P.S.Z.N.: Marine Ecology, 23, Supplement 1 (2002), 201 – 209

ISSN 0173-9565

Dynamics and Variability of Terra Nova Bay Polynya

Giannetta Fusco*, [1, 2], Daniela Flocco[3, 2], Giorgio Budillon[2],
Giancarlo Spezie[2] & Enrico Zambianchi[2]

[1] ENEA CRAM, P.O. Box 224, I-19100 La Spezia, Italy.
[2] Istituto di Meteorologia e Oceanografia, Università degli Studi di Napoli "PARTHENOPE" Napoli, Italy.
[3] Scott Polar Research Institute, Cambridge University, UK.

With 6 figures

Keywords: Air-sea exchange, dense water formation, High Salinity Shelf Water, ice production, polynya, Antarctic oceanography.

Abstract. We present a process study on the dynamics and variability of the Terra Nova Bay polynya in the western sector of the Ross Sea. The air-sea heat exchange is known to be particularly large in polynyas during the winter, when differences between air and sea temperatures are large. We apply a 1-D model (Pease, 1987; Van Woert, 1999a, 1999b), which is modified in the latent heat parameterisation in order to account for time-dependent relative humidity and cloud coverage. Furthermore, the Ice Collection Depth is correlated linearly with a variable wind speed. The model is forced with two different meteorological data sets: the operational analysis of the European Center for Medium Range Weather Forecasts atmospheric data set and the meteorological parameters measured by an Automatic Weather Station located on the coast of Terra Nova Bay. The results are compared in terms of polynya extension, ice, and High Salinity Shelf Water production. According to the two different wind velocities, the results obtained from the different data sets clearly differ. Qualitatively, however, the results are in good agreement.

Problem

In the polar regions, the heat exchange between the ocean and the atmosphere is strongly influenced by the evolution of the ice cover; it acts as an insulating layer over the ocean, hindering sensible heat fluxes and forming an effective barrier to evaporation, hereby preventing latent heat loss. In the Ross Sea, which is covered by ice many months per year, permanently ice-free areas, such as polynyas, are common. In these ice-free areas the air-sea heat exchange can be very large, especially in winter, when

---

* Author to whom correspondence should be addressed: fusco@santateresa.enea.it

large differences between air and sea temperature persist. Consequently, polynyas are thought to play an important role in air-sea heat exchange, ice production, dense shelf water formation, and sustenance of primary and secondary production in polar regions (Jacobs *et al.*, 1985; Smith *et al.*, 1990; Budd, 1991; Arrigo & McClain, 1994; Markus *et al.*, 1998; Arrigo *et al.*, 2000).

Typically, coastal polynyas are kept open by strong katabatic winds that remove the ice as soon as it forms (latent heat polynya); in contrast, open ocean polynyas are maintained by the heat input from the deep ocean (sensible heat polynya) (Smith *et al.*, 1990).

The topography of the continental shelf of the western sector of the Ross Sea is characterised by several banks and depressions, the latter deeper than the continental shelf edge. The shelf is about 500 m deep and is separated from the shore by the Drygalski

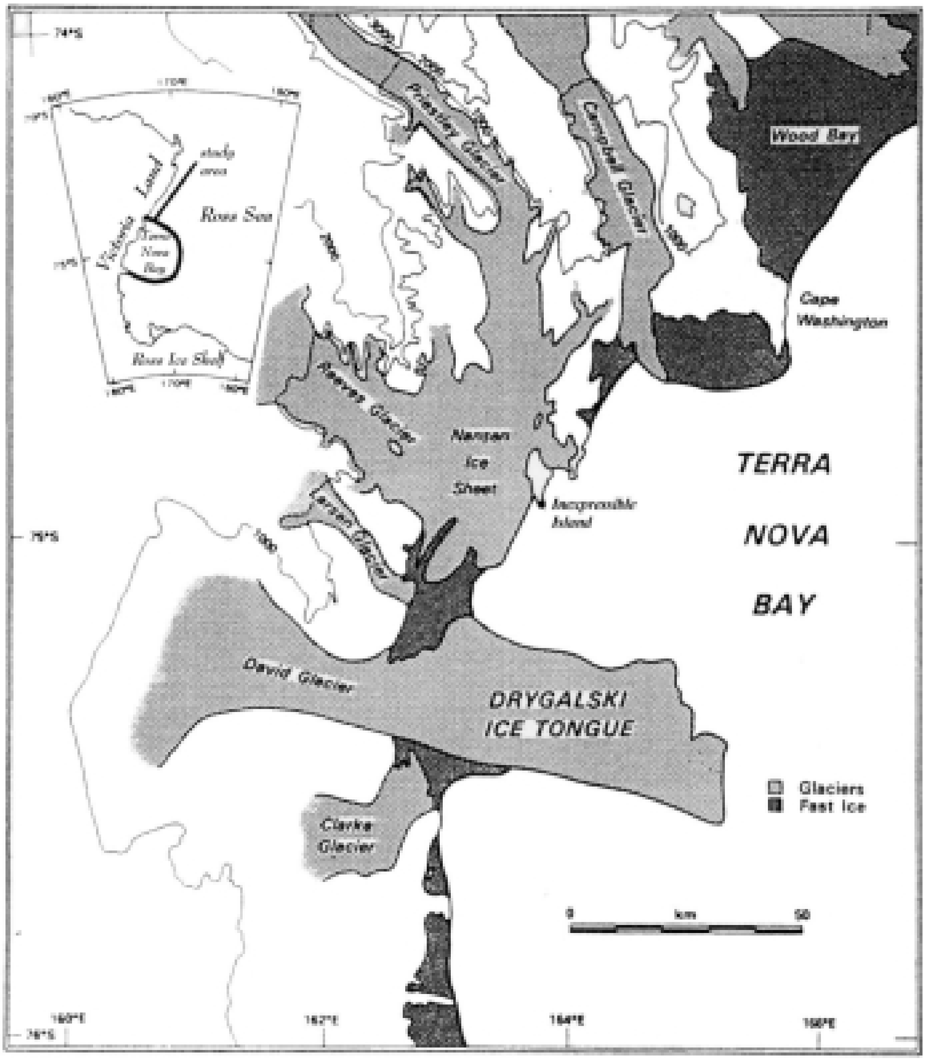

Fig. 1. Terra Nova Bay and surroundings (from Kurtz & Bromwich, 1985).

basin, a depression which is over 1000 m deep. Terra Nova Bay (TNB) (Fig. 1) occupies an area of approximately 6000 km^2 in the western sector of the Ross Sea. It is bordered by the Drygalski Ice Tongue (DIT) on the south and by the Campbell Ice Tongue on the north, which extends in a south-east direction.

TNB has a peculiar climatic setting: katabatic winds blow almost constantly in the offshore direction, keeping the area ice free, whilst the DIT acts as a barrier for the pack ice advection from the south and the south-west (Kurtz & Bromwich, 1983). This peculiar setting allows the TNB polynya to form and to be maintained. The existence of a winter polynya in TNB was first noted throughout the winter of 1912 (Priestley, 1962), but detailed observations have only been available since the 1970s thanks to infrared and microwave satellite imagery. Kurtz & Bromwich (1983) report polynya size observations from satellite images. The mean polynya area with a fixed north/south polynya dimension of 65 km was 1300 km^2, with a maximum open area up to 5000 km^2. More recently, Van Woert (1999a) applied a one-dimensional coastal polynya model forced by Automatic Weather Station (AWS) data; this approach did not consider the longwave heat flux in the total heat budget and obtained a mean polynya extent of about 21 ± 4 km. This is only slightly larger than the 20 km polynya extent derived from Kurtz & Bromwich (1985). The addition of the net longwave heat flux in the surface heat budget has the consequence of extracting additional heat from the polynya and further reducing the mean polynya extent to 17 ± 3 km (Van Woert, 1999a).

The presence of such a "latent heat" polynya (Smith *et al.*, 1990) plays an important role in the formation of salty water in the western Ross Sea. Brine release 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. The salinity and the volume of the HSSW in TNB shows an interannual variability in response to stronger winter surface forcing (Budillon & Spezie, 2000). Part of the HSSW 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 Antarctic Bottom Waters (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 surface pressure. DISW is found primarily on the central continental shelf (Budillon *et al.*, 2002), from where it moves northward onto the shelf break to contribute to the formation of the AABW (Jacobs *et al.*, 1985).

This paper presents the results of a process study aimed at a better understanding of the dynamics and variability of the Terra Nova Bay polynya in the Ross Sea, carried out in the framework of the activities of the Climatic Long-term Interaction for the Mass-balance in Antarctica (C.L.I.M.A.) project of the Italian National Programme for Antarctic Research (P.N.R.A.).

Material and Methods

The dynamics and variability of the TNB polynya are investigated for the years 1993 and 1994. In the next subsection we describe the data on which this study is based; thereafter we present the model utilised in the present work.

The data

In order to estimate the polynya extension, two meteorological data sets have been used: parameters measured by the AWS Manuela on Inexpressible Island and data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). Data of interest are mean sea level pressure, total cloud cover, wind speed, air temperature and relative humidity.

AWS Manuela was installed on Inexpressible Island (75 °S, 164 °E) in 1984 and provides meteorological data with 10 minutes time resolution. It does not provide cloud cover data. Strong winter events caused brief equipment failures, which are responsible for gaps in the data sets in January 1993 and in December 1994.

In contrast, ECMWF data are provided every 6 hours on 12 grid points with a spatial resolution of 0.5 ° × 0.5 °. In order to homogenise the two data sets the parameters are linearly interpolated in space and time to obtain daily averages. A careful study on the validation of the ECMWF operational analyses in Antarctica has been performed by Cullather *et al.* (1997). Their comparison of ECMWF analyses with pressure measurements from AWS units of the U.S. Antarctic Program shows a good agreement for the 10-year period from 1985–1994. In the same study, further comparisons of pressure, temperature, relative humidity and wind with data measured aboard the U.S. ice breaker R/V Nathaniel B. Palmer yield a substantially good agreement.

Surface heat fluxes, short wave radiation (Q_s), long wave radiation (Q_B) and turbulent fluxes (sensible heat Q_H and latent heat Q_E) are calculated from the two data sets and then used to force our model. Budillon *et al.* (2000) performed a sensitivity analysis of variations of different meteorological inputs from ECMWF on the surface heat fluxes in the Ross Sea. These analyses show that uncertainties in the mean sea level pressure during the summer have no noticeable effect on Q_B or Q_E. Variations in air temperature strongly affect the turbulent heat fluxes (± 39 % for Q_H and ± 14 % for Q_E) but only on the order of 5 % for the longwave Q_B. The uncertainties in the relative humidity have a small effect on the Q_E (6 %) but practically no effect on the remaining terms. Uncertainties in wind speed have the largest effect on the latent heat fluxes but are, as expected, not very different from the temperature effect in the sensible heat flux estimates (Budillon *et al.,* 2000).

The air temperature values provided by ECMWF and AWS are in very good agreement (Fig. 2).

In contrast, wind speed components (Figs. 3) are very different, particularly for the east-west component (Fig. 3b), which is the one affected by the presence of katabatic winds. On the other hand, ECMWF data are known to underestimate the wind intensity by at least 2.5 m s^{-1} (Markus *et al.,* 1998). The statistical comparison by Cullather *et al.* (1997) of ship data from the R/V Nathaniel B. Palmer cruise and corresponding ECMWF values shows the ECMWF wind intensity to be lower by about 5.7 m s^{-1}.

The major differences are primarily due to the occurrence of katabatic episodes in the winter season. Katabatic winds are due to the cooling of the air over the ice plateau and to the consequent acceleration by gravity when they blow down toward the coast. Therefore, local topographic conditions could have a remarkable in-

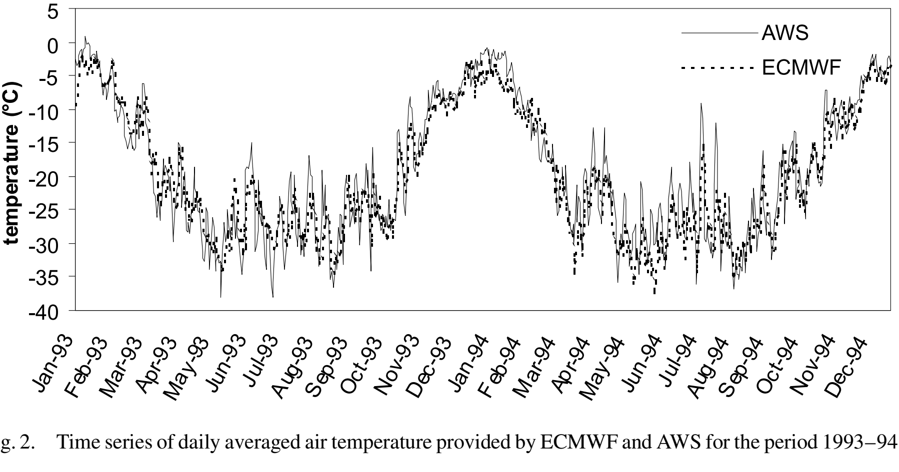

Fig. 2. Time series of daily averaged air temperature provided by ECMWF and AWS for the period 1993–94.

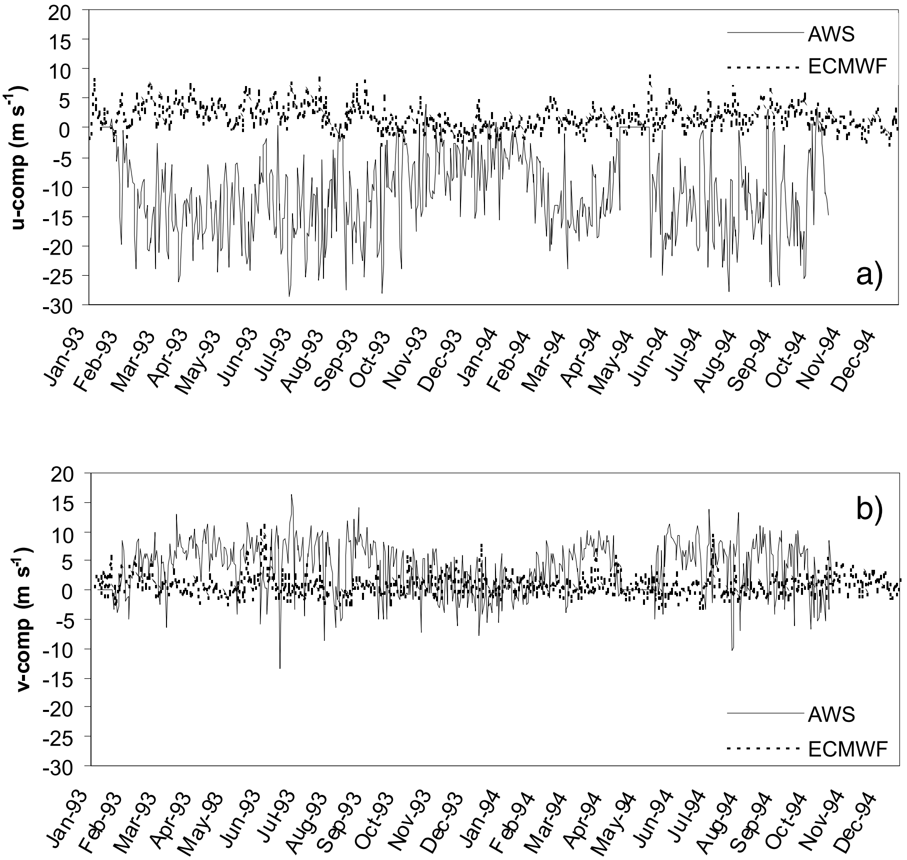

Fig. 3. Time series of daily averaged wind components provided by ECMWF and AWS for the period 1993–94: a) u-component; b) v-component.

fluence on the strength of these winds. Some case studies of mesoscale cyclogenesis near Terra Nova Bay point out the link with the katabatic episodes (Bromwich & Parish, 1988).

The model

In the following we apply a classical approach for modelling latent heat polynyas, namely the Lebedev and Pease one-dimensional flux model (Pease, 1987).

The polynya extension is defined as the distance between the area where frazil ice forms and the area where it piles up and starts to behave as a solid body (Martin & Kauffmann, 1981).

Ice drift is assumed to be constant along the polynya surface, and internal stresses in the ice are not considered. We do not account specifically for ice rheology, but following Van Woert (1999a, 1999b) we apply a coefficient to slow down the ice drift in order to compensate for the increasing ice concentration toward the polynya edge. The combination of katabatic winds and the blocking effect of the DIT allows the use of a one-dimensional flux model to describe the polynya dynamics. The polynya behaviour can thus be described by (Pease, 1987; Van Woert, 1999a, 1999b):

$$\frac{dX_p}{dt} = W_i \frac{P_i X_p}{H_i} \qquad 1$$

where X_p is the polynya width, W_i is the ice drift, H_i is the Ice Collection Depth (ICD) at the polynya's edge and P_i is the ice production.

The ICD is a very important but poorly understood parameter. The border of the polynya (and therefore the extent of the polynya) is defined as the position where the ice thickness becomes less than 95 % of the ICD. The ICD has been parameterised as (Winsor, 1997):

$$ICD = (0.68U_{10} + 1.58)\, 10^{-2} \qquad 2$$

where U_{10} is the wind speed 10 m above sea level.

The ICD will vary between 5 and 25 cm for wind speeds between 5 and 35 m s^{-1}. Considering mass conservation (see equation 3), we cannot assume a constant ICD for any wind speed. A strong wind leads to ice production that is in excess of the amount of ice collecting at the polynya edge (Biggs *et al.*, 2000):

$$H_i\left(w_i - \frac{\partial X_p}{\partial t}\right) = h\left(w_s - \frac{\partial X_p}{\partial t}\right) \qquad 3$$

where w_s is the current drift, h is the amount of ice forming and the other parameters have been previously defined. As mentioned above, a coefficient has been applied to the ice drift (Van Woert, 1999b):

$$W_i = U_{10}(0.03 - 0.05\,H_i) \qquad 4$$

in order to take into account the reduction in speed due to the presence of floating ice at the polynya edge.

The ice production is parameterised as:

$$P_i = \frac{Q_{tot}}{L_f \rho_i} \qquad 5$$

where $Q_{tot} = Q_S + Q_B + Q_E + Q_H$ is calculated for both AWS and ECMWF data sets. The heat flux parameterisations are adapted for polar regions (Budillon *et al.*, 2000). The density of ice ρ_i is 0.95 x 10^3 kg m^{-3} and L_f is the latent heat of fusion (3.34 x 10^5 J kg^{-1}).

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

$$P_s = \rho_i\, P_i\, A_p(s_w - s_i) \qquad 6$$

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

$$P_{HSSW} = \frac{P_S}{\rho_{HSSW}(S_{HSSW} - S_{LSSW}) \times 10^{-3}} \qquad 7$$

where ρ_{HSSW} is the density of HSSW (1030.45 kg m^{-3}), S_{HSSW} is the salinity of HSSW (34.8 PSU) and S_{LSSW} is the salinity of Low Salinity Shelf Water or Warm Core Water (34.5 PSU) (Jacobs *et al.*, 1985).

Results

The ice production calculated by the model is shown in (Fig. 4). As expected, it shows minimum values in summertime and maxima between March and October. In 1993 the ice production reaches the maximum value of 85 cm d^{-1} in August, while in 1994 the maximum is 72 cm d^{-1} (AWS data). According to our expectation, the ice production computed using the ECMWF data is substantially underestimated. Annual ice produc-

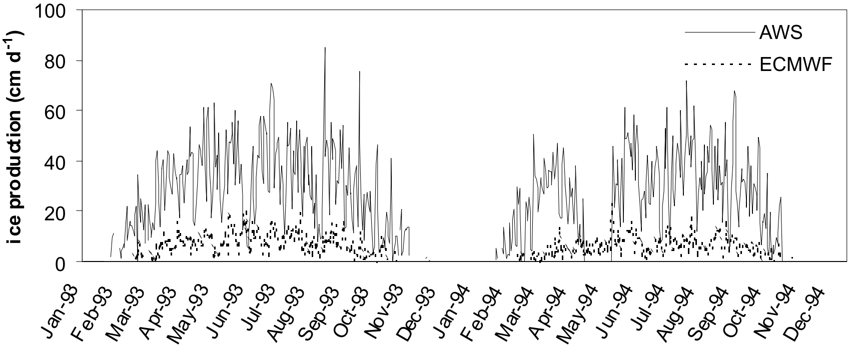

Fig. 4. Daily ice production computed from ECMWF and AWS data for the period 1993–94.

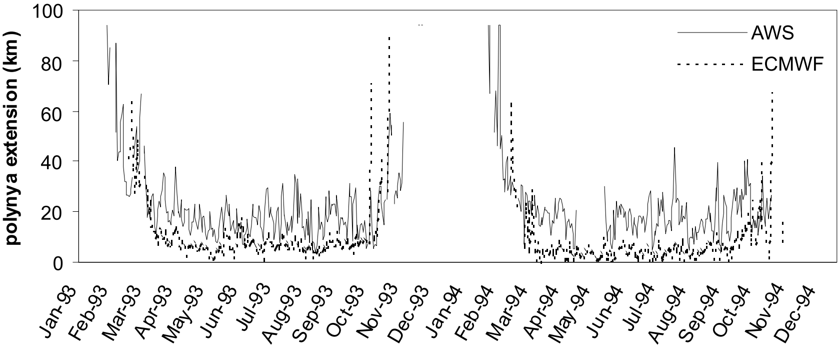

Fig. 5. Polynya extension computed by the model using surface heat fluxes calculated from the different data sets (ECMWF and AWS) for the period 1993–94.

tion depends primarily on the surface wind speed and is practically independent of the net heat flux (see also Van Woert, 1999b).

The polynya width (Fig. 5) varies in winter between 10 and 30 km for the AWS data set, while it ranges from 3 and 10 km in the ECMWF data set. These differences can be explained by the discussed difference in wind intensity. Since we assume that no ice enters from the Ross Sea because of the DIT, the maximum extension of the polynya is set as 94 km.

The production of HSSW (Fig. 6) shows the expected maxima in the austral winter when the ice production and brine release is strongest. In the years 1993–94 the computed salt rejection is about 4.6×10^{12} kg with an estimated HSSW production of 1.5 10^{13} m^3.

Note that our results obtained with the AWS forcing are in very good agreement with previous studies, namely with Kurtz & Bromwich (1985) and with Van Woert (1999a, 1999b), even though these authors report estimates relating to different years and to slightly different starting assumptions. In particular, our yearly averaged ice production amounts to 81.7 m for 1993 and to 68.8 m for 1994, whereas Kurtz & Bromwich (1985) estimate it for 1984 as 68.3 m. As to the monthly averages, our value for August 1994 is

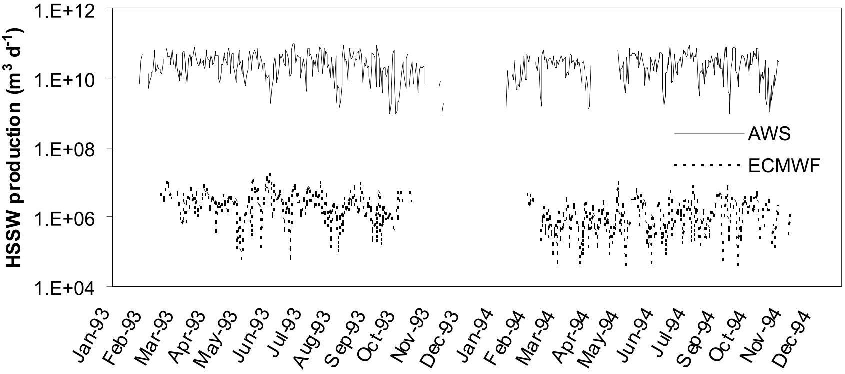

Fig. 6. Daily HSSW production computed from ECMWF and AWS data for the period 1993–94.

39 cm d^{-1}, theirs for August 32 cm d^{-1}. Van Woert (1999a) estimates the polynya parameters only for the austral winters 1988, 1989, 1990, and our results for 1993 and 1994 agree with his estimates within a maximum discrepancy of 10 % for ice production and polynya extension.

Conclusions

We have applied a one-dimensional polynya model to the Terra Nova Bay Polynya for the meteorological conditions relating to the years 1993 and 1994. The model was modified with respect to its classical version (Pease, 1987; Van Woert, 1999a, 1999b) by introducing the dependence of the ice collection depth on the wind intensity.

Meteorological data taken from the AWS Manuela and from the ECMWF were used to force the model, and the results were compared in terms of polynya extension, ice and HSSW production.

Given the chosen linear dependence of the ice collection depth on the wind intensity, the results obtained with the two different data sets clearly differ, i. e. the ECMWF data yield weaker polynya dynamics. Despite the different results obtained from the ECMWF and AWS data, the two experiments are qualitatively in good agreement with each other, suggesting that mesoscale dynamics may act as a preconditioning factor for local phenomena even though these latter may not be resolved by the ECMWF operational analysis.

Acknowledgements

This study was performed as part of the CLIMA (Climatic Long-term Interactions for the Mass-balance in Antarctica) project of PNRA (the Italian National Program for Antarctic Research) and was financially supported by ENEA through a joint research program. The operational analysis data were supplied by ECMWF. The authors wish to thank A. Accornero for useful discussions.

References

Arrigo, K. R., G. R. Di Tullio, R. B Dunbar, D. H. Robinson, M. Van Woert, D.L. Worthen & M. P. Lizotte, 2000: Phytoplankton taxonomic variability in nutrient utilization and primary production in the Ross Sea, J. Geophys. Res., **105**: 8827–8846.

Arrigo, K. R. & C. R. McClain, 1994: Spring phytoplankton production in the Western Ross Sea, Science, **266**: 261–263.

Biggs, N. R. T., M. A. Morales Maqueda & A. J. Willmott, 2000: Polynya flux model solutions incorporating a parameterisation for the collection thickness of consolidated new ice, J. Fluid. Mech, **48**: 179–204.

Bromwich, D. H. & T. R. Parish, 1988: Mesoscale cyclonic interactions with the surface wind field near Terra Nova Bay, Antarctica. Antarctic United States Review Issue: 1–15.

Budd, W. F., 1991: Antarctica and global change. Clim. Change, **18**: 271–300.

Budillon, G., S. Cordero Gremes & E. Salusti, 2002: On the Dense Water Spreading off the Ross Sea shelf. J. of Mar. Syst. **35** (3–4) 207–227.

Budillon, G., G. Fusco & G. Spezie, 2000: A study of surface heat fluxes in the Ross Sea (Antarctica). Antarctic Science **12**(2): 243–254.

Budillon, G. & G. Spezie, 2000: Thermohaline structure and variability in the Terra Nova Bay polynya (Ross Sea) between 1995–98. Antarctic Science **12**(4): 501–516.

Budillon, G., S, Tucci, A. Artegiani & G. Spezie, 1999: Water masses and suspended matter characteristics of the western Ross Sea. In: Faranda F.M., L. Guglielmo & A. Ianora (Eds.) "Ross Sea Ecology", Springer-Verlag: 63–93.

Cullather, R. I., D. H. Bromwich & R. W. Grumbine, 1997: Validation of operational numerical analyses in Antarctic latitudes. J. Geophys. Res., **102**(D12): 13 761–13 784.

Jacobs, S. S., R. G. Fairbanks & Y. Horibe, 1985: Origin and evolution of water masses near the Antarctic continental margin: evidence from H_2O-18/ H_2O-16 ratios in seawater. Antarctic Research Series, **43**: 59–85.

Kurtz, D. D. & D. H. Bromwich, 1983: Satellite observed behaviour of the Terra Nova Bay Polynya. J. Geophys. Res., **88**(C14): 9717–9722.

Kurtz, D. D. & D. H. Bromwich, 1985: A recurring, atmospherically forced polynya in Terra Nova Bay. Antarctic Research Series, **43**: 177–201.

Martin, S. & P. Kauffman, 1981: A field and laboratory study of wave damping by grease ice. Journal of Glaciology, **27**(96): 283–313.

Markus, T., C. Kottmeier & E. Fahrbach, 1998: Ice formation in coastal polynyas in the Weddel Sea and their impact on oceanic salinity. Antarctic Research Series, **74**: 273–292.

Pease, C. H., 1987: The size of wind-driven coastal polynya. J. Geophys. Res., **92**(C7): 7049–7059.

Priestley, R. E., 1962: Scott's Northern Party. Geogr. J., **128**: 129–140.

Smith, S. D., R. D. Muench & C. H. Pease, 1990: Polynyas and leads: an overview of physical processes and environment. J. Geophys. Res., **95**(C6): 9461–9479.

Van Woert, M. L., 1999a: Wintertime expansion and contraction of the Terra Nova Bay polynya. In: G. Spezie & G.M.R. Manzella (Eds.), Oceanography of the Ross Sea-Antarctica. Springer-Verlag, Milano, 145–164.

Van Woert, M. L., 1999b: Wintertime dynamics of the Terra Nova Bay polynya. J. Geophys. Res., **104**(C4): 7753–7769.

Winsor P., 1997: A wind-driven coastal polynya model. Thesis, Institution of Earth Sciences, Department of Oceanography, Goteborg University, S-413 81 Goteborg.