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Surface heat fluxes and thermohaline variability in the Ross Sea and in Terra Nova Bay polynya

Giannetta Fusco, Giorgio Budillon, Giancarlo Spezie

Dipartimento di Scienze per l'Ambiente, Università degli Studi di Napoli "Parthenope", Italy

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ABSTRACT

The Ross Sea is an important area for the ventilation of the deep layers of the Southern Ocean (e.g. [Jacobs, S.S., Fairbanks, R.G., Horibe, Y., 1985. Origin and evolution of water masses near the Antarctic continental margin: evidence from H218O/H216O ratios in seawater. In: Jacobs, S.S. (Ed.), Oceanology of the Antarctic Continental Shelf. Antarctic Research Series, vol. 43. pp. 59–85; Orsi, A.H., Johnson, G.C., Bullister, J.L., 1999. Circulation, mixing, and the production of Antarctic bottom water. Progress in Oceanography 109, 43–55]). These processes are driven by the atmospheric forcing which, at high latitude, plays a key role in the formation and thickness of sea ice. In order to investigate the effect of the atmospheric forcing variability at different time scales, we analysed the surface heat budget over the Ross Sea continental shelf and in Terra Nova Bay (TNB) polynya, using analyses for the period 1990–2006 provided by European Centre for Medium-range Weather Forecast (ECMWF). This study was also performed using thermohaline data collected within the activities of Climatic Long-term Interaction for the mass-balance in Antarctica project of the Italian National Programme for Antarctic Research for the summer periods from 1994 until 2001.

The annual average of the heat budget over the continental shelf of the Ross Sea estimated in the period 1990–2006 shows an interannual variability ranging between -97 and $-123\,\mathrm{W\,m^{-2}}$. Assuming that the heat loss must be compensated by the sensible heat carried by the Circumpolar Deep Water we estimated its transport (3.1 Sv) and its variability (0.2 Sv). Similarly in the TNB polynya the heat loss reaches its maximum in 2003 ($-313\,\mathrm{W\,m^{-2}}$) and its minimum ($-58\,\mathrm{W\,m^{-2}}$) in 1996. The related production of sea ice and the High Salinity Shelf Water (HSSW) were also estimated. The HSSW production switched from the lowest values during the first 10 years of the investigated period (1990–2000) to the highest values for the remaining period (2001–2006).

The thermohaline characteristics of the water column in TNB show a general decrease in salinity with a superimposed variability. Comparison between the estimated HSSW production and the salinity observed within the TNB water column show similar tendency in the last years after 2002, while during the period 1995–1998 the behaviour is different. Our hypothesis concern a possible role of the CDW inflow in the TNB area and our results could be explained by a different contribution of CDW transport and HSSW production to the salt content within the water column.

1. Introduction

Near surface and boundary layer conditions play a uniquely dominant role in the atmospheric circulation over Antarctica. Physical processes within the lowest few hundred meters of the atmosphere, primarily the katabatic wind regime, produce the most significant forcing of the atmospheric flows (e.g., Parish, 1988). The variability associated to temperature, wind forcing, cloud cover, etc., is not well investigated in Antarctica because of the limited in situ observations which are primarily collected during the austral summer season. Missing data result from a variety of events that may occur, in some locations, particularly in the Terra Nova Bay (TNB) (Bromwich, 1989), the force of the wind may at times be sufficient to render structural damage to the unit. Hence, the lack of continuous information (in space and time) due to environmental constrains is one of the most relevant problems for the not exhaustive knowledge of the atmospheric behaviour in Antarctica. This shortcoming can be alleviate using the atmospheric analyses provided by the large-scale weather forecast models. In this work we used the operational analyses and re-analyses provided from the ECMWF to estimate the surface heat budget over the Ross Sea and in Terra Nova Bay area.

The Ross Sea is an important area for the ventilation of the deep layers of the Southern Ocean (e.g., Jacobs et al., 1985; Orsi et al., 1999). These processes are driven by the atmospheric forcing which also plays a key role in the formation and thickness of sea ice. Moreover the Ross Sea is an oceanographic environment

E-mail address: giannetta.fusco@uniparthenope.it (G. Fusco).

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of particular interest being characterised by the presence of some persistent ice-free area during the austral winter (polynyas), one of which is recurrently detected in the coastal area of TNB (e.g., Kurtz and Bromwich 1983, 1985; Bromwich and Kurtz, 1984) close to the Italian base ''Mario Zucchelli Station'' (MZS). The impact of coastal polynyas on the polar oceans is known to be relevant for both physical and ecological aspects; in particular the air–sea heat exchange within a polynya is 1 or 2 orders of magnitude greater than through the surrounding sea ice, and the local ocean forcing is likely to be dominated by the polynya contribution. This is a crucial region oceanographically cause in the Ross Sea a large portion of Antarctic Bottom Water (AABW, the most extensive water mass in the world ocean, Orsi et al., 1999) is thought to be generated through a number of pathways. Most of the pathways have as a starting point the High Salinity Shelf Water (HSSW), formed by salinization of Circumpolar Deep Water (CDW) over the continental shelf; such salinization is directly caused by the production of sea ice. Then the presence of this polynya at TNB plays an important role in the modification of the thermohaline structure of the whole Ross Sea and in particular in the western sector (Jacobs et al., 1985; Budillon and Spezie, 2000; Budillon et al., 2003). Recently the thermohaline structure and the internal dynamics of the Ross Sea have been object of several studies and some results can be found in the literature (Trumbore et al., 1991; Locarnini, 1994; Jacobs and Giulivi, 1998, 1999; Bergamasco and Carniel, 2000; Budillon and Spezie, 2000; Gordon et al., 2000; Budillon et al., 2003; Gordon et al., 2004).

The purpose of this work is to investigate the effect of atmospheric forcing variability on the water column at different spatial and time scales. First we analyse the surface heat budget over the Ross Sea continental shelf during the last 17 years inferring also the average CDW incoming flow needed to compensate the heat loss from the sea to the atmosphere. Second we focused on the surface heat budget of the polynya which recurrently forms off TNB evaluating the sea ice and HSSW production. Third we analysed the measured thermohaline changes in the water column of TNB and close the north-western continental slope where the shelf waters interact with the CDW ventilating the deep ocean.

2. Study area

The geographical area considered in this work is bounded in the western sector by the coast of Victoria Land, in the eastern sector by the Marie Byrd Land and by the Ross Ice Shelf (RIS) in the southern part. A physical limit of the Ross Sea is constituted by the continental slope, which connects Cape Adare in northern Victoria Land on the west to Cape Colbeck on Edward VII Peninsula on the east (Fig. 1). The isobath of 1000 m may be used as a limit separating the continental shelf and the open ocean. This separation is not trivial because some oceanic processes as the ice formation and the brine rejection may have substantially different thermohaline consequences if they occur in a continental area or in open ocean. Moreover the different features of the bottom topography play an important role acting as reservoir for the densest waters and/or forcing the pathways of the intermediate and deep flows.

As said before, the Ross Sea is a site of dense water formation related to the winter surface heat losses. The dense water formation process is likely to be extremely sensitive to the interannual variability of the atmospheric forcing, making different amounts of dense water available for the bottom water formation processes and for the ventilation of the deep layers outside the continental shelf break.

The hydrography and the dynamic of the Ross Sea are clearly linked to the most important dynamic feature of the Southern Ocean, the Antarctic Circumpolar Current (ACC) which moves west to east around Antarctica and interacts with different water masses along its path. It carries the CDW that flows into the Ross Gyre and, on reaching the southern limb of the continental slope, mixes isopycnally with the shelf waters of the continental shelf (Locarnini, 1994). The mixing of the CDW with the surface and shelf waters on the shelf of the Ross Sea forms a distinct water mass, the Modified Circumpolar Deep Water (MCDW) or Warm Core (WMCO), characterised by a subsurface potential temperature maximum and a dissolved oxygen minimum (Jacobs et al., 1985). The MCDW interacts actively with the cold atmosphere, sea and glacial ice to form shelf waters in the Ross Sea (Jacobs et al., 1985; Trumbore et al., 1991; Locarnini, 1994).

The shelf waters in the Ross Sea are formed during the austral winter when the upper layers cool and freeze, thus delivering part of their saline content, which increases the salinity of the subsurface waters (Jacobs et al., 1985). Shelf waters generally have temperatures close to the surface freezing point, between -1.95 and $-1.75\,^{\circ}$C, and display higher salinity values in the western sector than in the eastern one (Locarnini, 1994). The high salinity in the western sector could be accounted for by the large size of the Terra Nova Bay polynya even during the winter period (Kurtz and Bromwich, 1983, 1985).

In this work we focused on TNB coastal polynya as it is considered to be by far the largest producer of HSSW. Indeed, despite the well-known presence of a polynya in the Mc Murdo region, this has never been regarded as a relevant HSSW formation area for the lack of adequately intense air–sea interactions. Furthermore, previous hydrographic studies (e.g.,

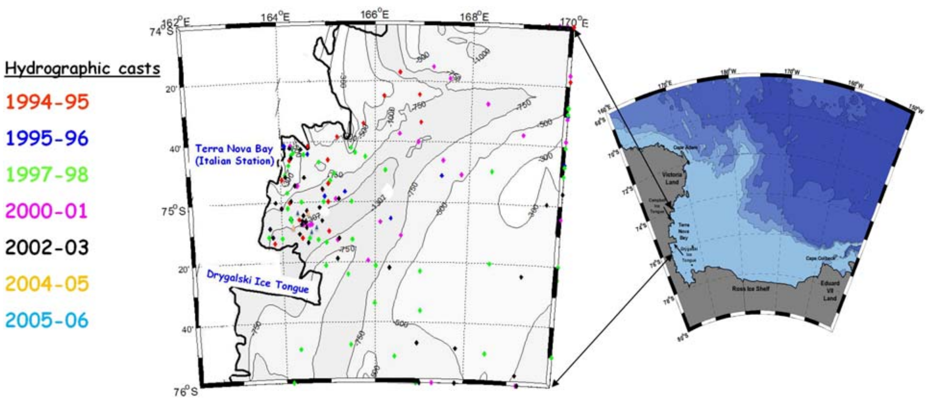

Fig. 1. The study area and the focus on the Terra Nova Bay (TNB). The hydrological casts TNB polynya used to estimate the thermohaline changes are reported. Symbols indicate the casts performed during the austral summers from 1994/95 to 2005/06 (see also Table 1).

Budillon et al., 2003; Gordon et al., 2009) which analysed the physical properties of the bottom layers showed a clear salinity gradient towards the TNB polynya area confirming its major role in HSSW production.

Terra Nova Bay occupies an area of approximately 6000 km^2 in the western sector of the Ross Sea and it is bordered by the Drygalski Ice Tongue (DIT) on the south and by the Campbell Ice Tongue on the north. The DIT act as barrier for the pack ice advection from the south and the south-west (Kurtz and Bromwich, 1983), whilst katabatic winds blowing almost constantly in the offshore direction, keep the area ice free. This peculiar setting allows the TNB polynya to form and to be maintained. The rejected brine increases the salinity (from 34.75 to 35.00) of the subsurface waters, thus forming the densest waters of the Southern Ocean, HSSW (Jacobs et al., 1985). The presence of the modified CDW in the subsurface layer of the western sector of the Ross Sea plays an important role in HSSW formation: when the surface waters freeze during the winter, the released brine is added to the subsurface waters which already have relatively high salinity values due to the direct influence of the MCDW (Locarnini, 1994). Part of the HSSW is known to move northward along the western sector of the Ross Sea extending as far as the continental shelf break and takes part in the formation of the AABW. Another branch goes southward and flows under the Ross Ice Shelf giving rise to a different type of water named Ice Shelf Water (ISW) which is characterised by a temperature lower than the freezing point at the sea surface (Jacobs et al., 1985).

3. Data and method

3.1. Data set

Hydrographic data (depth, temperature and conductivity) where obtained using a multiparameter CTD probe (SBE 9/11 plus) equipped with two temperature and two conductivity sensors and with a SBE Carousel water sampler. Moreover, CTD-salinity acquisitions were also calibrate with salinometer analysis of bottle samples collected in each station at several depths. The CTD records were acquired at the highest frequency (24 Hz) allowed by the probes spanning the water column from the surface to the nominal depth of 1 m above the bottom. They were subsequently processed following standard procedure and algorithms (UNESCO, 1983, 1988), and averaged over 1 dbar in the final data set (more details can be found in Budillon et al., 1999, 2003; Budillon and Spezie, 2000).

The hydrological results presented in this paper originate from eight quasi-synoptic surveys carried out by the R/V Italica in the western sector of the Ross Sea in the framework of the multidisciplinary campaigns conducted by the Italian CLIMA project (Fig. 1). In Table 1 are reported the period and number of the hydrological casts used for each survey.

Direct observations of the surface energy budget within polynyas are rare and only cover short periods such as scientific cruises typically in the summer periods. Hence other data sources must be used to estimate surface heat fluxes, for example, observations from automatic weather stations (AWS) positioned on the edge of the DIT or at the MZS Italian Base, generally just upwind of the coastal polynya. Unfortunately in situ observational data for the atmospheric boundary layer over TNB polynya do not cover the entire period investigated (1990–2006) because of the difficulty of placing and maintaining instruments in such location. Hence in this study we analyse meteorological data extracted from numerical weather prediction model analyses. The choice of the numerical weather prediction model to be used was difficult as at present all the models used by the major forecasting centres

Table 1
Acronyms, date, period, and number of the cast used in this study for the oceanographic analysis in the TNB polynya.

Survey	Summer	Period	Total casts
X PNRA	1994/95	18–20 February 1995	7
XI PNRA	1995/96	02–05 February 1996	4
XIII PNRA	1997/98	07–09 December 1997	8
		08–13 February 1998	5
XVI PNRA	2000/01	02–18 January 2001	6
XVIII PNRA	2002/03	17–27 January 2003	13
XIX PNRA	2003/04	January/February 2004	2
XX PNRA	2004/05	10–15 January 2005	2
XXI PNRA	2005/06	08–16 January 2006	3

(e.g., ECMWF and US National Centers for Environmental Prediction—NCEP) have some serious deficiencies particularly in the polar regions (e.g., Cullather et al., 1997; Turner et al., 1999; Bromwich et al., 1999; Hines et al., 1999, 2000).

Recently a comparison between the ECMWF data and those acquired by the AWS "Manuela", the only AWS working close to the area of the TNB polynya – located at 75°S and 164°E (on Inexpressible Island) – indicates for the period 1993–1994 a satisfactory correspondence in air temperature with a correlation of 0.9 (Fusco et al., 2002). Thus we can assume the ECMWF are representing the boundary layer temperature of the area with a satisfactory precision. Comparisons with the near-surface wind observations do not fare so well as with temperature, with large errors occurring at all times of the investigated period (Fusco et al., 2002). However the study on the comparison between the Antarctica numerical analyses and available rawinsonde, AWS, ship performed by (Cullather et al., 1997) shows that pressure, temperature, relative humidity and wind fields by ECMWF are in substantial agreement with the observational data. In particular the ability of the ECMWF analyses to reproduce the observed wind is more consistent than NCEP analyses with standard errors generally in the range of between 2–4 $m\,s^{-1}$.

ERA40 re-analyses for the period 1990–2001 and operational analyses for the period 2002–2006 provided by the ECMWF were utilised. In particular we used air temperature, u and v wind components, mean sea level pressure, total cloud cover and relative humidity having a temporal resolution of 6 h and a spatial resolution of 0.5° both for latitude and longitude. This study was carried out in two steps. In the first the area investigated contains only the whole area of the continental shelf of the Ross Sea, assumed to be the $3.9\times10^5\,km^2$ region between the 1000 m isobath and the RIS. The means were calculated over this domain to analyse the average heat exchanged at the surface for the period 1990–2006 and then to estimate the CDW flow needed to preserve the surface heat budget. In the second step we focused on surface heat fluxes, ice and HSSW production estimation in Terra Nova Bay polynya considering a subdataset of the ECMWF representative of the area.

Despite the key role on the energy exchanges between ocean and atmosphere, data and observations on sea ice thickness in the Ross Sea are very scarce and inadequate. Moreover space and time variability, both in vertical and horizontal scales, may largely modify the fluxes between the ocean and the cold atmosphere during the winter. Actually in case of high concentrations or in the lack of sea ice, like in polynyas or leads areas, the surface heat fluxes may change considerably.

Then, quantifying these fluxes to a high degree of accuracy is a study in itself. Therefore in this study we concentrate on the estimates of energy exchange using weekly data of sea ice concentration and thickness of the Ross Sea which has been estimated by National Ice Centre and National Climatic Data Centre (NIC/NCDC). Ice concentration for the period 1990–2006 was used to estimate the presence or absence of ice cover in the investigated area. Because of the ice thickness lack for the periods 1990–1993 and 1995–2006, weekly averaged ice-thickness obtained from the 1994 data set was used (as a 'climatology') for the all period. In order to homogenise this data set with the data provided by the ECMWF, the sea ice data were linearly interpolated in space and time (Budillon et al., 2000).

3.2. Heat flux parameterisation

Empirical formulae (see, for instance, Berliand and Berliand, 1952; Simonsen and Haugan, 1996) have been used to estimate the surface radiative fluxes. Such formulae are frequently used in the polar regions and appear to work rather well, with the only significant uncertainty due to cloud cover (e.g., Makshtas et al., 1999; Van Woert, 1999b). Unfortunately, satellite-retrieved cloud data, and therefore satellite-based climatologies, are rather inaccurate in the polar regions.

The ice concentration was used to identify ice covered areas and so to modify the heat flux parameterisation in the presence or absence of the ice cover.

It is well known that in the no-ice condition the net heat budget at the ocean–atmosphere interface Q_T can be written as:

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

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. In the presence of sea ice the surface heat budget has to take into the account also the conducted heat flux Q_C through the sea ice layer. The heat flux parameterisations are adapted for polar regions (for more details see Budillon et al., 2000). The ice thickness was utilised in the computation of the sea albedo and of the fraction of the shortwave radiation which penetrated the ice (Budillon et al., 2000).

The net heat loss from the ocean to the atmosphere was estimated every 6 h in each grid point, then averages in time and space were computed to obtain monthly and yearly means for the period 1990–2006 over the continental shelf of the Ross Sea and in TNB polynya (for more details see Fusco et al., 2002).

3.3. CDW transport estimated

CDW coming from the ACC provides the major source of heat (and salt) in the Ross Sea, intruding into the shelf region and mixing with the shelf waters (Locarnini, 1994). The yearly heat loss in this continental region must be compensated for by deep-level currents and mixing processes. We estimated the necessary CDW flow that must intrude on to the continental shelf in order to preserve the annual average of heat budget (considering in this case only the advective heat transport) updating the results of (Budillon et al., 2000) and using the following formulae

$$F_{CDW} = Q_T(T_{CDW} - T_{SW})^{-1}\rho^{-1}C_p^{-1}\,Area$$

assuming a mean shelf water temperature T_{SW} of $-1.6\,^\circ$C and a temperature for the incoming CDW (T_{CDW}) of $+1.5\,^\circ$C, a specific heat (C_p) of 3978 J kg^{-1} K^{-1}, a reference averaged density (ρ) of 1028.00 Kg m^{-3}, a constant area of 390,000 km^2.

3.4. Sea ice and HSSW production

The ice production rate in a polynya depends on the net heat flux and it is parameterised (Pease, 1987) as

$$P_i = \frac{Q_T}{L_f\rho_i}$$

where ρ_i is the density of ice (0.95×10^3 kg m^{-3}) and L_f is the latent heat of fusion (3.34×10^5 J kg^{-1}).

The total ice production is given by

$$\sum_{ice}\int \text{Area}\,\frac{Q_T(t)}{L_f\rho_i}\,dt$$

assuming a constant polynya area of 1300 km^2. This value is obtained considering a polynya extent of 20 km, derived from AVHRR data (Kurtz and Bromwich, 1985), and a fixed north/south dimension of 65 km.

The salt released in a polynya per day (see Markus et al., 1998) is:

$$P_S = \rho_i P_i A_p (s_w - s_i)$$

where A_p is the polynya area, s_w the water salinity and s_i the salinity of frazil ice, which is: $s_i = 0.31 s_w$ (Martin and Kaufmann, 1981). The HSSW production (Van Woert, 1999a) is given by:

$$P_{HSSW} = \frac{P_S}{\rho_{HSSW}(S_{HSSW} - S_{SW})\times10^{-3}}$$

where ρ_{HSSW} is the density of HSSW (1030.45 kg m^{-3}), S_{HSSW} the salinity of HSSW ($S = 34.8$) and S_{SW} the salinity of the Low Salinity Shelf Water or Warm Core water ($S = 34.5$; Jacobs et al., 1985) which is involved in the sea ice formation processes.

3.5. Hydrology

The interannual variability can be described in terms of the salt and heat flux divergence required producing the observed change. Following Klink (1998) and updating the results of Budillon and Spezie (2000), at each depth values of salting (R in units of g m^{-3} s^{-1}) and heating rate (Q in units of W m^{-3}) are calculated in this work as:

$$R = \frac{\rho\Delta S}{\Delta t} \quad (1)$$

$$Q = \frac{\rho C_p \Delta T}{\Delta t} \quad (2)$$

where ρ is the reference density (1028.00 kg m^{-3}) as defined before, C_p is the specific heat (3980 J Kg^{-1} K^{-1}), ΔS and ΔT are respectively the salinity and temperature ($^\circ$C) change, and Δt is the time interval (s) between measurements (cf. Klink, 1998).

These calculations were made for some selected stations chosen in the deepest region of TNB (Fig. 1) in order to examine a homogeneous data set in terms of number and location of casts. For each survey (see Table 1) these casts were averaged in order to obtain a standard thermohaline profile representative of the investigated period, which has been used to calculate the heat and salt fluxes.

Typically in the western Ross Sea the greatest variability in the water column occurs in the upper layer (100 m) primarily due to the strong atmospheric forcing (Jacobs et al., 1985; Locarnini, 1994; Budillon et al., 2000). Moreover, because the high-frequency variability (e.g., internal waves) may be interpreted as a seasonal change of heat and salt, to some extent, this bias can be eliminate integrating the data over selected depth ranges.

Thermohaline water properties in TNB were measured for a number of occasions and are always found to have similar properties except for seasonal changes in the upper pycnocline; therefore, in this work, to study the interannual variability the salt changes, below the pycnocline to the bottom, have been computed and averaged at different depths with thickness of 100 m. Actually as shown in TNB by Budillon and Spezie (2000) using both hydrographic and current meter data, the high-frequency variations are not a fundamental source of aliasing for

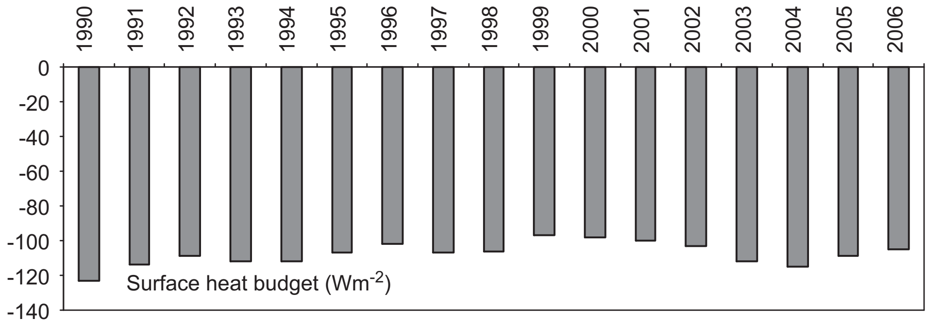

Fig. 2. Annual mean of the surface heat budget ($W\,m^{-2}$) over the Ross Sea continental shelf for the period 1990–2006.

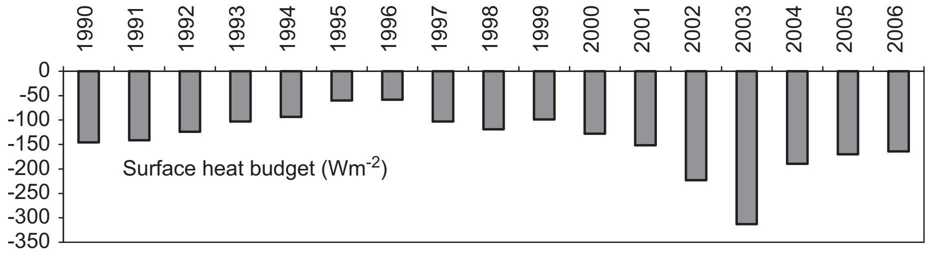

Fig. 3. Annual mean of the surface heat budget ($W\,m^{-2}$) in TNB polynya for the period 1990–2006.

the subsurface layers (below the thermocline) but they could be relevant in the surface layer (100 m); therefore we analyse only the results obtained for depths below it.

4. Results and discussion

The surface energy budget components for ECMWF model time series are calculated, as said in Section 3.2, following the parameterisations adapted by Budillon et al., (2000). By integrating the surface heat fluxes over the Ross Sea continental shelf we obtained the yearly mean of the heat budget that shows an interannual variability (Fig. 2). As we expected such estimation is constantly negative (i.e. the ocean loses heat to the atmosphere) during the all available period (1990–2006). The heat loss reaches its maximum in 1990 ($-123\,W\,m^{-2}$) and its minimum ($-97\,W\,m^{-2}$) in 1999. In particular the annual average of the heat budget during the first 6 years (1990–1995) varies between -107 to $-123\,W\,m^{-2}$ while in the remaining period (1996–2006) it fluctuates between -97 to $-115\,W\,m^{-2}$. A mean value for the entire period is $-108\,W\,m^{-2}$ with a standard deviation of about $7\,W\,m^{-2}$. These yearly mean heat loss, from the sea to the atmosphere, must be compensated by the heat provided by horizontal advection and mixing processes. Actually there are horizontal heat fluxes within the portion of the sea over the continental shelf, as the heat provided by the incoming CDW in the Ross Sea. Consequently we use the yearly mean heat loss estimations to infer the mass transport provided by the CDW to preserve the annual average of the heat budget. The CDW transport estimated ranges from 2.8 to 3.6 Sv with an average of 3.1 Sv and standard deviation of about 0.2. As we expected, the trend of CDW transport reaches its maximum value (3.6 Sv) in 1990 and its minimum (2.8 Sv) in 1999 and 2000.

The conversion of heat loss to CDW transport assumes that there is no heat loss along the way, i.e. a cooling of ISW or other resident shelf waters flowing beneath the RIS. It also assumes that the heat needed to melt the ice shelf is negligible compared to the surface heat budget. These hypothesis are supported by a recent study performed by Smethie and Jacobs, 2005. Actually they show

Table 2
Annual mean values (1990–2006) for the shortwave, longwave, sensible, latent and total terms estimated in TNB polynya with mean and standard deviation (std) values over the entire period. All units are in $W\,m^{-2}$.

Year	Q_S	Q_B	Q_H	Q_E	Q_T
1990	100	−38	−151	−57	−145
1991	90	−36	−140	−54	−141
1992	93	−37	−129	−50	−124
1993	97	−38	−118	−44	−103
1994	91	−36	−107	−42	−94
1995	99	−38	−86	−35	−60
1996	100	−39	−84	−35	−58
1997	98	−38	−119	−44	−103
1998	103	−40	−133	−48	−119
1999	105	−40	−118	−45	−99
2000	104	−41	−137	−54	−128
2001	109	−44	−156	−61	−151
2002	121	−48	−215	−81	−223
2003	101	−48	−264	−102	−313
2004	111	−47	−183	−70	−189
2005	109	−45	−165	−69	−170
2006	108	−45	−160	−68	−164
Mean	102	−41	−145	−57	−140
Std	8	4	45	17	62

that the freshening of HSSW during its conversion to ISW under the RIS yielded average net melt rates of 57 and $60\,km^3$/yr, whereas the rate calculated from the cooling of HSSW yielded only $20\,km^3$/yr.

We now investigate the 17 year surface heat budget integrated over the coastal polynya area of Terra Nova Bay. It is clear that the greatest heat loss occurs in years with large polynya areas, but the relationship is not one to one. For example, a cold spell with a small polynya area could yield greater energy exchange than a warmer spell with a larger polynya area. The length of the freezing season does not appear to be related to the total energy exchanged.

Using a subdataset of the ECMWF representative of the TNB polynya and a slightly different parameterization – which does not consider the presence of the sea ice, but only its formation (for

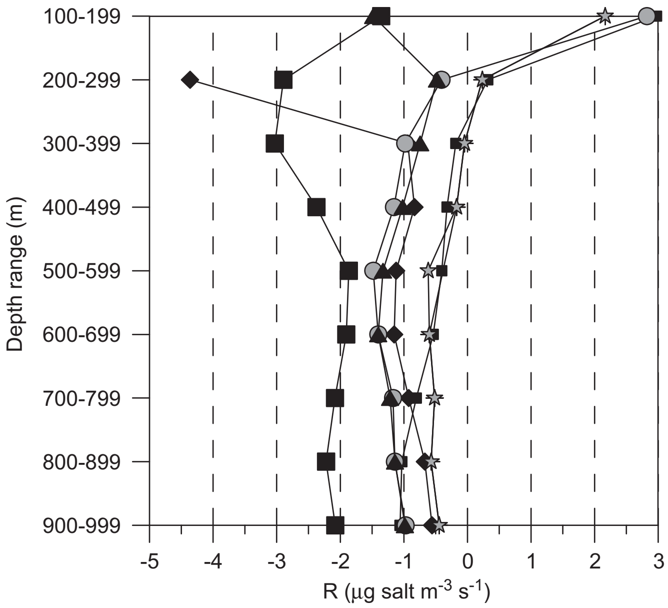

Fig. 4. Salt fluxes (μg salt $m^{-3}\,s^{-1}$) during the different cruises in the water column of Terra Nova Bay using the stations in the polynya area of Fig. 1 for the 1995/96 (crosses), 1997/98 (diamonds), 2000/01 (squares), 2002/03 (circles), 2003/04 (triangles), 2004/05 (open squares) and 2005/06 (stars) surveys.

Table 3
Annual sea-ice thickness (m per unit surface), average sea-ice production and HSSW transport in TNB polynya estimated by the surface heat losses.

Year	Ice thickness (m)	Ice production (km^3)	HSSW transport (Sv)
1990	19	25	1.2
1991	18	24	1.2
1992	17	22	1.1
1993	15	20	1.0
1994	14	18	0.9
1995	11	15	0.8
1996	11	15	0.7
1997	16	20	1.0
1998	16	21	1.1
1999	16	20	1.1
2000	18	23	1.2
2001	20	26	1.3
2002	30	39	1.8
2003	35	45	2.0
2004	25	32	1.6
2005	22	29	1.4
2006	22	29	1.5
Mean	19	25	1.2
Std	6	8	0.3

Average and standard deviation (std) values over the entire period are also reported.

more details see Fusco et al., 2002) – we focussed on the air–sea interaction in TNB polynya. The time series of the surface heat budget in the TNB polynya (Fig. 3) show higher values from 2001–2006 when it reached its maximum heat loss in 2003 ($-313\,W\,m^{-2}$). The minimum heat loss occurs in 1996 and its values is $-58\,W\,m^{-2}$. A mean value for the entire period is $-140\,W\,m^{-2}$ with contributions of -145, -57, $61\,W\,m^{-2}$ from the sensible, latent, and radiative terms, respectively (see Table 2).

During the freezing season it can be assumed that the heat flux from the ocean to the atmosphere results directly in ice production considering the ocean column is at freezing point. In order to appreciate these results, it is possible to show – applying the Q heating rate formulae (2) – that the cooling of a 100 m deep column of water from $-1.5\,°C$ to its freezing point can be achieved by only around 10 h of $400\,W\,m^{-2}$ surface cooling. We can therefore speculate on the relevance of the katabatic winds in TNB which are the most important factor for the heat loss at the sea surface in this region.

Assuming that the yearly heat loss calculated reflects the average conditions, it is possible to estimate the annual ice production which would be needed to balance the deficit at the surface. The ice thickness production computed during the period 1990–2006 ranges between 11 m (1995 and 1996) and 35 m (2003) (per surface unit) with a mean value of 19 m and a standard deviation of 6 m (Table 3). The annual rate of sea ice formation over the 1300 km^2 polynya amounts to a total of 15–45 km^3 (Table 3), or enough to cover 15,000–45,000 km^2 with ice 1 m thick. According to our expectation, because of the underestimation of the wind intensity provided by ECMWF, these values are lower than the estimates provided by Kurtz and Bromwich (1985) and Van Woert (1999 a, b).

Moreover, because of their dependence on total ice production, it is possible to calculate the total productions of salt released and the HSSW volume (see Van Woert, 1999 a, b; Fusco et al., 2002). In Fusco et al. (2002) the ECMWF and data from an AWS available for a limited period in TNB were compared, obtaining a strong underestimation of the total heat budget and consequently also an underestimation of the ice and the HSSW production when using ECMWF data. In reality, as shown by Fusco et al. (2002), the production of HSSW by AWS and ECMWF data shows similar trends but with a high difference in magnitude, the ECMWF data yield weaker polynya dynamics. Using the conclusions of this paper and comparing HSSW production by AWS and ECMWF, we have estimated a correction of approximately $0.15\times10^2\,m^3\,day^{-1}$ to apply to the values of HSSW production when these are calculated by the ECMWF data. The estimates obtained of HSSW transport (Table 3) show a mean value of 1.2 Sv with a standard deviation of 0.3 Sv. Our results demonstrate that the HSSW production switched rapidly from the lowest value during the first decade, when reach its minimum in 1995 (0.7 Sv), to the higher in the last period (2000–2006) with its maximum of 2.0 Sv in 2003. It must be stressed that such results are in good agreement with those obtained by Van Woert (1999 a, b) using a shorter meteorological data set acquired by the AWS "Manuela" only for three winter seasons (1988–1990).

In order to compare and validate these estimations obtained by a simple parameterization of very complex phenomena such the sea ice formation, brine rejection and HSSW production, we now analysed the measured thermohaline changes in the water column of TNB using the hydrological casts collected during seven austral summers from 1994/95 to 2005/06. Actually, as a direct consequence of the HSSW variability, a change in both salinity and volume of HSSW is expected in the deeper layers. In particular, a stronger (lower) winter surface forcing – which produces a more (less) quick extraction of newly formed sea ice – should increase (decrease) the salinity of the HSSW. To evaluate this reaction, we analysed the deep layers of the water column in the TNB extending and improving, for some aspects, the results already analysed by Budillon and Spezie (2000) for a smaller dataset (in space and time).

It must be noted that the width of the area used in this investigation is about 50 km; assuming a mean speed of 0.05 m s^{-1} for both surface and deep layers, the advective time can be estimated at about 25 days. Therefore hydrological measurements performed with a time lag of 1 month or more, as in our data set, can describe primarily the variability produced by the horizontal advection. Therefore the subsurface thermohaline variability can be attributed primarily to the large-scale atmospheric forcing

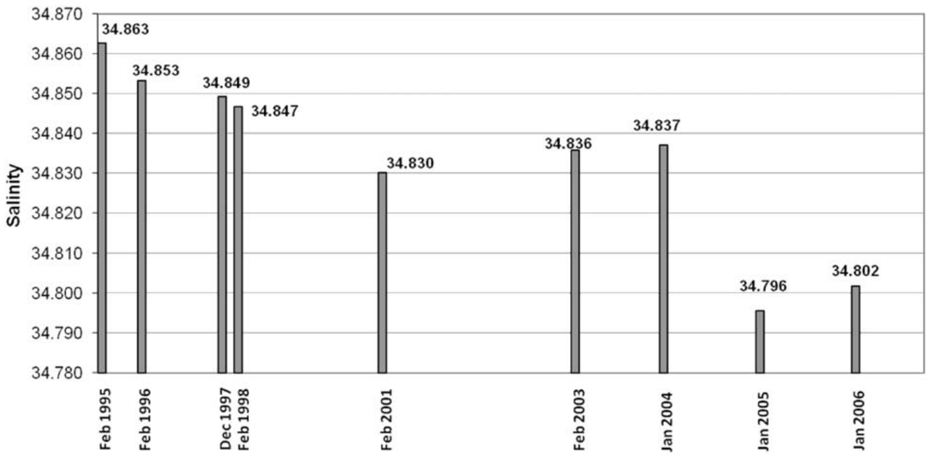

Fig. 5. Average salinity in a 10 m thick layer at 900 m depth (that is the maximum common depth for all the analysed cruises) from 1995 to 2006.

acting on the Ross Sea, since the low variability of the other source of heat for the water column (the MCDW) cannot modify substantially the thermohaline properties of the shelf waters (Jacobs and Giulivi, 1998).

In order to highlight the interannual variability we calculated the salt (μg salt $m^{-3} s^{-1}$) fluxes for each survey from the surface to the deeper common layer. The results have been compared with the first cruise (summer 1994/95) and have been expressed as salt flux differences at several depths. It must be stressed that the vertical integral of the flux divergence is equivalent to the net heat or salt flux over a water column with an area of 1 m^2 and extending over the depth range considered, here 100 m each. These integrated fluxes can be thought of as the net surface flux required to make the observed changes. This conversion is used merely for the sake of interpretation and we do not affirm that all measured changes are only due to fluxes at the ocean–atmosphere interface. As a convenient conversion we note that a salt flux of $\pm$1 mg salt $m^{-2} s^{-1}$ is equivalent to a daily sea ice production of 3 mm of ice (assuming water and ice salinities of 34 and 5, respectively) or a precipitation of 2.5 mm per day (Klink, 1998).

In Fig. 4 is shown the salt flux R (μg salt $m^{-3} s^{-1}$) obtained comparing the measurements with the "reference" cruise of 1994/95. Surface and deep layers exhibits a distinct behaviour: in the surface layers the salinity increases and decreases with no apparent trend, while a quasi-constant freshening of the water column is detected from 400 to 900 m.

Moreover the differences in sign and magnitude for the salt fluxes in the upper and in the lower pycnocline indicate a weak connection in the summer period between the surface and the deep waters.

The averaged salinity has been evaluated at 900 m depth, the maximum common depth for all the cruises analysed, resulting in a freshening of about 0.06 over 11 years (Fig. 5) which is appreciably larger than that observed by Jacobs and Giulivi (1998). This apparent discrepancy is probably due mainly to the different periods examined and to the large short-term thermohaline changes over which the freshening trend is superimposed.

Such freshening of HSSW should produce temporal changes also in the characteristics or volume of the bottom water formed at the continental shelf break. Actually the particularly saline variety of AABW formed in the western Ross Sea requires a suitable salinity enhancement which is provided by rejected brine occurring during the ice formation over the shelf. In the Ross Sea a considerable amount of sea ice is formed in the TNB polynya (10% of the whole Ross Sea according to Kurtz and Bromwich, 1985, with the maximum value of 85 cm day^{-1} by Fusco et al., 2002).

As shown by Foster (1995) the Ross Sea Bottom Water (RSBW) formed along the Western shelf break, which is saltier than the surrounding bottom waters, spreads west to Australian–Antarctic Basin along the margin reaching 140°E. More recently Rintoul (1998) suggested a minor influence of the RSBW in the Australian–Antarctic basin where it interacts with the relatively fresh locally formed Adelie Land bottom water. We speculate on the possibility of a recent modification on the volume production of RSBW in the Western sector as a consequence of the decrease of the HSSW production in TNB which, in turns, affect the entire Ross Sea hydrology.

Focusing on the period 1995–2006 and comparing the estimated HSSW production and the salinity observed (CTD data) within the TNB water column (Fig. 6), similar tendency is found in the last years after 2002, while during the period 1995–1998 the behaviour is different. Our hypothesis concern a possible role of the CDW inflow (Fig. 6) in the Ross Sea continental shelf and consequently in TNB polynya: in the first period the observed freshening is due to a period of HSSW production below the average (negative anomalies), the following increase (1999–2003) of HSSW production does not produce a significant increase in the salinity of the deep layers because the raise in the CDW transport creates a more active redistribution of the salt released during the freezing processes in TNB. This hypothesis is in good agreement with the last period (2003–2006) when both CDW inflow and HSSW production decrease and a significant freshening of the deep layer has been observed in TNB. As already asserted by Jacobs et al. (2002) the freshening observed during the late 20th century in the Ross Sea appears to have resulted from a combination of factors among which the import of fresher and/or more surface water relative to the inflow of CDW. Moreover the study of Dinniman et al. (2003) on the transport of CDW show that strength of CDW intrusion onto the shelf appears to depend on two mechanisms. Consequently our results could be explained by a combination of such factors and by a different contribution of CDW transport and HSSW production to the salt content within the water column.

5. Conclusion

In this paper we focused on the surface energy budget during the period between 1990 and 2006 over the Ross Sea continental shelf and Terra Nova Bay polynya. Our results show a clear different behaviour of the atmospheric forcing over the Ross Sea continental shelf with higher values of heat loss during the first 6 years. The estimation of CDW flow needed to compensate these

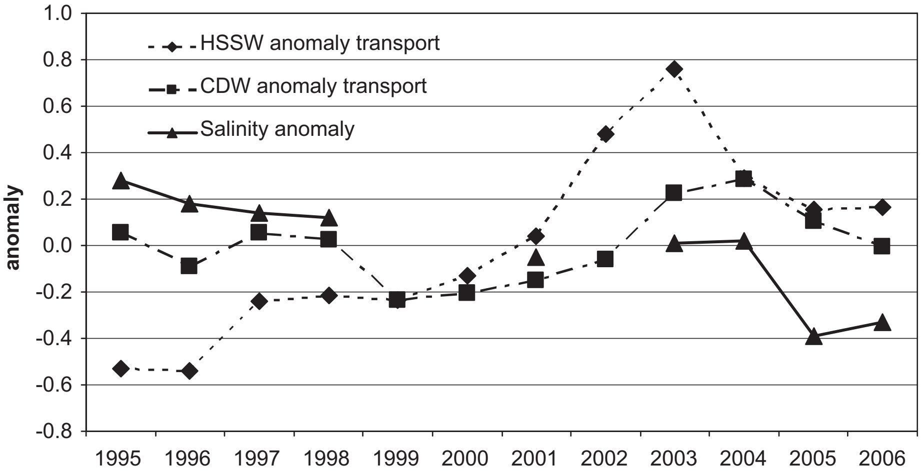

Fig. 6. HSSW anomaly transport referred to a mean value of 1.2 Sv for the period 1995–2006 in TNB polynya; CDW anomaly transport referred to an average value of 3.0 Sv for the period 1995–2006 in the Ross Sea continental shelf; salinity anomaly (CTD data) referred to an average value of 34.835 for the period 1995–2006.

heat loss at the sea surface, ranging from 2.8 to 3.6 Sv, represents a significant fraction of the total baroclinic transport (8.5 Sv) estimated by (Gouretski, 1999) of the Ross Gyre that drives the clockwise circulation patterns outside the continental shelf of the Ross Sea carried by the CDW along the shelf break.

The distinct behaviour of the surface energy budget has been also detected in the coastal area of BTN where an active polynya is recurrently identified. In this area a large interannual variability has been estimated with surface heat budget switching from -58 to $-145\,\mathrm{W\,m^{-2}}$ in the first period to -103 to $-313\,\mathrm{W\,m^{-2}}$ in 1997–2006.

Wintertime freezing seasons are characterized by episodes of high heat fluxes interspersed with more quiescent periods probably controlled by coastal polynya dynamics. The high heat fluxes are primarily due to the sensible heat flux component, with smaller complementary latent and radiative flux components (Table 2). The turbulent heat fluxes are characterized by episodes of high heat fluxes, separated with more quiescent periods. Coastal polynya dynamics of TNB set the timescales for these changes: strong offshore winds blow open the polynyas, which then refreeze at rates determined by the atmospheric forcing and the oceanic conditions.

It must be stressed that the heat budget over the Ross Sea continental shelf has been estimated considering constant sea ice coverage, while obviously in the TNB the presence of sea ice was not considered. Consequently we speculate on the key role of the sea ice which acted as barrier to prevent large fluctuation in the heat loss. In contrast, the high atmosphere variability in TNB is directly transferred to the water column due to the absence of a permanent sea ice layer.

During the freezing season, positive surface heat fluxes have been equated with ice production rates; the mean average of the TNB coastal polynya ice production per unit area is 19 m; the interannual variability is large: the standard deviation is 6.2.

Focusing on the period 1995–2006, similar tendency between HSSW production and the salinity observed within the TNB water column is found in the last years after 2002, while during the period 1995–1998 the behaviour is different. Our hypothesis is that in the first period the observed freshening is due to a period of HSSW production below the average (negative anomalies), in the period 1999–2003 the HSSW production does not produce a significant increase in the salinity of the deep layers because the raise in the CDW transport and finally when both CDW inflow and HSSW production decrease, a significant freshening of the deep layer has been detected from the analysis of the hydrological casts collected in this area in several oceanographic cruises between the austral summers in 1994/1995 and in 2005/2006. These results show a freshening of about 0.06 in 11 years which is noticeably larger than that estimated by Jacobs and Giulivi (1998), ($\Delta S = -0.03$ per decade in the entire Ross Sea).

During this study a number of directions for future research have become evident. The transformation of this surface energy budget into an oceanic buoyancy forcing could be one of the objectives of future work. To do this will involve the assessment of a number of physical processes that affect both the heat flux and, in particular, the freshwater flux, for example, precipitation, blowing snow deposition, ice shelf melt, and changes in the oceanographic conditions.

The detection of a large interannual variability within the surface energy budget asks for the question: what is causing it? It is clear that coastal polynya dynamics are related to offshore winds and air temperature, among other thing. Similarly, the surface energy budget is strongly related to wind speed and temperature through the turbulent heat flux terms. These meteorological parameters are determined on the mesoscale and synoptic-scale by a variety of weather systems. Hence, for the western Ross Sea, variations in the synoptic-scale storm track, in mesoscale cyclones, in barrier-forced winds, and in katabatic surges will all play a key role. A detailed examination of coastal polynya forcing and its variability will be an essential step toward understanding the atmosphere–ocean–ice system of this region.

The overall scenario clearly indicates how the whole Ross Sea is still far from the steady state and it is very sensitive to the atmospheric changes. Moreover we emphasize the substantial role played by the TNB polynya in regulating the characteristics of the shelf waters, at least in the western sector, which mix at the continental shelf break ventilating the deep ocean.

Finally we stress the relevance to monitor the thermohaline characteristics along the Drygalski Basin which represents a sort of intermediate reservoir and a primarily path followed by the shelf waters to reach the shelf break before being involved in the mixing processes and ventilating the deep ocean.

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