NOTES AND CORRESPONDENCE

Sea Ice Motion in Response to Surface Wind and Ocean Current in the Southern Ocean

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Abstract

Using satellite-derived daily sea ice motion, this paper presents maps showing the relationship between the ice motion and surface wind, and mean ocean current in the Southern Ocean. The daily ice motions were derived from Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I) images. The mean ice motion field is characterized by eastward circumpolar drift; northward drifts in the Weddell Sea, Ross Sea, and areas around 80°E; and narrow westward coastal currents. A linear formula is used to examine the relationship between the ice motion and wind. It was found that daily variation in the ice motion is closely correlated with wind speed fluctuation, and that features of mean ice motion are mainly attributable to atmospheric forcing. The speed reduction factor (ratio of ice speed to wind speed) is relatively small near the coast, and increases with distance from the coast. Surface ocean currents beneath the ice cover were derived by subtracting the wind effect from the ice motion. It is revealed that the ocean current field is associated with the bottom topography.

1. Introduction

It is important to understand the global climate system, in order to comprehend the processes controlling variations in extent of sea ice. One significant aspect of these processes is the spatial distribution of ice motion, and its relation to atmospheric and oceanic conditions. Sea ice motion in the Southern Ocean has been examined mostly by drifting buoy data (e.g., Wadhams et al. 1989; Martinson and Wamser 1990; Kottmeier and Sellmann 1996). However, these data gave only a limited picture of the ice motion field. Recently, some studies demonstrated that sequential imagery from satellite passive microwave sensors can provide observations of sea ice motion (Agnew et al. 1997;

Emery et al. 1997; Kwok et al. 1998; Liu and Cavalieri 1998; Martin and Augstein 2000; Kimura and Wakatsuchi 2000). Passive microwave measurements, which are not subject to weather conditions, provide daily views of sea ice cover, and enable routine monitoring of ice motion. Emery et al. (1997) presented mean ice motion derived from the satellite passive microwave measurements in the Southern and Northern Hemisphere.

By using satellite derived daily ice motion and surface wind, this paper first demonstrates the relationship between them by means of correlation coefficient, turning angle, and speed reduction factor. Furthermore, a map of the mean ocean current calculated by subtracting the wind effect from the ice motion is also presented.

2. Data and method

The data used in this study consist of daily sea ice velocity and surface wind velocity, over

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the Southern Ocean. The records span 10 years from 1992 to 2001. The sea ice velocity is derived by a brightness temperature field from 85.5-GHz horizontally polarized channel images of the SSM/I, with roughly 2% missing values especially in low latitude regions. Prior to the tracking, these missing data are replaced with the mean value in the neighborhood of the pixel. The procedure for detecting ice motion is based on the maximum cross-correlation method described in Ninnis et al. (1986) and Emery et al. (1991). The method involves finding the spatial offset that maximizes the cross-correlation coefficient between two brightness temperature arrays in consecutive one-day separated images. The 6×6 (75×75 km) pixel arrays are utilized for this procedure. Starting with an approximate location in the second image, the correlation coefficient between an array from the first image and that of the same size in the following image is calculated. The computation is repeated at each position as the array in the second image is shifted at 1 pixel intervals on a two-dimensional grid to obtain an array of correlation coefficients. This technique can detect the displacement of features with large spatial dimensions compared to the 75×75 km window. The displacement of structures in the images are assumed to be explained by a simple translation; rapid deformation and rotation in the ice field on a daily timescale are neglected. Regions of open ocean are masked out using analyzed fields of ice concentration derived from the other channels of the SSM/I. The resulting displacement vectors are filtered using: 1) the magnitude of the maximum cross-correlation coefficient; 2) sharpness of the correlation peak; and, 3) the consistency with the displacement vectors in the neighborhood, to eliminate results by false match. After all, a daily ice-motion data set for a 75×75 km grid is made up.

This study uses reanalysis data of 10-m wind velocity at 1200 (UT), produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), as the surface wind. The wind velocity data were mapped onto a 75×75 km grid, the same as for the ice velocity data set.

To examine the relationship between ice motion and surface wind, this study adopted a linear relation rule described by Thorndike and Colony (1982). This rule relates sea ice velocity

(U, V) , wind velocity (u, v) for the same day, speed reduction factor F , turning angle θ , and mean ocean current $(\bar{c}_u, \bar{c}_v)$ as follows:

$$\begin{bmatrix} U \\ V \end{bmatrix} = F \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} \bar{c}_u \\ \bar{c}_v \end{bmatrix}.$$

In this formula, time variations of θ, F , and $(\bar{c}_u, \bar{c}_v)$ are assumed to be negligible.

Optimum values of $\theta, F, \bar{c}_u$, and $\bar{c}_v$ are calculated by using a least squares technique. In this study, following forms shown by Kimura and Wakatsuchi (2000) were adopted to calculate these constants.

$$\theta = \arctan \left[\frac{\sum u'V' - \sum v'U'}{\sum u'U' + \sum v'V'} \right],$$

$$F = \frac{c_1 + c_2 - c_3 + c_4}{\sum u'^2 + \sum v'^2},$$

$$\begin{bmatrix} \bar{c}_u \\ \bar{c}_v \end{bmatrix} = \begin{bmatrix} \bar{U} \\ \bar{V} \end{bmatrix} - F \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \bar{u} \\ \bar{v} \end{bmatrix},$$

where

$$c_1 = \cos \theta \sum u'U', \quad c_2 = \sin \theta \sum v'U',$$

$$c_3 = \sin \theta \sum u'V', \quad c_4 = \cos \theta \sum v'V',$$

and $\bar{u}, \bar{v}, \bar{U}$ and $\bar{V}$ show mean values of u, v, U and V . u', v', U' and V' show anomalies defined by $(u - \bar{u}), (v - \bar{v}), (U - \bar{U})$ and $(V - \bar{V})$, respectively. Furthermore, the correlation coefficient r was calculated by the following formula:

$$r = \frac{c_1 + c_2 - c_3 + c_4}{\sqrt{\sum u'^2 + \sum v'^2} \sqrt{\sum U'^2 + \sum V'^2}}.$$

3. Results

At first, analyses were carried out for each of the four seasons. There are some seasonal differences in the ice motion field, mostly caused by the seasonal differences in the wind field. However, there were no significant seasonal differences in the ocean current and relative factors. Hence, this paper is not concerned with seasonal dependency.

For ease of discussion, we divided the Southern Ocean into the following three sectors by longitude: the Atlantic sector, between 60°W and 60°E ; the Indian sector, between 60°E and 150°E ; and the Pacific sector, between 150°E and 60°W . Figure 1 shows the field of mean ice

Fig. 1. Mean ice motion for 10 years in a polar stereographic projection. Ice drifting speeds are presented by lengths of vectors and background colors. The vectors are plotted at a reduced 150×150 km resolution (the original result has 75×75 km resolution).

motion in the Southern Ocean averaged over the 10 years. The mean ice motion field is close to that by Emery et al. (1997) for 1988–1994, but the mean speed from our results is generally larger than that of Emery's. The most outstanding feature is the eastward circumpolar ice motion lying around 60°S in the Atlantic sector and around 65°S in the Pacific sector, with a maximum speed greater than 15 cm s^{-1} . In the Atlantic and Indian sectors, there exists a narrow coastal current that flows westward at a speed of $5\text{--}10\text{ cm s}^{-1}$. The coastal current is not so evident in the Pacific sector. We can also see the broad northward ice flows in the Weddell Sea and Ross Sea along the contours of the land. A northward flow is also seen around 80°E in the Indian sector. These ice motion patterns form large cyclonic circulations in both

the Atlantic sector (called the Weddell Gyre) and Pacific sector.

Next, Fig. 2 shows squared correlation coefficients (r^2) between ice velocity and surface wind velocity. These values give a fraction of the variance of the ice velocity that is attributable to the wind velocity. In the Atlantic and Pacific sectors, r^2 exceeds 0.5, except for the regions within ~ 200 km of the coast. Low correlations near the coast were also reported in studies of the Arctic by Thorndike and Colony (1982) and Kimura and Wakatsuchi (2000). Except for coastal regions, the linear relation rule explains the majority of variation in ice velocity. This rule accounts for 50–70% of the total variance of the ice motion in most of the Atlantic and Pacific sectors. However, r^2 is less than 0.5 in most of the Indian sector.

Fig. 2. Squared correlation coefficients (r^2) between ice motion and surface wind.

The spatial distribution of the turning angle (θ) from surface wind to ice motion is presented in Fig. 3; positive θ indicates that sea ice drifts toward the left of the wind direction. In most of the Atlantic and Pacific sectors, θ ranged between 10° and 20° , and reaches more than 30° in coastal regions of the Indian sector.

Likewise, Fig. 4 presents the spatial distribution of the speed reduction factor (F), which gives ratios of ice drifting speed to surface wind speed. The value of F is relatively smaller near the coast, and increases with distance from the coast. In most of the Indian sector, F takes a value of no more than 1.5% from the coast to the ice edge. In the Atlantic and Pacific sectors, it is less than 1.5% near the coast, and increases nearly continuously to $\sim 2.5\%$ in the northern limit of the ice area. In the Weddell Sea, F has also been estimated by using a

drifting buoy motions. The spatial differences of F are fairly similar to those obtained in a previous analyses by Kottmeier and Sellmann (1996), which give values less than 0.5% of the geostrophic wind speed near the coast and up to 1.5% in the northern, central, and eastern regions of the Weddell Sea, and by Vihma et al. (1996), which show nearly the same values. When we carried out the same calculation of this study by using geostrophic wind instead of surface wind, resulting values of F became very close to these observational results.

Figure 5 shows the residual ocean current ($\overline{c_u}, \overline{c_v}$) derived by subtracting the wind driven motion from the sea ice motion; that is, the mean ocean current not linearly related to the variation of wind speed, on timescales longer than a day. Over the entire area, the speed of the ocean current is much slower than that of

Fig. 3. Turning angle (θ) of ice motion to surface wind. Positive values show that sea ice moves leftward from the wind direction.

the ice motion. The strong eastward flows seen in the ice motion are less evident in the ocean current map. The locations of the eastward currents, with a speed of $\sim 5 \text{ cm s}^{-1}$ seen in zones 50°W – 10°E and 150°E – 150°W , agree well with relatively shallow bathymetry areas and correspond to eastward current areas in the geostrophic current map by Gordon et al. (1978). The narrow currents along the coast are also weak compared to the ice motion, but remain noticeable especially in the Atlantic sector.

Lastly, Fig. 6 shows magnified ocean current maps with bottom topography corresponding to the insets in Fig. 5. Figure 6a shows the coastal area of the Atlantic sector. The coastal current is noticeable within $\sim 200 \text{ km}$ of the coast maintaining a speed of $4\text{--}8 \text{ cm s}^{-1}$, with a 99%

confidence interval of width of $0.5\text{--}1.2 \text{ cm s}^{-1}$, which is equal to 10–30% of the current speed. The current flows from the Indian sector and is enhanced by inshore recirculation of the Weddell Gyre at around 50°E and 10°E . At around 20°W , the current splits off the coastline following the isobath. In addition, it is clear that the coastal current is associated with the bottom topography. The bold white arrows in Fig. 6a show the locations of bottom ridges. We can see the curve of the coastal current, which is likely induced by the bottom topography over the northward extending ridges. Figure 6b illustrates the northward current occurring over the Kerguelen Plateau located around 60°S , 80°E . The current is also modified by the bottom topography, and becomes stronger to the east side of the plateau.

Fig. 4. Speed reduction factor (F) of ice motion to surface wind.

4. Summary and discussion

Using daily sea ice motion data derived from satellite microwave observations, mean ice motion and ocean current maps were produced, and regional differences of several factors in relation to ice motion and wind were examined.

The derived mean ice motion field is fairly consistent with that from the buoy data in the Weddell Sea (Kottmeier and Sellmann 1996) and in the eastern part of the Southern Ocean (Heil and Allison 1999). However, it is very difficult to estimate the error of daily ice motion derived from SSM/I, because comparable observational data are very sparse. Some previous studies have compared satellite derived ice motion with drifting buoy motion. For example, Heil et al. (2001) showed a low correlation between SSM/I derived ice velocity and buoy ve-

locity, and concluded that the SSM/I derived ice velocity does not detect the motion of individual ice floe. We have also carried out a comparison between 4212 pairs of SSM/I derived daily ice velocity and ice velocity derived from the daily position of drifting buoys edited by the National Snow and Ice Data Center. By this, we have found that the correlation coefficient between them is 0.56, and the speed of SSM/I derived ice motion is 31% lower than that derived from the buoy data. This relatively low correlation between the two ice velocities does not mean that the reliability of the SSM/I derived ice motion is low, instead, it seems that the low correlation is mainly due to the difference in spatial scales of the two data sets. In fact, we can see a high correlation coefficient (r) between the SSM/I derived ice motion and surface wind speed of up to ~ 0.9 in this study

Fig. 5. Mean surface ocean current ($\overline{c_u}, \overline{c_v}$), not in relation to the change of wind velocity. Current speed is indicated by length of vectors and background color. The vectors are plotted at a reduced 150×150 km resolution (the original result has 75×75 km resolution). Blue rectangles delineate the areas shown in Fig. 6.

Fig. 6. Enlargements of (a): the coastal area of the Atlantic sector and (b): near the plateau around 80°E , corresponding to the insets in Fig. 5. The length and direction of arrows show the speed and direction of surface ocean currents. The vectors are plotted at 75×75 km resolution. Gray tones represent the bottom topography.

(seen in Fig. 2 as r^2), and therefore, it leads to strong evidence of high reliability of both the SSM/I derived ice motion and ECMWF 10-m wind. This paper insists that SSM/I derived ice motion is a reliable indicator of the motion of the ice field with a spatial scale of ~ 100 km, which is highly correlated with the synoptic scale wind field. Concerning the magnitude of the speed, the slower speed of SSM/I derived ice motion is also mainly due to the difference in the spatial scale. Buoy motion traces small-scale ice motion caused by ocean eddy or others, and takes a faster speed than SSM/I derived motion, which traces a movement of ice field averaged over a large area. On the other hand, there remains a possibility of the underestimation of the SSM/I derived ice motion and speed reduction factor F .

As mentioned above, the linear relation formula incorporating the wind speed is a reasonable estimator of ice motion in large parts of the Southern Ocean, except for coastal regions. Sea ice variability on timescales longer than a day is strongly influenced by atmospheric fluctuations. The spatial variations of the squared correlation coefficient r^2 (Fig. 2) and speed reduction factor F (Fig. 4) are very much alike. The similarity in distribution of the low-value areas is thought to be brought about by physical causes related to internal ice stress. In general, the internal ice stress gradient depends on the ice thickness and concentration (Hibler 1979; Overland and Pease 1988). Thick ice and high ice concentration near the coast cause a large ice stress gradient and enhance nonlinear effects in sea ice, which lead to a small r^2 and act to suppress ice motion, and hence, lower the value of F (Steele et al. 1997). Conversely, large r^2 and F in the northern area, which is covered with relatively thin ice of low concentration, can be explained by a smaller ice stress gradient compared to the coastal area. It should be noted that there is a possibility of another cause for this similarity. Mathematically, a low value of r^2 generally results in a low value of F . The low value of r^2 is caused, not only by physical effects, but also by small scale variation in ice motion, temporal variations of the ocean current or relational factors such as θ and F , and errors in the sea ice motion and wind velocity data.

A comparison of the mean ice motion (Fig.

1) and ocean current (Fig. 5) indicates that the dominant features of mean ice motion described above are mainly attributable to atmospheric forcing. The contribution of wind driven motion to mean ice motion is 60–90% in most regions of the Southern Ocean.

The derived ocean current is very reasonable compared with the results from previous numerical studies (e.g., Beckmann et al. 1999), and is associated with bottom topography. This strong relationship can provide evidence for the reliability of the derived ice motion and ocean current. In general, measurements of ocean current are very difficult in the polar region due to the existence of sea ice cover. In this study, however, the existence of sea ice led to the derivation of the ocean current. This study confirms that satellite microwave observations, which are almost unhampered by weather conditions and provide continuous sea ice images, are very valuable in investigations of ice-covered regions where in-situ observations are sparse.

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