The use of ERS scatterometer data to investigate the surface circulation of Antarctic mesocyclones

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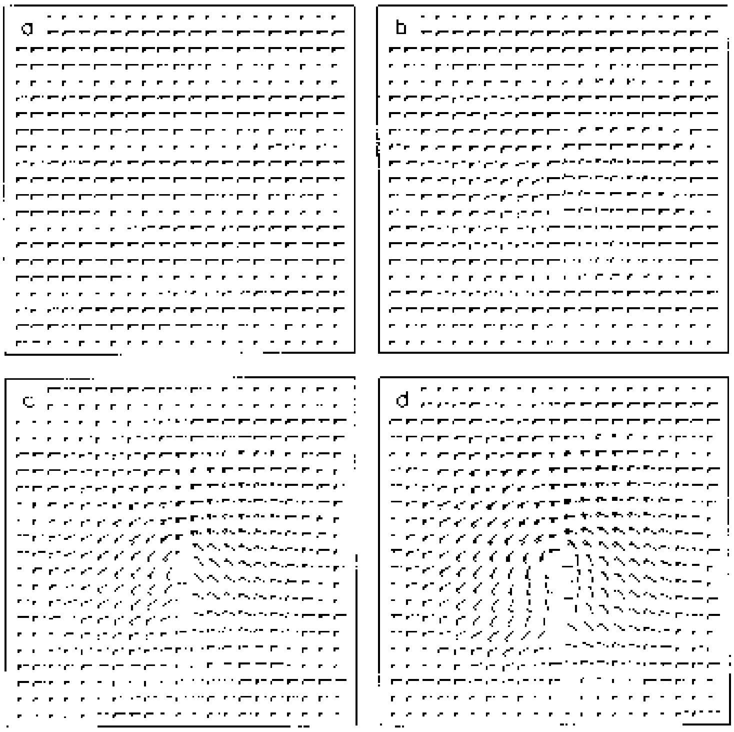
Abstract

The value of ERS-1 scatterometer data as a tool for studying the wind fields of Antarctic mesocyclones is assessed by using one year's observations of these systems derived from satellite imagery. The scatterometer processing scheme utilized can affect the resultant wind fields, particularly the accuracy of the external forecast winds used for "meteorological ambiguity removal". Very few of the mesocyclones (9%) were "captured" by the scatterometer data because (1) ~60% of the vortices did not form over the open ocean (25% of those that did were included in the scatterometer data) and (2) the narrow scatterometer swath results in a poor temporal resolution. Most systems had a surface circulation, varying from a slight deviation from the geostrophic flow to a closed circulation; however, 25% of mesocyclones did not exhibit a surface circulation. Derived maximum cyclonic relative vorticity varied between ~-100 and ~-400 H 10^{-6} s^{-1}.

Keywords: Antarctica, mesocyclones, scatterometer

Introduction

Mesocyclones are high latitude atmospheric low pressure systems with a horizontal length of less than 1000 km. They typically have a lifetime of less than 24 hours and are usually found over the ice-free ocean areas of both polar regions. In certain parts of the Arctic these lows can be very vigorous and have near-surface winds of 70 kts or more, although in the Antarctic they are not usually so vigorous since the air-sea temperature differences are less than in the north, giving smaller fluxes of heat into the atmosphere.



Being a short-lived phenomenon occurring in data-sparse regions, mesocyclones were only discovered when satellite imagery became available in the 1960s and satellite data are still the most valuable tool for observational investigation of these systems. To date, satellite imagery, TOVS sounder data and SMMR and SSM/I passive microwave data have all been employed in the study of mesocyclones. However, it has not been possible to investigate the surface wind field of these lows and the only indications about the speed and direction of the surface flow had to come from the few ship reports or when the lows made landfall. The wind speed data from SSM/I observations could provide information on how vigorous these lows were but it was only with the arrival of ERS scatterometer data that it became possible to get a full knowledge of the surface wind field of mesocyclones. Such data could be obtained over the ice-free ocean around the Antarctic providing information on their surface circulation.

In this paper we describe the various surface circulation patterns observed in association with Antarctic mesocyclones over the Southern Ocean using ERS-1 scatterometer winds. Firstly, as an aid to interpreting such data, we consider the wind field that we may expect around mesocyclones in various stages of development using a simple model of a vorticity perturbation on a steady flow. The range and frequency of different types of circulation observed in the scatterometer data are then described, together with the derived cyclonic relative vorticity values. A case study is also presented to illustrate some of the strengths and weaknesses of the scatterometer wind field data.

The scatterometer data used own

The data used in this study have been processed using the offline IFREMER (Institut Francais de Recherche pour l'Exploitation de la Mer) algorithm, and have been made available in the form of a CD-ROM archive.

A simple model of a mesocyclone wind field

To help understand the wind fields that are discernible in the ERS-1 scatterometer data of Antarctic mesocyclones, a simple model of the resultant wind vectors of a vorticity anomaly placed in a constant flow was utilised. The model data has a grid-spacing of 25 km, duplicating that of the scatterometer data. In Figure 1a a westerly uniform wind of 7.5 ms^{-1} is indicated. The results of superimposing a circular (Southern Hemispheric) cyclonic vortex of increasing strength - in terms of an increasing maximum velocity in the centre and a corresponding proportional increase in linear wind-speed gradient away from the centre on this constant flow are illustrated in Figs. 1b-d. The maximum wind speeds of the anomaly in the three stages are 2.5, 7.5, and 12.5 ms^{-1}, with wind speed gradients away from the centre of -0.01, -0.03, and -0.05 ms^{-1} km^{-1}, respectively.

Resultant >maximum= relative vorticities (ζ) corresponding to the wind fields in Figures 1*bBd* are B180 H 10^{B6}, B540 H 10^{B6}, and B900 H 10^{B6} s^{B1}; note that in the Southern Hemisphere cyclonic vorticity is negative and thus the values above are minima. This terminology is used throughout this paper when referring to Southern Hemisphere cases, that is, the >greatest= relative vorticity corresponds to the most negative value, calculated using

$$\zeta = (\mathrm{M}v/\mathrm{M}x \ ! \ \mathrm{M}u/\mathrm{M}y), \qquad (2)$$

where *u* and *v* are the velocity components in the *x* (longitudinal) and *y* (latitudinal) directions.

In Figure 1*b* - when the maximum wind speed of the anomaly is less than the uniform flow - the resultant winds show evidence of north-south troughing, with (assuming a westerly uniform wind in the Southern Hemisphere for the following description of the model wind fields) slight increases (decreases) in the wind speed on the equatorward (poleward) sides of the system. This troughing and corresponding north-south wind speed asymmetry is enhanced in Figure 1*c*, when the maximum anomaly wind speed is equal to that of the uniform wind. At the point where the two wind fields are equal and opposite - immediately poleward of the anomaly centre – a col (with no resultant wind vector) develops. When, as in Figure 1*d*, the anomaly wind-speeds exceed the uniform flow a closed circulation is formed and the col migrates poleward away from the system=s centre. Thus, the anomaly centre is always situated at the most equatorward point of the region of relatively light winds C where the wind speed gradient, irrespective of direction, is greatest.

4. The mesocyclone dataset

The mesocyclones analysed in this study were observed in AVHRR satellite imagery obtained by the receiving system at Rothera Station (67° 34' S, 68° 08' W) between 1 March 1993 and 29 February 1994. A total of 452 possible mesocyclones were identified from their cloud signatures in the TIR data using a wholly manual subjective analysis. The total number of observations of these systems was 1438; thus, on average each vortex was visible in three images. To ascertain whether near-coincident ERS-1 scatterometer data were available for the TIR observations, the IFREMER archive was interrogated temporally C to "3 hours of the AVHRR image being acquired C and spatially C using a box centred on the mesocyclone and having a length of side equal to (to the nearest degree) the diameter of the system at that time.

Only 58 TIR observations (4.0%) were found to have near-coincident ERS-1 scatterometer data; these encompassed 43 cases, (9.4% of the total mesocyclone dataset). Seven of these were included within a scatterometer swath more than once in their lifetime. The other eight observations result from scatterometer data near-coincident with TIR observations from more than one NOAA satellite pass.

A detailed study was limited to 20 cases. The frequency distribution of the type of wind field circulation pattern associated with these is given in Table 1. In addition to the basic four patterns, shown in Figures 1*aBd*, a fifth was introduced because the majority of wind fields (50%) displayed a more distinct troughing than Figure 1*b* but less pronounced than Figure 1*c*, and without the col. As expected, there is some relationship between the deviation of the wind field from the background geostrophic flow and the evolutionary stage of the mesocyclone derived from its cloud signature in the near-coincident AVHRR TIR imagery: all vortices that showed a strong troughing with col or closed circulation were mature systems, while all those indicating only a slight troughing were either incipient or in the early stages of developing. However, those mesocyclones demonstrating medium troughing encompassed both the developing and mature stages of evolution, as did the 25% of systems that had no signal in the scatterometer data. None of the 20 cases examined were dissipating.

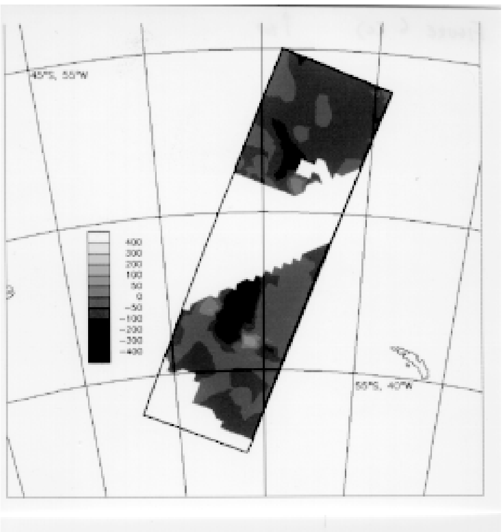
The mean (μ) maximum cyclonic relative vorticity for the 15 Antarctic mesocyclones that had visible circulations within the scatterometer data was B217 H 10^{B6} s^{B1}, with a standard deviation (σ) of 80 H 10^{B6} s^{B1}. Although the mean ζ of the systems in each model stage increases progressively from stages *b* to *d* (Table 1), there are too few vortices in the dataset for this to be considered statistically significant; indeed, the mesocyclones with the >lowest= (B111 H 10^{B6} s^{B1}) and >highest= (B400 H 10^{B6} s^{B1}) values of the maximum cyclonic relative vorticity both had a >medium troughing= circulation.

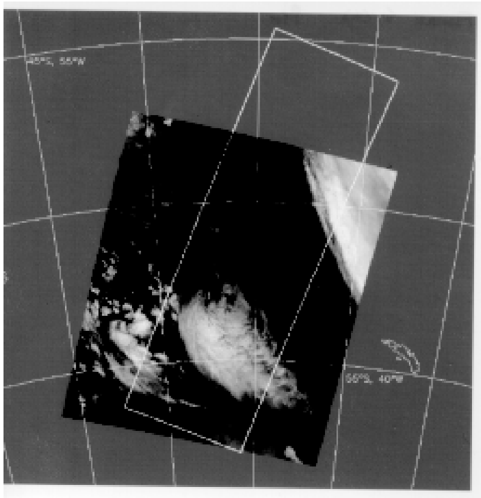
5. Case study

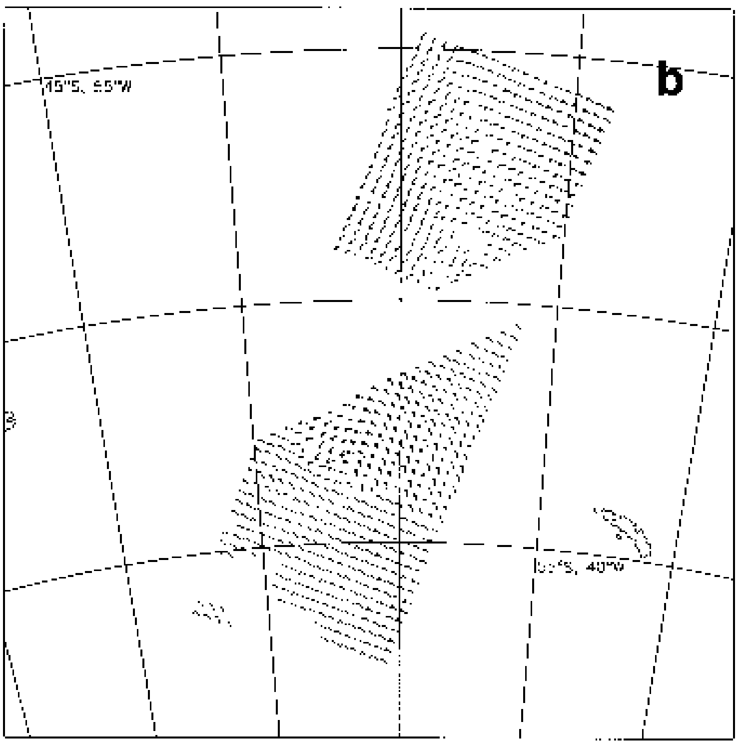
This system formed from a large mass of medium-level cloud over the Scotia Sea, first apparent at 00:37 UTC 5 June 1993. At this time there was no evidence of a circulation; however, by 05:53, a hook had appeared at the northern point of the cloud mass at 51ES, 52EW, and the system may be considered as being incipient. Further development produced a weak comma; Figure 2*a* illustrates this developing stage at 10:37 UTC, after the vortex had tracked south-east to 52ES, 48EW. No further AVHRR data are available until 19:41, by which time the vortex had matured into a classic comma.

The scatterometer data (Figure 2*b*), obtained at 12:17, are disrupted by considerable data loss caused by the unavailability of backscatter data from one antenna. Nevertheless, the mesocyclone is clearly distinguishable in the wind field, its centre at 53ES, 47EW. The system looks remarkably symmetric about an axis orthogonal to the geostrophic flow and similar to the model outlined in Section 3 (cf. Figure 1*c*). The cyclonic curvature around the equatorward side of the system is clearly apparent, with a maximum velocity of 15.8 ms^{B1}, as compared to the 10 ms^{B1} geostrophic flow estimated from the 12 UTC UK Meteorological Office (UKMO) chart (this is difficult to obtain from the scatterometer swath because of the missing data). On the eastern side of the system the wind speed appeared to decline gradually; for example, in a transect at 45E to the swath direction the wind speed decreased from 14.9 ms^{B1} to 5.1 ms^{B1} in a distance of 318 km, equivalent to ~3.1 ms^{B1} per 100 km. There is no indication within the scatterometer data that the mesocyclone had a closed circulation at this stage in its development; however, it is possible that the signal may be complicated by the light winds south of the mesocyclone resulting from a decreasing pressure gradient C directional errors are much more likely to occur at low wind speeds.

In Figure 2*c* the region of maximum cyclonic relative vorticity lies perpendicular to the geostrophic wind. The maximum determined cyclonic vorticity of B400 H 10^{B6} s^{B1} is the >highest= computed among all the mesocyclones examined, and indeed may have increased further as the system matured. Nonetheless, this value is significantly smaller than the figure of ~2000 H 10^{B6} s^{B1} obtained for the intense Arctic polar low. Also note the two small zones of anticyclonic relative vorticity at the locations where the resultant wind field departs from and returns to the geostrophic flow. The second, smaller zone of >high= relative cyclonic vorticity (< B100 H 10^{B6} s^{B1}) centered around 48.5ES, 43.5EW is not associated with any distinctive cloud features in Figure 2*a*. However, a comparison with the UKMO chart of 00 UTC on 6 June reveals that it represents a synoptic trough.







6. Discussion and conclusions

The close agreement between the mesocyclone winds fields observed in the scatterometer data and those predicted by the simple model suggests that the concept of the mesocyclone as a vorticity anomaly on a uniform flow is essentially valid. However, the single or multiple bands of cloud that are associated with mesocyclones are indicative of a weak or moderate frontal band, but the fields of scatterometer winds appear to have little success in resolving the sharp turning of the wind direction in these regions. This may well be because the fronts are very weak with virtually no signal at the surface or because the circulation is mainly at mid and upper levels. The fact that the scatterometer data indicated a very uniform flow in 25% of the cases when a well-defined cloud vortex was visible on the satellite imagery does suggest that some mesocyclones have a significant upper-level circulation, but no signal at the surface.

Generally, however, a surface circulation was apparent within the scatterometer data, varying from a slight deviation from the uniform flow to a closed circulation; the majority of systems could be described as having a signature showing >medium troughing=, with a maximum deviation from the uniform flow of ~90E. The derived maximum cyclonic relative vorticities, between ~B100 and ~B400 H 10^{B6} s^{B1} with a mean of ~B220 H 10^{B6} s^{B1}, are considerably lower, by an order of magnitude, than that calculated for an Arctic mesocyclone.

The routine availability of scatterometer winds, at least during the lifetime of the ERS-1/2 satellite series, offers the opportunity to carry out a number of new research investigations into mesocyclones. Clearly, case studies over the ice-free ocean will benefit by having fields of surface wind data instead of having to rely on data from ships and meteorological stations on isolated islands, or wind speed data alone from other satellite-borne remote sensing instruments; the ability to derive the differential properties of the wind field, such as the relative vorticity, is of particular importance. However, the relatively narrow swath of the ERS-1 scatterometer is a significant problem with regards to the multitemporal coverage of a mesocyclone during its existence. Ideally, therefore, scatterometer wind fields should be used in conjunction with wind speeds obtained from passive microwave and/or altimeter data C both of which have a much better frequency of coverage C to allow the analysis of a vortex throughout its entire development, and, of course, additional meteorological data determined from AVHRR, SSM/I, TOVS, and other satellite sensors.