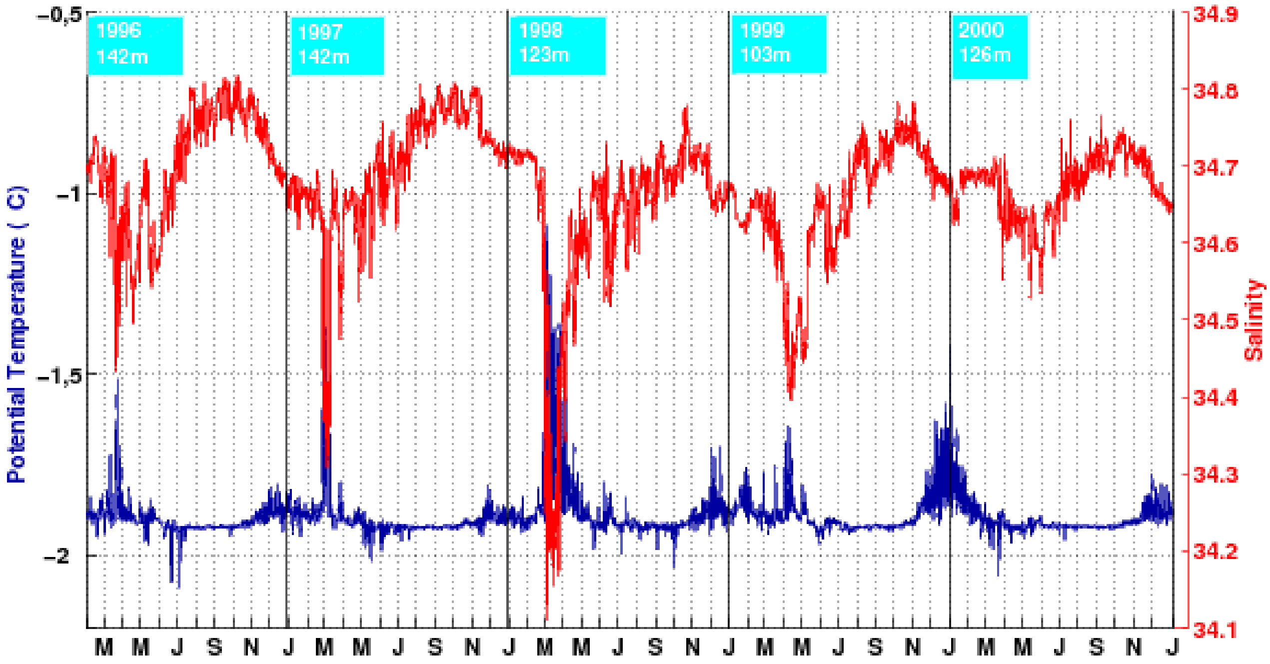

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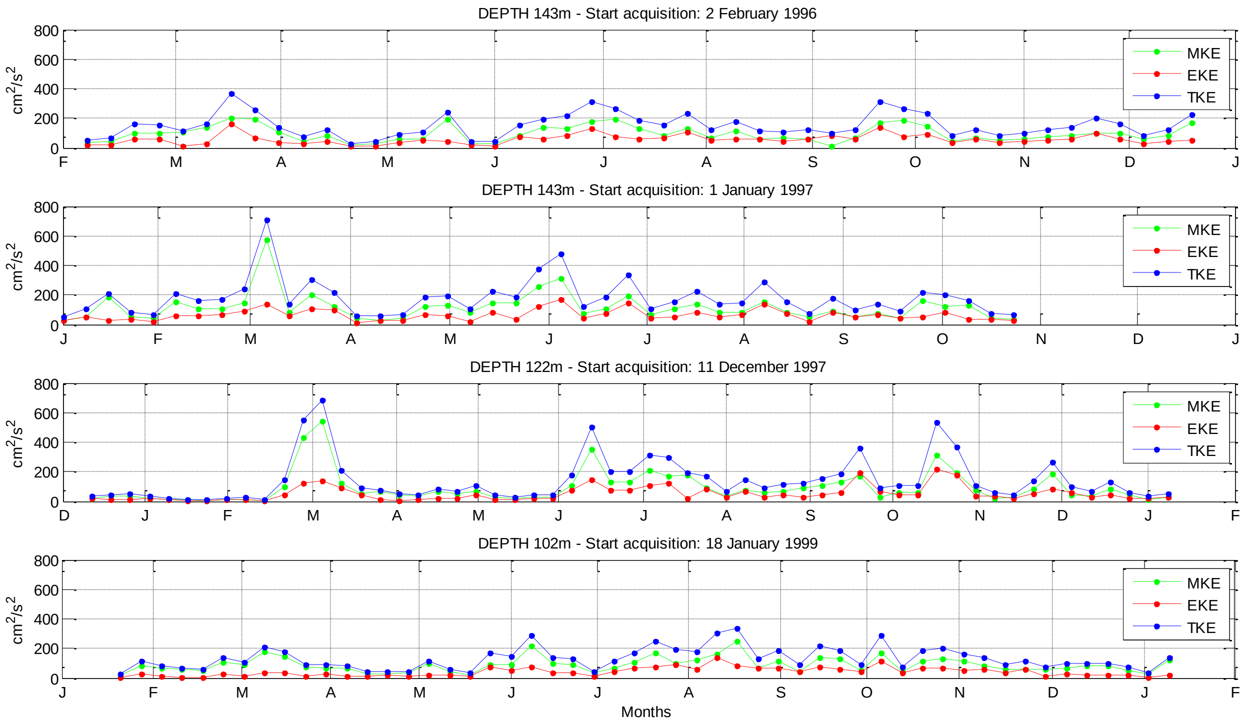

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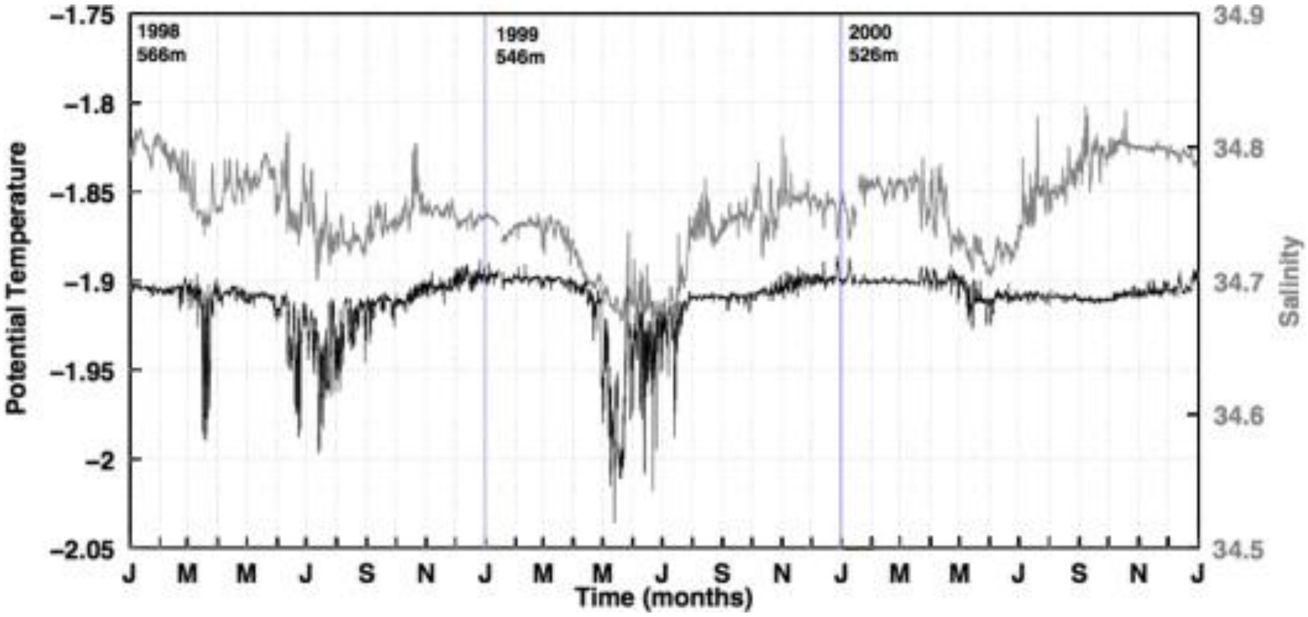

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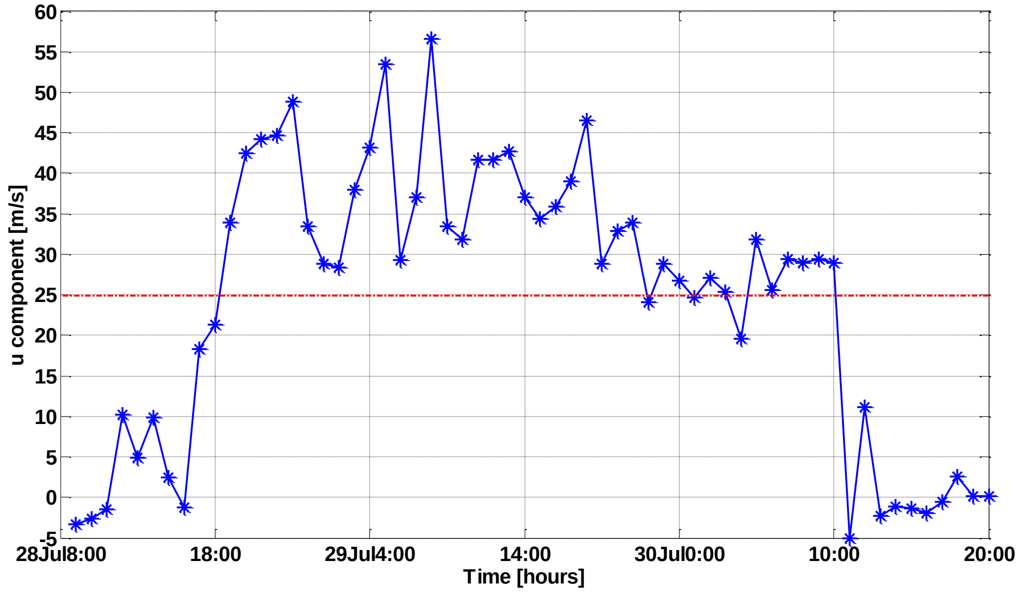

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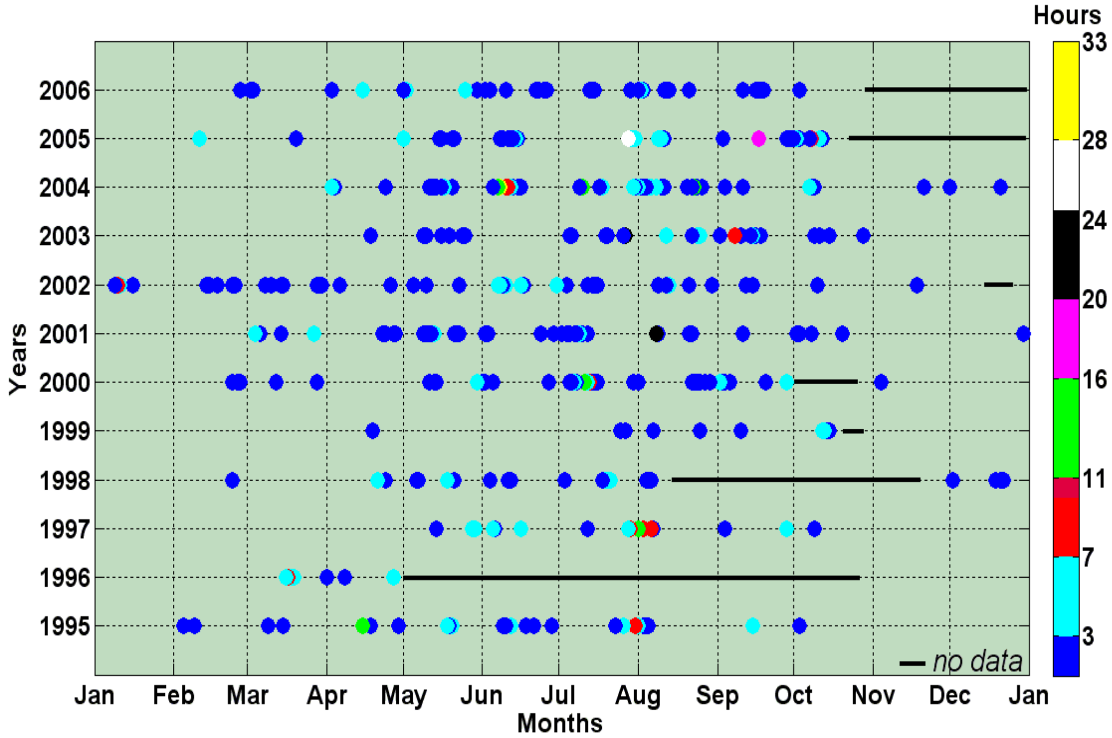

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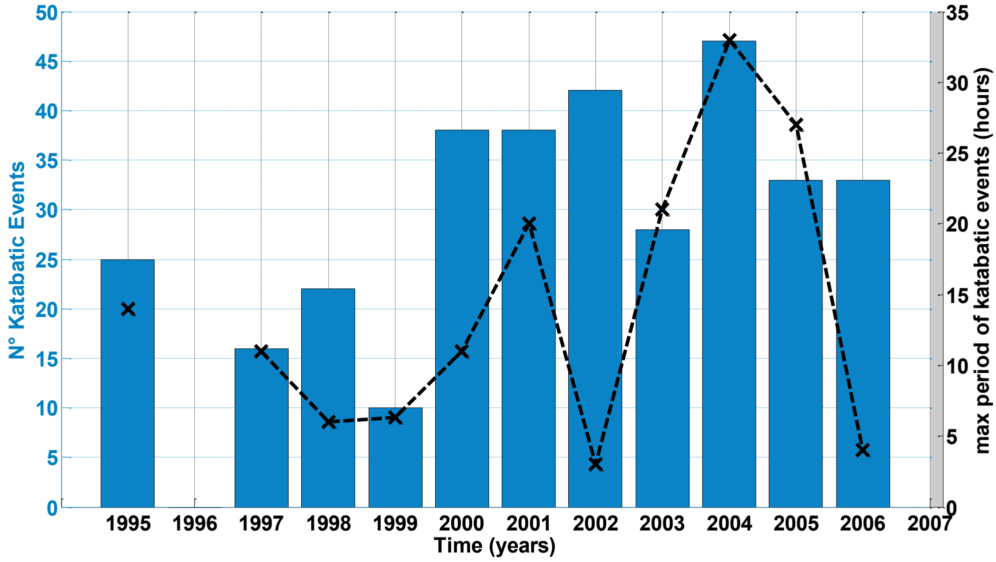

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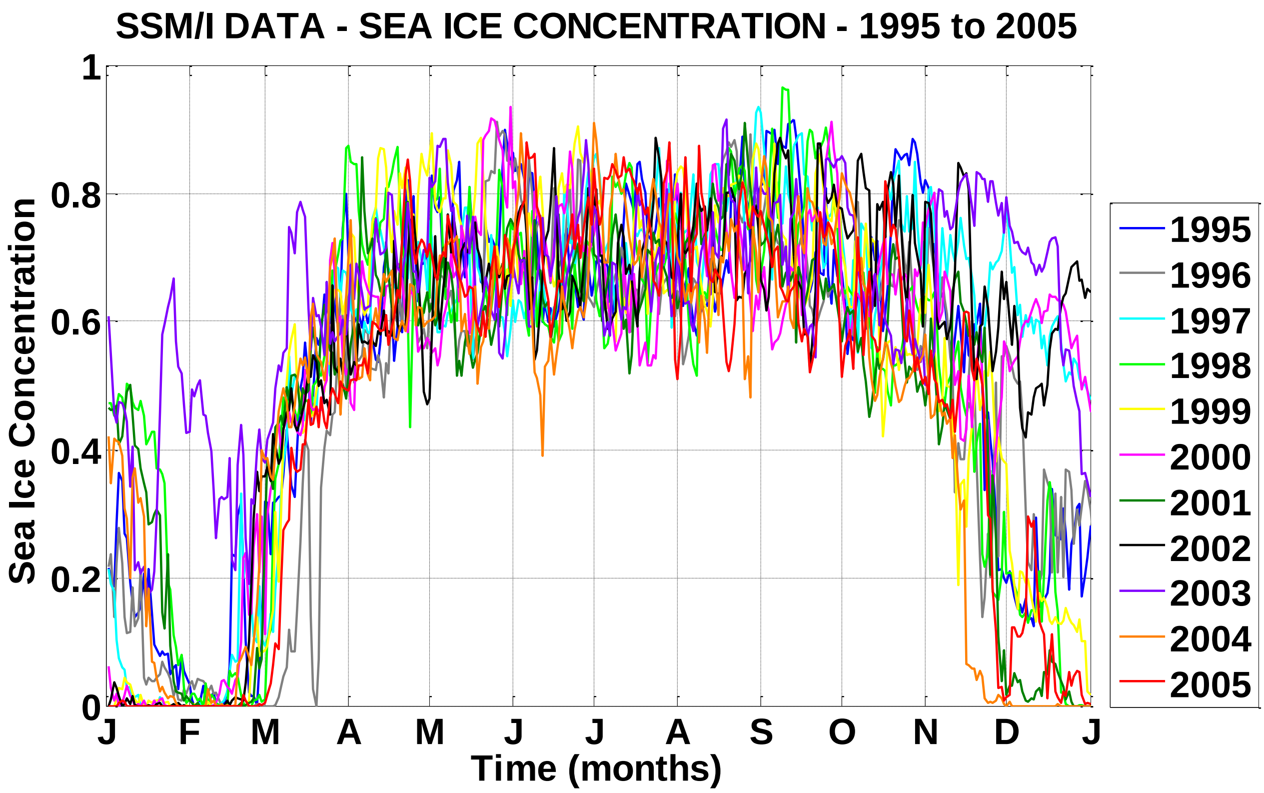

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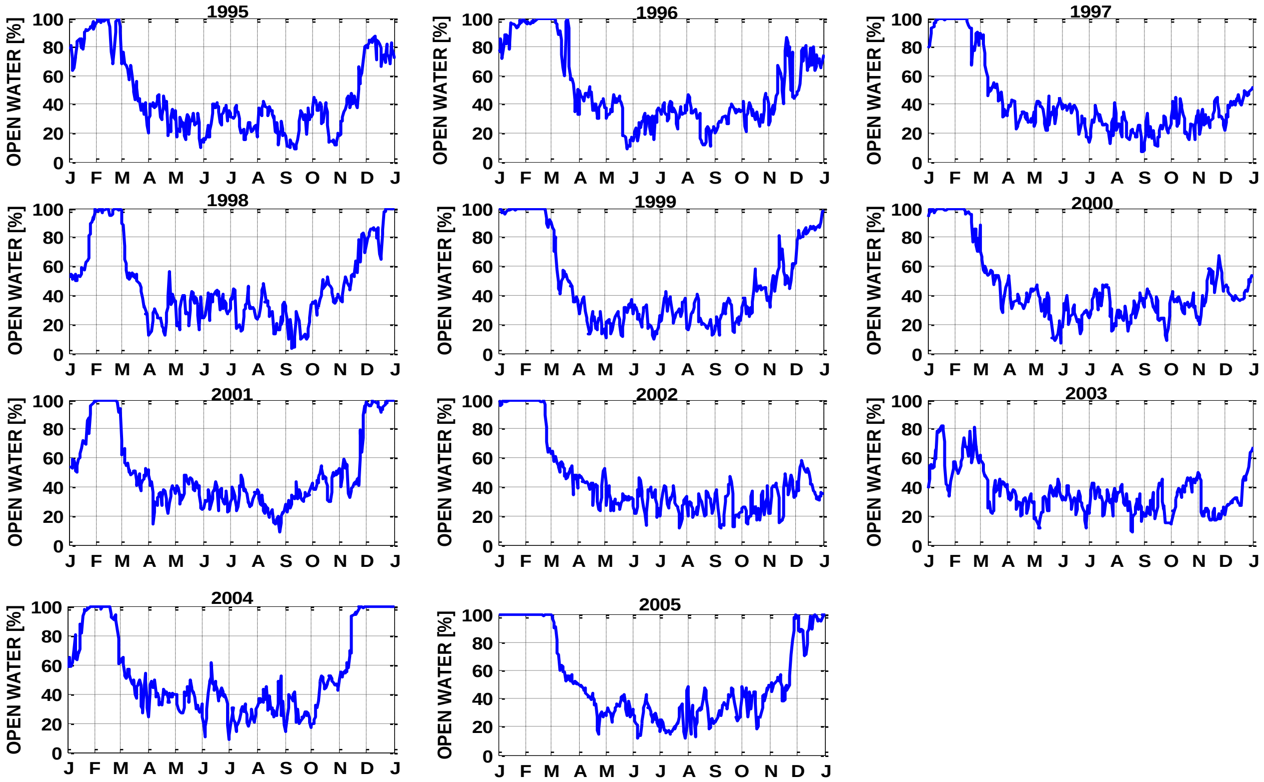

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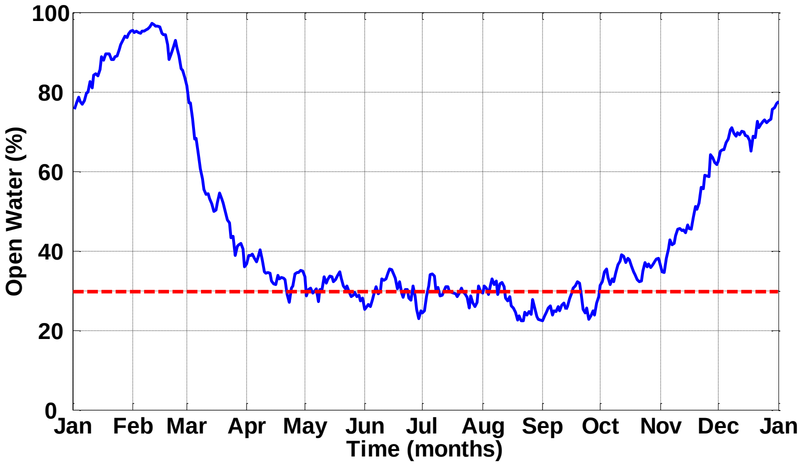

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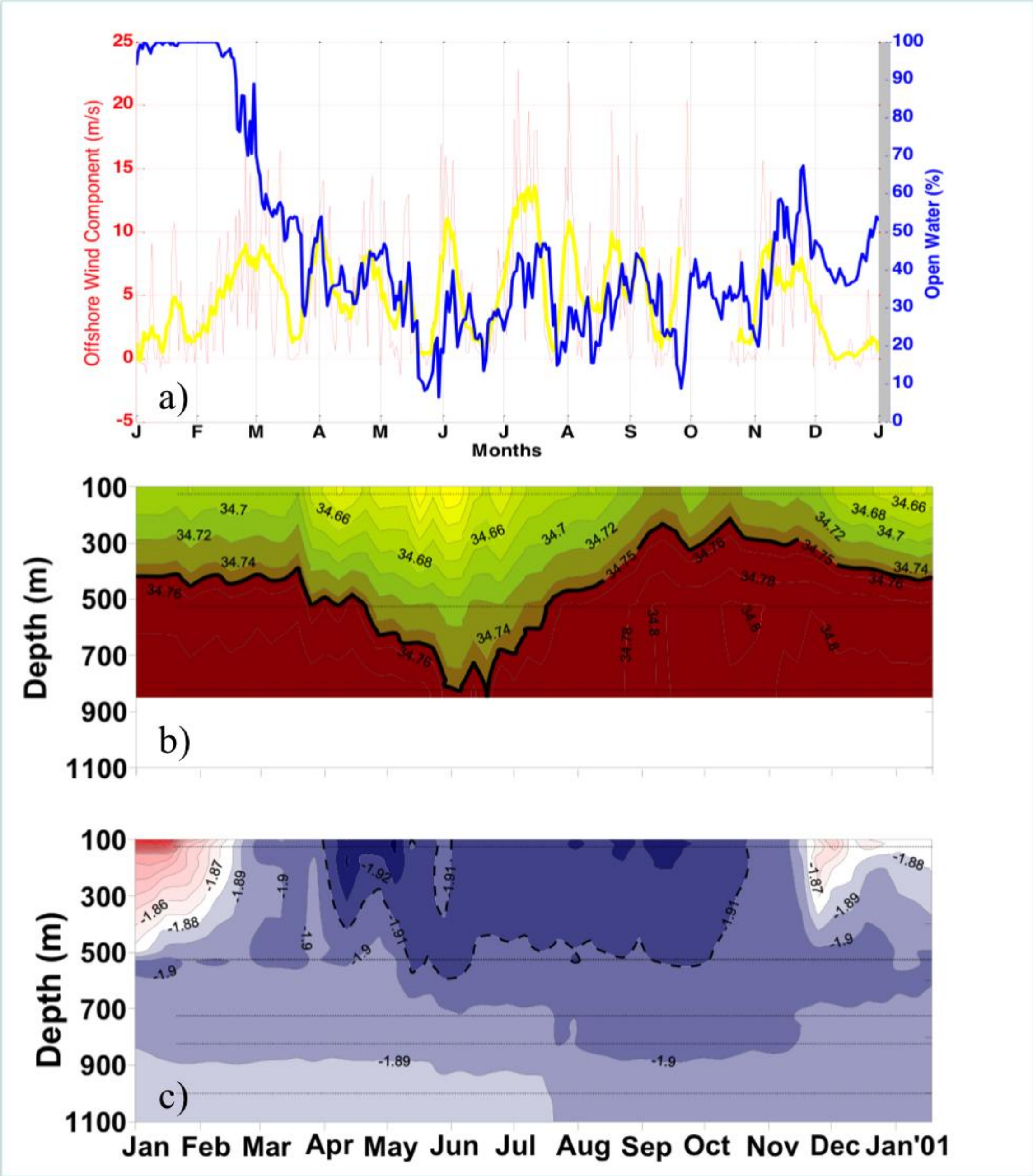

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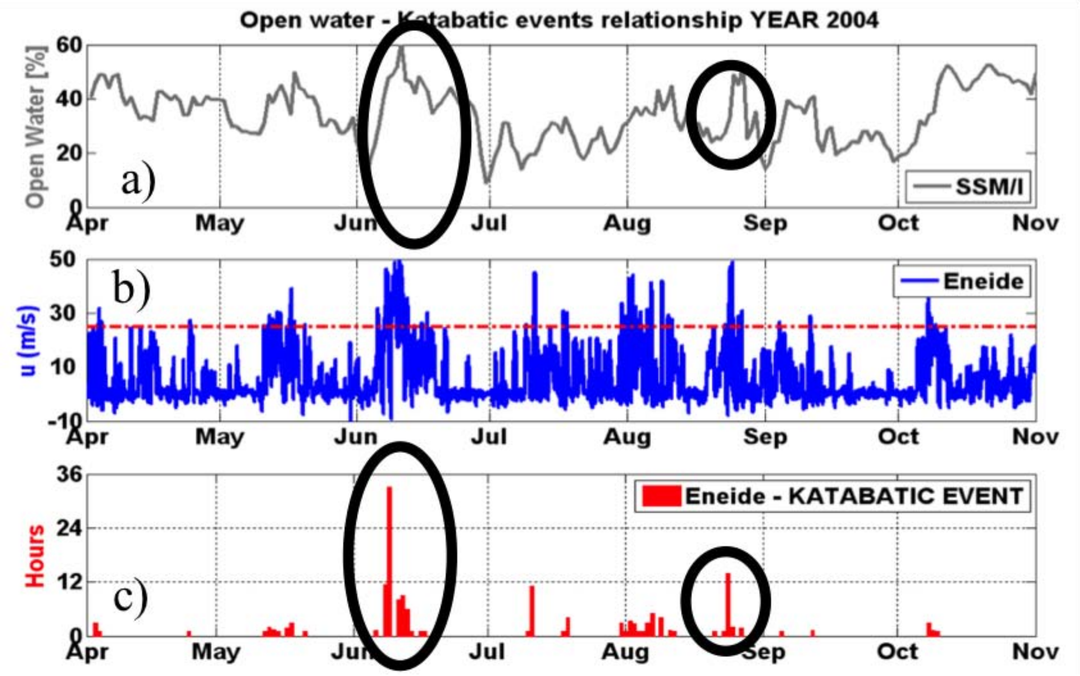

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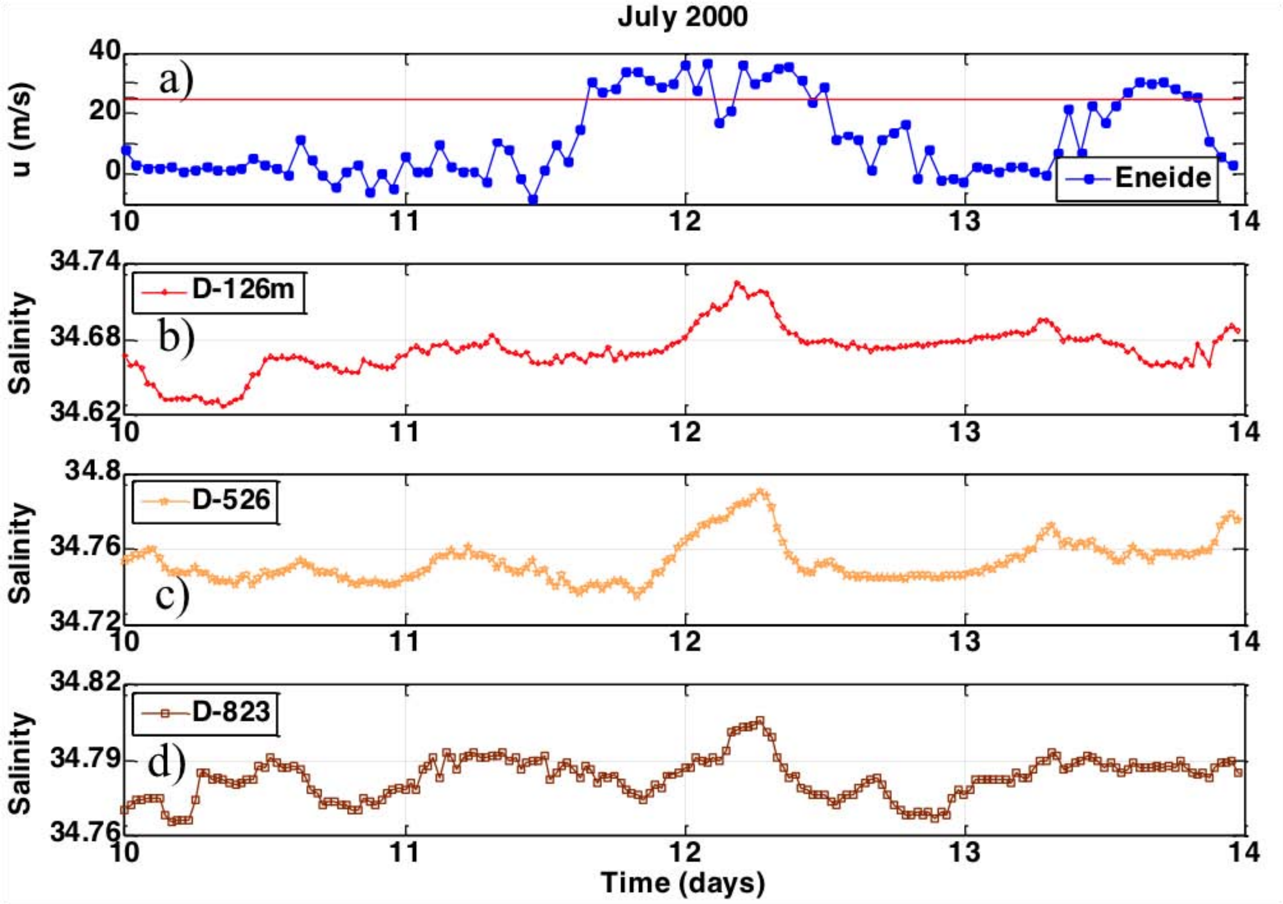

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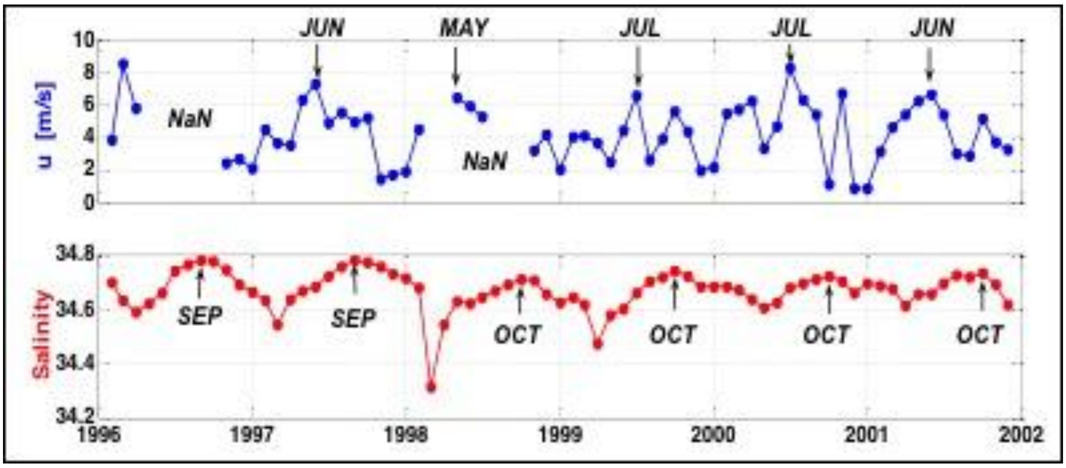

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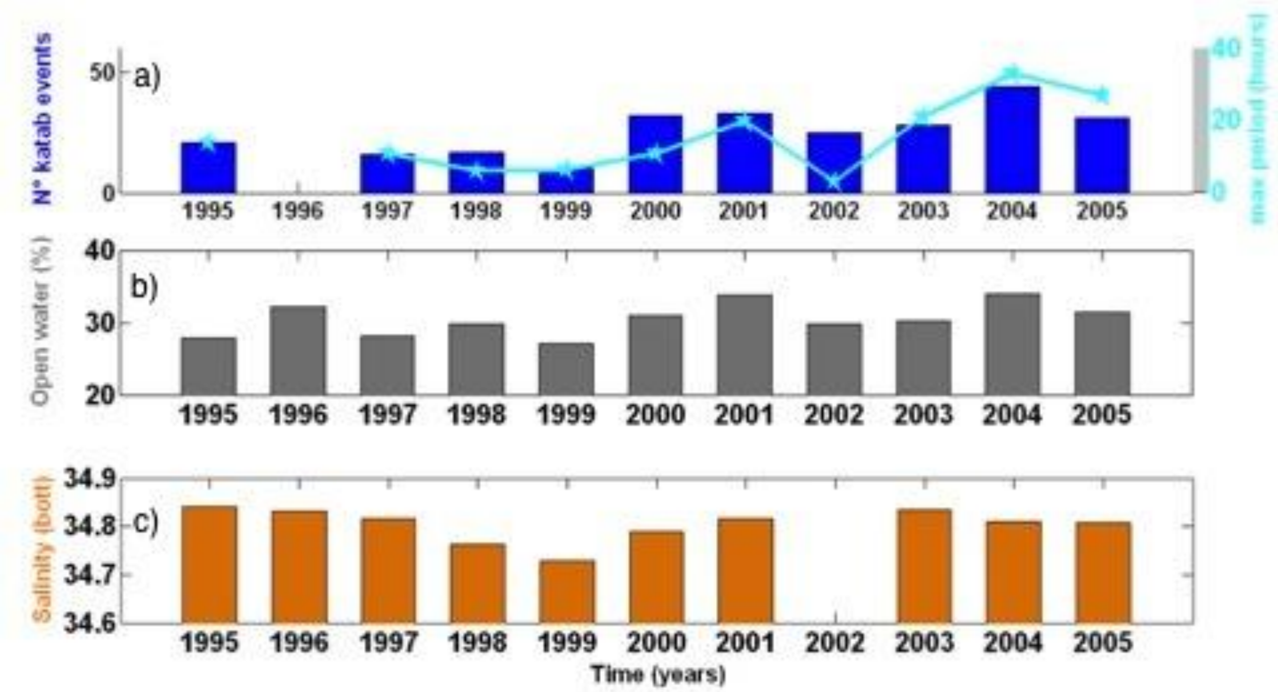

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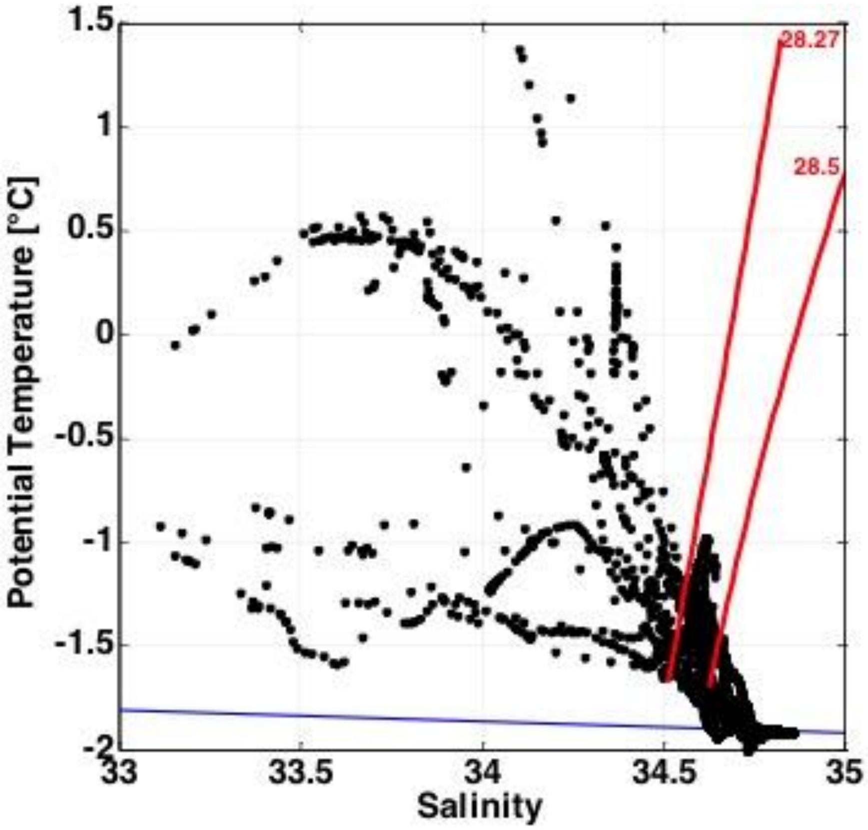

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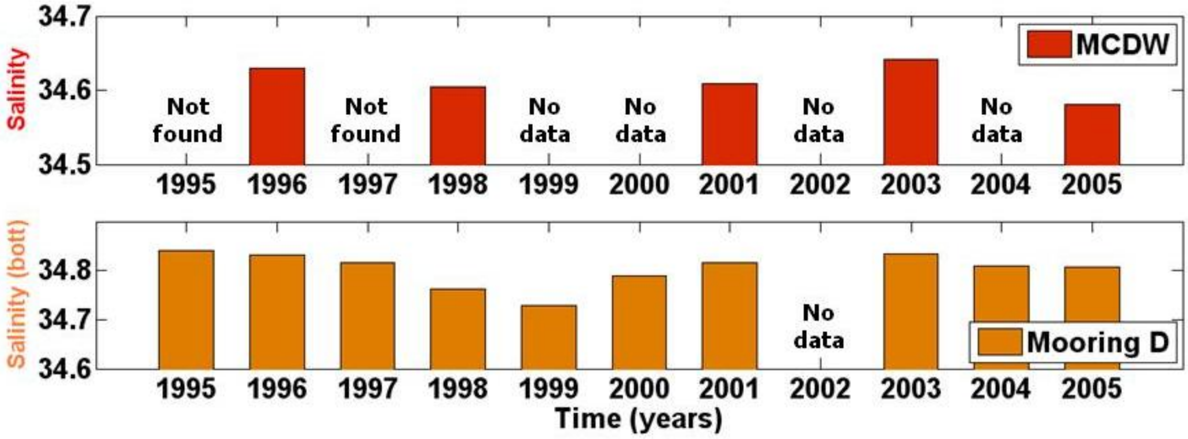

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