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Surface current measurements in Terra Nova Bay by HF radar

D. FLOCCO[1,2]*, P. FALCO[1], P. WADHAMS[2] and G. SPEZIE[1]

[1]*Scott Polar Research Institute, University of Cambridge, Lensfield Road, Cambridge CB2 1ER, UK*
[2]*Università degli Studi di Napoli "Parthenope", Via De Gasperi 5, 80133 Napoli, Italy*
**Df217@hermes.cam.ac.uk*

Abstract: During summer (2 December 1999–23 January 2000) an Ocean Surface Current Radar (OSCR-II) was used to provide surface current measurements within the Terra Nova Bay polynya, one of the most important coastal polynyas of the Ross Sea. This represents an important step towards a continuous monitoring of the area. Useful information is now available as a basis for future work in this field, although the two radar sites, necessary to calculate the total current vector, did not work together throughout the whole period of the experiment as one of the units was damaged. The results demonstrate the feasibility of this kind of measurement and suggest that very important dynamical characteristics of the polynya could be deduced from long term deployment of such a system.

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Introduction

The Terra Nova Bay (TNB) polynya is an example of a latent heat polynya. These are of great importance in ice production, and hence in deep water production. Surface current measurements are of special relevance in modelling, being one of the main inputs to a polynya flux model (Pease 1987). The annual ice production in the TNB polynya is about 10% of the total for the Ross Sea (Kurtz & Bromwich 1985, Van Woert 1999) and measurements of the dynamics and energy exchanges within the polynya area are therefore of great relevance to studies on sea ice mass balance, water structure and local climate.

One of the main problems encountered in these areas is the inaccessibility of the sites over the winter. During such periods analyses and monitoring have up to now been carried out by satellite imagery (e.g. the use of the 85 GHz SSM/I (Special Sensor Microwave Imager) channel to map thin ice occurrence) but this provides only a partial solution. Continuous monitoring of the area with an autonomous *in situ* radar would provide much better and more detailed data.

Radar measurements are especially useful because of their ability to detect small scale features (Shay *et al*. 2000). Data can also be collected synoptically and frequently over a wide area, providing a detailed description of the surface current field.

The aim of this work was to test the feasibility of using coastal radar to map surface currents in polar regions. The field experiment was carried out in Terra Nova Bay in December 1999–January 2000 within the framework of the CLIMA (Climatic Long-term Interactions for the Mass balance in Antarctica) project of the Italian National Programme for Antarctic Research (PNRA) and in cooperation with the Scott Polar Research Institute of Cambridge. This was the first time a shore-based HF radar system has been used to map surface currents in the area.

The radar system

OSCR-II (Ocean Surface Current Radar) is a shore based, remote sensing system designed to measure sea surface currents in coastal waters. It was originally developed by Marex Ltd., Cowes, UK, and then developed further at Southampton Oceanography Centre.

High frequency radars can be used to map current patterns over a wide area. Electromagnetic waves are reflected strongly by sea waves (Crombie 1955). By using Bragg scattering theory (Graber *et al*. 1996), it can be inferred that in the case of a monostatic radar, i.e. backscattering, resonance only occurs when the wavelength of the surface wave is one half of the transmitted electromagnetic wavelength.

In open water there is plenty of wave energy at a wavelength of about 5.5 m (Wadhams & Holt 1991). Thus the wavelength of the transmitted signal should be about 10 m, which corresponds to a frequency of 27 MHz. Both advancing and receding waves, which show up as Bragg peaks in the power spectrum, can be detected by this method (Graber *et al.* 1996). The position of the Bragg peak is due to the combined effect of surface waves and current drift in the antenna direction. The difference between the theoretical position of the Bragg peak (due to wave phase in zero current conditions) and its actual position can therefore be used to measure the component of current in the antenna direction (Barrick 1986). If the current is moving towards the radar there is a small positive shift in the Bragg peak relative to the zero current condition and if the current is moving away, a small negative shift. A current vector is created from the combination of data from two antennae looking at the same patch of sea from different directions

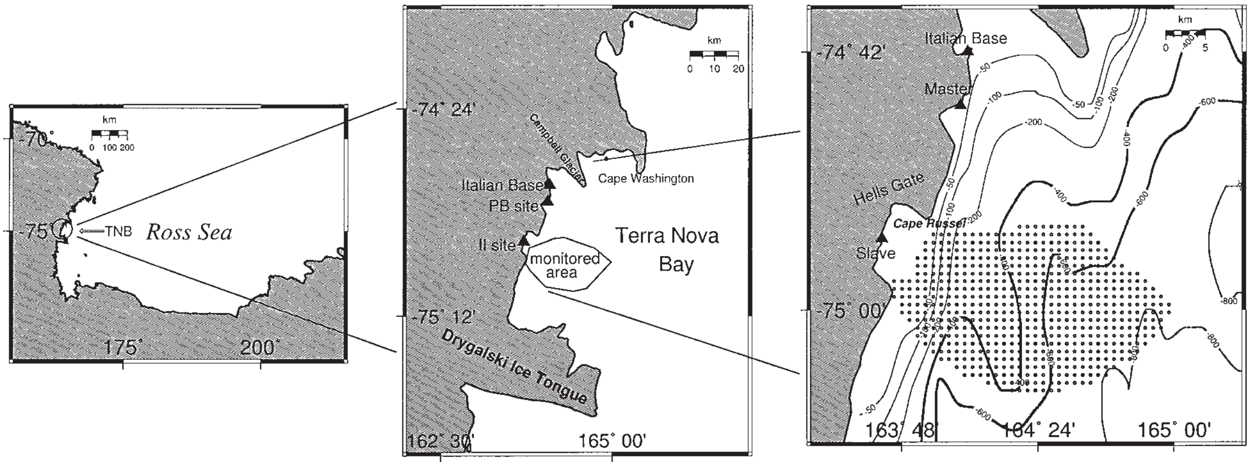

Fig. 1. Survey area and location of radars.

(Barrick *et al.* 1977).

The transmitted frequency of a radar strongly influences both the resolution and the range of measurement, i.e. a high frequency gives high resolution but a short range. For a radar operating at 27 MHz, the maximum working range is about 40 km, but several environmental factors can influence the wave absorption over an area and reduce the range. In particular, the sea surface salinity and temperature, and thus conductivity, must be taken in account. A detailed description of the relationship of the range to conductivity, frequency and sea state can be found in Gurgel *et al.* (1999).

The transmitting antenna used in this experiment was a four-element Yagi-Uda array mounted vertically with all elements clear of the ground. This provided a directional performance with a forward beam width of about 90 degrees. The receiving antenna consisted of 16 monopole elements in a broadside phased array.

The area

Terra Nova Bay is situated in the western part of the Ross Sea near 75°S, 164°E (Fig. 1). It is bordered by the Drygalski Ice Tongue on the south, by Cape Washington on the north, and on the west by the Nansen Ice Shelf, which is fed by the Reeves and Priestley glaciers. In winter katabatic winds blow almost constantly in the offshore direction and the Drygalski Ice Tongue acts as a barrier for the pack ice that comes from the southern Ross Sea, keeping the area ice-free. The area of the TNB polynya varies between 500 and 5300 km^2 (Kurtz & Bromwich 1985). The estimated ice production in the area is about 50 km^3 yr^{-1}, yielding an annual average production of High Salinity Shelf Water (HSSW) of around 1 Sv (Van Woert 1999).

Table I. Heat fluxes: Q_{tot} represents the total heat flux, Q_s the solar radiation, Q_{lw} the net long wave radiation, Q_e the latent heat and Q_b sensible heat (12 December 1999–15 December 1999)

	Q_{tot}	Q_s	Q_{lw}	Q_e	Q_b
W m^{-2}	248	341	-31	-0.22	-16

When current data were available, the ice concentration in the area was observed by using SSM/I data at 85GHz. The ice concentration was estimated with the SEA LION algorithm (Kern & Heygster 2001). The resolution of the SSM/I images is 12.5 x 12.5 km^2. The area where OSCR measurements were taken shows an ice concentration lower than 20% (Fig. 2). It is important to emphasize that for low values of sea ice concentration, the SEA LION algorithm tends to overestimate the presence of ice: due to the influence of the weather, the accuracy of the algorithm is about 5–10% for sea ice concentrations < 50% and 2–5% for higher sea ice concentrations. Furthermore, since the current measurements were taken very close to the coast, the SSM/I pixels used to map the sea ice coverage probably contain some land. Therefore, the SSM/I sea ice concentration may exceed the real sea ice conditions along the coast (Kern personal communication 2002).

An AVHRR (Advanced Very High Resolution Radiometer) image from 15 December 1999 (Fig 2d) is available and supports the SSM/I data (Fig. 2a–c). Bulk formulae have been used to calculate average heat fluxes in the polynya area, with ECMWF (European Centre for Meteorological Weather Forecasting) meteorological data as input (Markus *et al.* 1998, Van Woert 1999, Budillon *et al.* 2000). Results confirm a positive heat flux typical of ice free areas, and are shown in Table I.

The general surface circulation in the area was first detected by Jacobs (Jacobs *et al.* 1970), and more recently described in numerical models. A prevalent northward jet has been detected, which is deflected in the vicinity of the Campbell Glacier to join the main circulation of the Ross Sea (Commodari & Pierini 1999). Models also show that topography and the local wind field play an important role in driving the circulation. Results from the models are

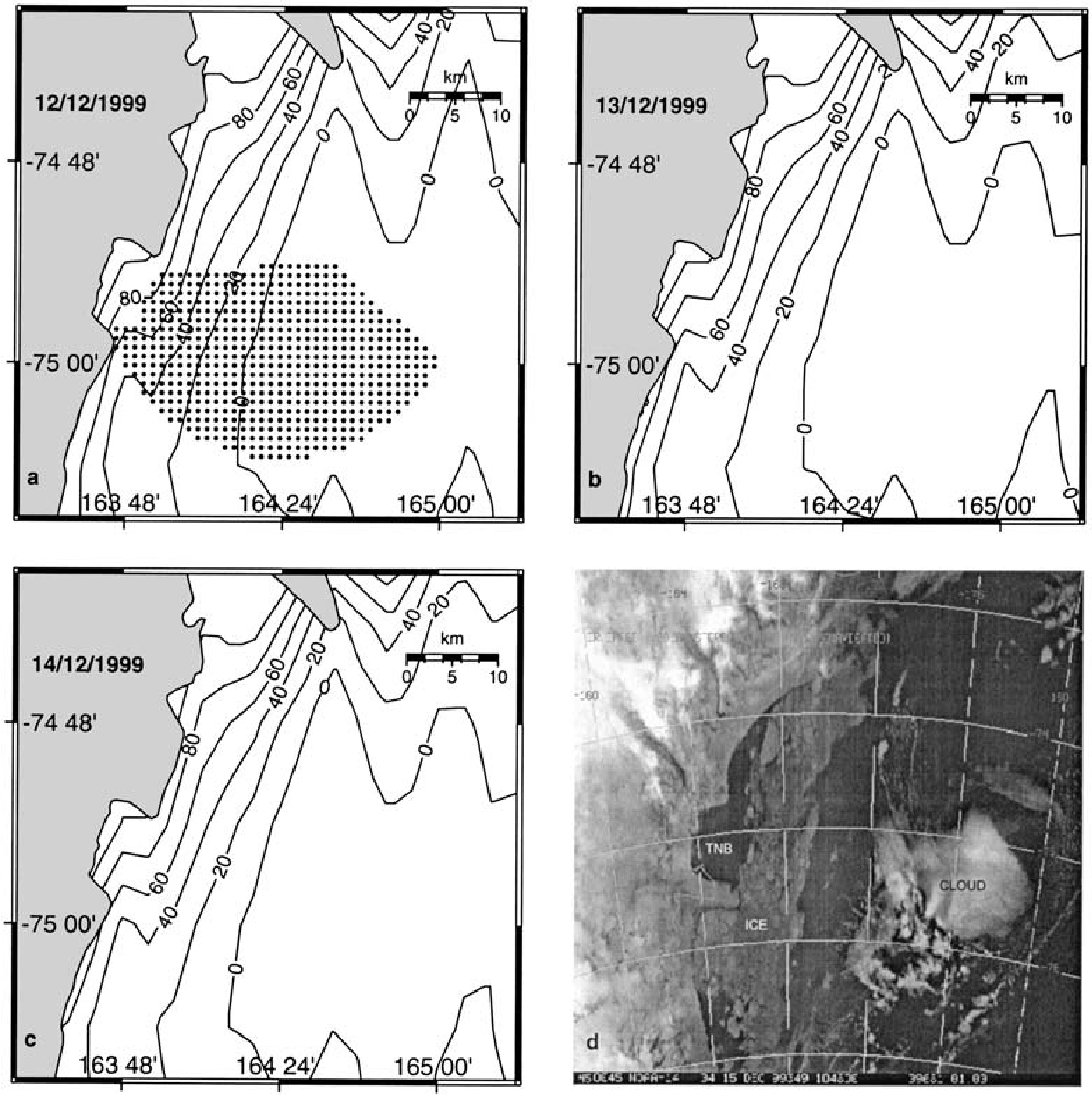

Fig. 2. a, b, c. Ice concentration from SSM/I data. **d.** AVHRR images of 15 December 1999 (band 4, 10.3–11.3 μm).

confirmed by current meter data, which show a barotropic character for most of the year, observed to weaken in correspondence with the spreading of HSSW toward the Ross Ice Shelf at greater depth (e.g. Manzella *et al*. 1999).

The experiment

The two HF radars were installed on the northern edge of Penguin Bay (74°46'S, 164°04'E – Master station) and on Inexpressible Island (74°55'S, 163°42'E – Slave station) (respectively PB and II hereafter) (Fig. 1). The PB antenna was very close to the sea, on the top of a steep wall about

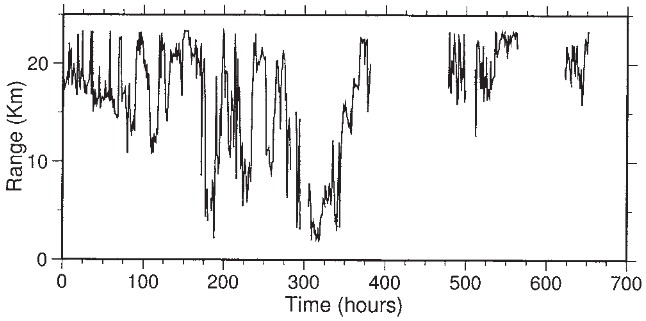

Fig. 3. Working range of the slave antenna over the period of measurement (7 December 1999–4 December 2000)

Table II. Results of the survey indicating the percentages of time when the two antennae were functional.

	Part 1 7/12/99–27/12/99	Part 2 27/12/99–31/12/99	Part 3 01/01/00–04/01/00
Master	6%	None	None
Slave	79.3%	51.5%	33.0%

50 m a.s.l. The II site was at the top of a wide beach and, because of the rocky nature of the soil, had to be positioned a few hundred metres from the sea (Fig. 1).

Measurement were taken at 20 min intervals over a grid with resolution of 1 km. Unfortunately the two sites worked together for less than two days (12–14 December 1999), because the electronics of the master station were damaged by water during shipping of the equipment to the Antarctic.

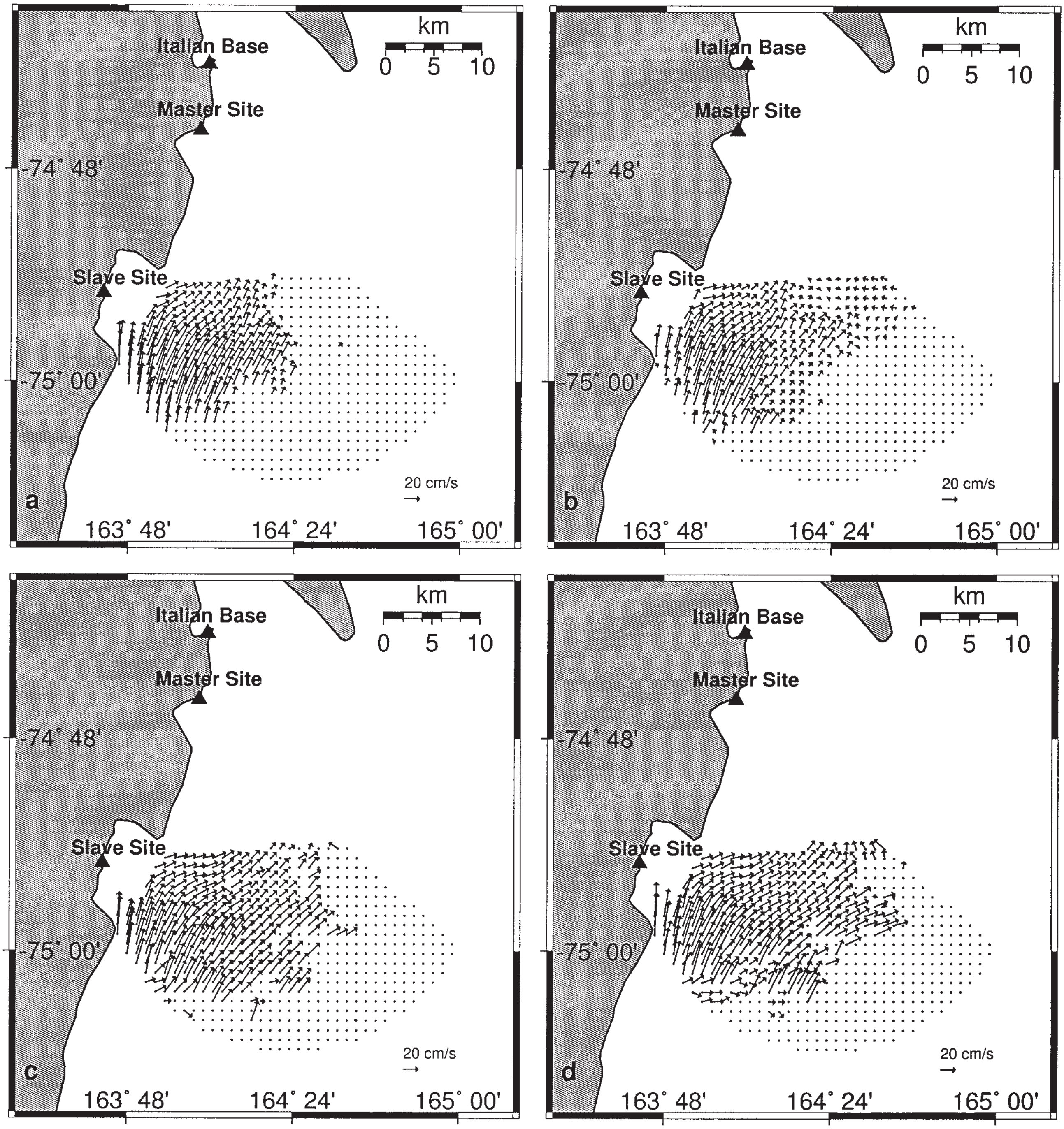

Fig. 4. Hourly current maps showing the prevalent northward component of the surface current (02h00–05h00 on 12 December 1999).

This is still the first dataset of this kind collected from the Antarctic. A detailed description of the survey is provided in Table II, where the data available are expressed in percentage of the number of days of each period of measurement.

Only the slave antenna provided data throughout the three periods of the experiment, so that only a radial component of the real current is available. The OSCRII never recorded data over its greatest range (approximately 40 km for radar operating at 27 kHz in optimal conditions). The working range is defined as the square root of the area of measurements covered by the radar, and depends on the signal-to-noise ratio (SNR). SNR is dependent on several different environmental parameters including sea state and near sea surface conductivity (Gurgel *et al.* 1999). An average value of the surface salinity in TNB is about 34.3‰

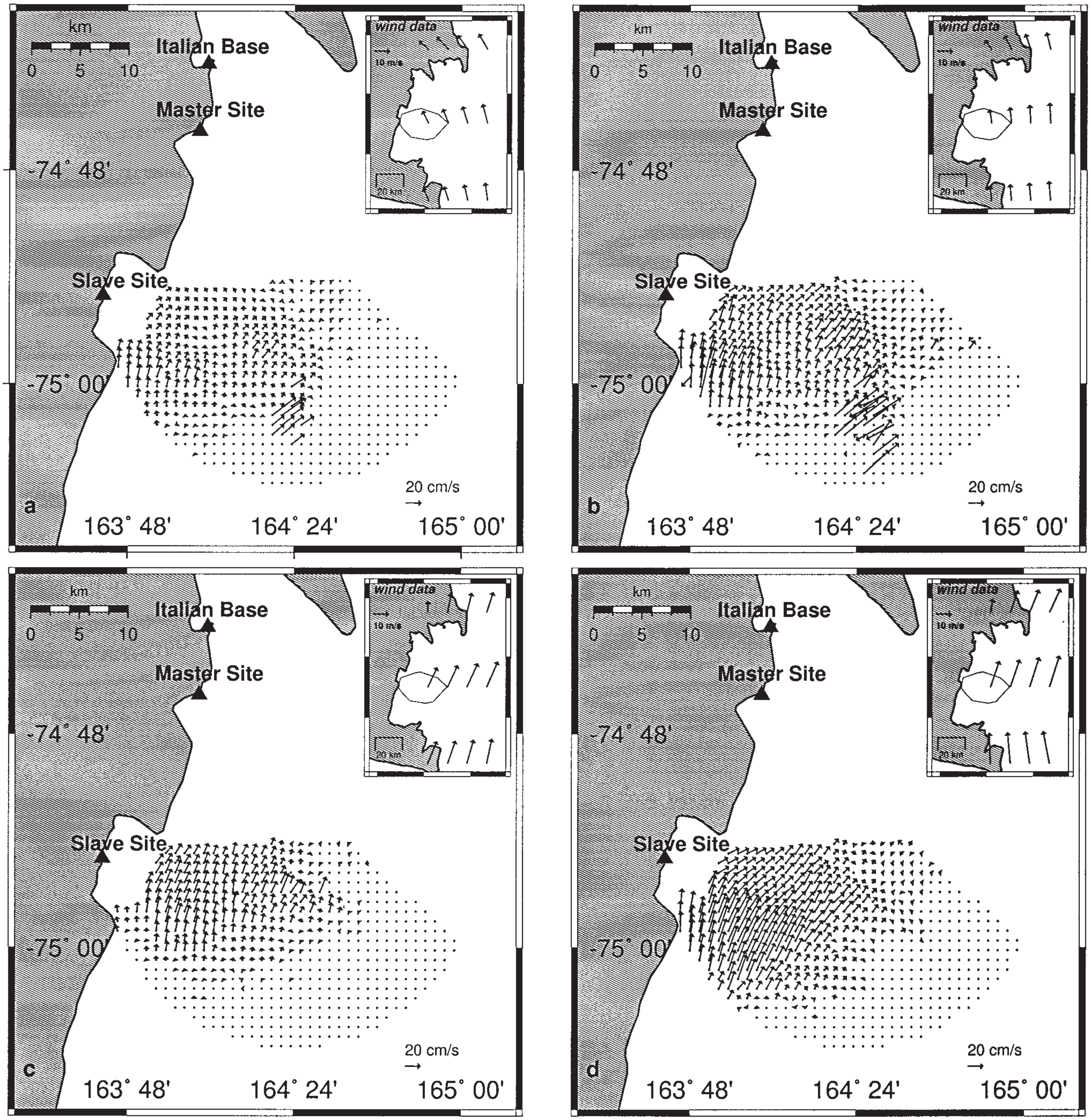

Fig. 5. Six hours averaged current map plotted together with ECMWF wind data.

(Budillon & Spezie 2000), only slightly lower than an average value for the ocean. Obviously the temperature reaches very low values (approximately between 0°C and -2°C).

The working range of the radar never reached 25 km (Fig. 3), and distances over 20 km were reached during only 23% of the total time. During 48% of the time, the working range reached values over 15 km (includes the previous figure), but in 43% of cases, it covered a working range of less that 10 km. This is considered to be due both to the geographical positioning of the slave antenna and to the presence of ice in front of it.

The location of the slave site prevented the northern extension of the monitored region from being wider, as Cape Russell (Fig. 1) acted as a barrier to the transmitted signal. Moreover, since the antenna was located a few hundred metres inland part of the received signal was lost through soil absorption. The presence of grounded land ice

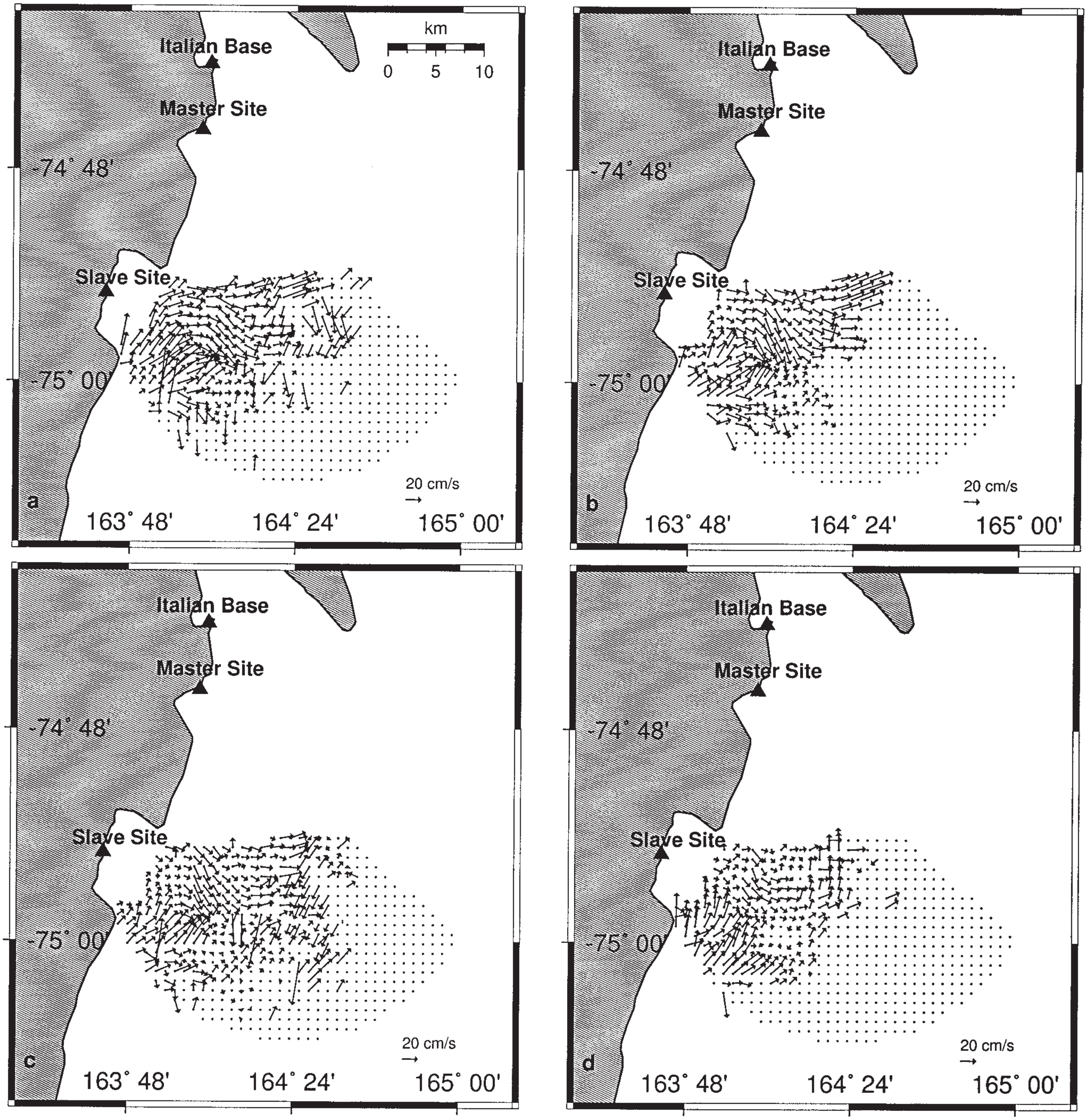

Fig. 6. Hourly current map: example of low velocity current pattern (03h00–06h00 on 13 December 1999).

in front of the antenna, that could not have been detected in advance but only *in situ*, caused a further attenuation of the signal.

As the experiment was carried out in a polynya, a frequency of 27 MHz, typical of ice-free areas was chosen. Observations during the fieldwork indicated that the predominant wavelength in the area was shorter than the resonant value corresponding to 27 MHz. More accurate measurements of the wave field are necessary to confirm this. A higher frequency would thus improve the resolution of the wave pattern of Terra Nova Bay.

Results

In the period when the current field was measured, the surface velocity often reached values of 25 cm sec^{-1}, and showed a prevalent northward direction. In the hourly maps (Fig. 4), the current intensity shows a drop as the current crosses a sea-floor ridge, which runs NW–SE within the bay (Fig. 1). A high shear is observed in the offshore direction with stronger intensities closer to the coast. The flow also shows a deflection in a north-easterly direction. This can be explained by considering the combined effects of topographical constraints and the local wind, blowing eastward from Hell's Gate.

The surface layer seemed to respond very quickly to changes in the local wind pattern. Data have been averaged over a 6 h period and then compared and plotted together with ECMWF operational analysis wind speed and directions (Fig. 5). These are provided every 6 h on 12 grid points with a spatial resolution of 0.5°x 0.5°. ECMWF data show a prevalent northward component over the two days when current vector data are available.

In Fig 5, the first day of observations is shown. The ECMWF winds blow from a south-easterly direction at the start, then intensify and rotate toward the south-west. The current field moves in the same way. In this limited experiment, it can only be qualitatively concluded that the current responds to the local meteorological pattern as there are too few data for any quantitative analysis. In addition it is recognized that many contributions, such as tidal current, topographic forcing, friction effects and geostrophic current, as well as the Ekman component contribute to the current drift. A more complete data set would have been very useful to detect all the components of the current.

At low velocity (Fig. 6) the dynamics of the flow are more complicated. The flow exhibits some instability, and eddy activity is detectable. In the vicinity of Hell's Gate a deflection of the flow occurs with a meander shape that almost develops into a gyre structure. This behaviour is confirmed by numerical models (Commodari & Pierini 1999). The results are also in agreement with calculation of surface current from satellite imagery: in mid April 1998 a cyclonic gyre was observed. The surface current was retrieved from the ice drift by applying a maximum cross-correlation to the satellite images. The intensity of the current was found to be about 30 cm s^{-1} (Van Woert *et al.* 2001).

Conclusions

An OSCR-II has been used to map the surface current field in TNB for two days. This has provided basic insights into the water motion in the bay. The surface layer flows in a general northward direction with a jet like structure in the proximity of the coast. It also seems to respond very quickly to local meteorological changes although the mesoscale pattern in general acts as the forcing of the local circulation.

The feasibility of this approach has now been established but for TNB a better location of the slave site is needed to increase the range of the radar. The local sea state and the wave pattern suggest a higher frequency of the transmitted wave would be advantageous.

A more global study of the area ought to be done in order to have a complete description of the surface dynamics to correlate with numerical models and to complete a 3-D view of the circulation. To this end, continuous monitoring over the polar winter would provide valuable information on the ice drift, one of the main inputs for polynya flux models.

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References

BARRICK, D.E. 1986. The role of dispersion relation in HF radar measurements of the sea surface. *IEEE Journal of Oceanic Engineering*, **11**, 286–292.

BARRICK, D.E., EVANS, M.W. & WEBER, B.L. 1977. Ocean surface currents mapped by radar. *Science*, **198**, 138–144.

BUDILLON, G., FUSCO, G. & SPEZIE, G. 2000. A study of surface heat fluxes in the Ross Sea (Antarctica). *Antarctic Science*, **12**, 243–254.

BUDILLON, G. & SPEZIE, G. 2000. Thermohaline structure and variability in the Terra Nova Bay polynya, Ross Sea. *Antarctic Science*, **12**, 493–508.

COMMODARI, V. & PIERINI, S. 1999. A wind and boundary driven circulation model of the Ross Sea. *In* SPEZIE, G. & MANZELLA, G.M.R., *eds*. *Oceanography of the Ross Sea, Antarctica*. Milan: Springer, 135–144.

CROMBIE, D.D. 1955. Doppler spectrum of sea echo at 13.56 Mc/s. *Nature*, **175**, 681–682.

GRABER, H.C., THOMPSON, D.R. & CARANDE, R.E. 1996. Ocean surface features and current measured with synthetic aperture radar interferometry and HF radar. *Journal of Geophysical Research*, **101**(C11), 25 813–25 832.

GURGEL, H.K., ESSEN, H.-H. & KINGSLEY, S.P. 1999. HF radars: physical limitations and recent developments. *Coastal Engineering,* **37**, 201–218.

JACOBS, S.S., AMOS, A.F. & BRUCHHAUSEN, P.M. 1970. Ross Sea oceanography and Antarctic Bottom Water formation. *Deep-Sea Research,* **17**, 935–962.

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

KERN, S. & HEYGSTER, G. 2001. Sea-ice concentration retrieval in the Antarctic based on the SSM/I 85.5 GHz polarization. *Annals of Glaciology,* **33**, 109–114.

MANZELLA, G.M.R., MELONI, R. & PICCO, P. 1999. Current, temperature and salinity observations in the Terra Nova Bay polynya area. *In* SPEZIE, G. & MANZELLA, G.M.R., *eds*. *Oceanography of the Ross Sea, Antarctica*. Milan: Springer, 165–173.

MARKUS, T., KOTTMEIER, C. & FAHRBACH, E. 1998. Ice formation in coastal polynyas in the Weddell Sea and their impact on oceanic salinity. *Antarctic Research Series*, **74**, 273–292.

PEASE, C.H. 1987. The size of wind-driven coastal polynya. *Journal of Geophysical Research*, **92**(C7), 7049–7059.

SHAY, L.K., COOK, T.M., HAUS, B.K., MARTINEZ, J., PETERS, H., MARIANO, A.J., VAN LEER, J., KILLINGSWORTH, J., AN, P.E., SMITH, S., SOLOVIEV, A., WEISBERG, R. & LUTHER, M. 2000. A submesoscale vortex in the coastal ocean detected by Very High Frequency radar. *EOS Transactions,* **81**, 209–213.

VAN WOERT, M.L. 1999. Wintertime expansion and contraction of the Terra Nova Bay polynya. *In* SPEZIE, G. & MANZELLA, G.M.R., *eds*. *Oceanography of the Ross Sea, Antarctica*. Milan: Springer, 145–164.

VAN WOERT, M.L., MEIER, W.N., ZOU, C., ARCHER, A., PELLEGRINI, A., GRIGIONI, P. & BERTOIA, C. 2001. Satellite observations of upper-ocean currents in Terra Nova Bay, Antarctica. *Annals of Glaciology,* **33**, 407–412.

WADHAMS, P. & HOLT, B. 1991. Waves in frazil and pancake ice and their detection in Seasat synthetic aperture radar imagery. *Journal of Geophysical Research*, **96**(C5), 8835–8852.