平成25年度修士論文要旨

（東京大学大学院　新領域創成科学研究科　海洋技術環境学専攻）

High resolution analysis of sea ice variability using visible infrared satellite data

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1. Introduction

The Arctic Ocean is characterized by a large amount of sea ice which varies in extent and thickness seasonally. However, sea ice extent is drastically declining in the Arctic region. The satellite observation of September sea ice extent has a dramatically decrease rate at 11.3% per decade, which is severely faster than projected by even the most advanced computer models. It is important to investigate the small-scale ice motion since it is obvious that the mechanism of the variability of sea ice extent has still not been revealed completely by current models. On the other hand, with the drastic reduction of Arctic sea ice extent, it will open new areas for the exploration of natural resources and Arctic Routes. In order to utilize these vital and hazardous passages, it is indispensable to predict the sea ice distribution of summer especially in the coastal regions. Hence, to contribute to the forecast and models, it is necessary to investigate the ice motion of the coastal region. One objective of this study is to obtain high-resolution ice motion to better comprehend the mechanism of the variability of sea ice. Furthermore, the relationship between ice motion and the 10-meter wind is revealed in the form of the speed reduction factor (F) and turning angle (θ). Additionally the variability of sea ice between 2000-2006 and 2007-2012 is investigated.

2. Data

In this study, the latest version of the Moderate Resolution Imaging Spectroradiometer (MODIS) data is used to obtain the ice drift velocity. This data set, observed from infrared sensors onboard Terra satellite of MODIS, consists of 951 × 951 pixels in size, which corresponds to approximately 954 km by 954 km at a resolution of 1002.7010 m per pixel gridded in the Lambert Azimuth Equal Area map projection. The temporal coverage of this data set is from Feb. 24, 2000 to Aug.31, 2012 while the temporal interval is daily. The defect of this MODIS data set is the susceptiblility to cloud because of the infrared sensors.

The 10-meter wind data applied in this study is obtained from the ERA-Interim data provided by ECMWF (European Centre for Medium-Range Weather Forecasts). This wind data set is a product of reanalysis (as well as analysis) which is a process by which model information and observations of many different sorts are combined in

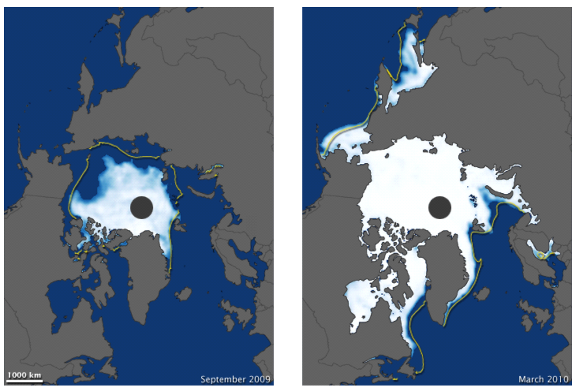

Fig. 1 Sea ice extent in Sep. 2009 (left) & Mar. 2010 (right)

an optimal way to produce a consistent, global best estimate of the various atmospheric, wave and oceanographic parameters. The acquisition time of 10-meter wind is 12:00:00 (UTC) and only analysed fields is utilized. Grid size of this dataset is 1.5° × 1.5°.

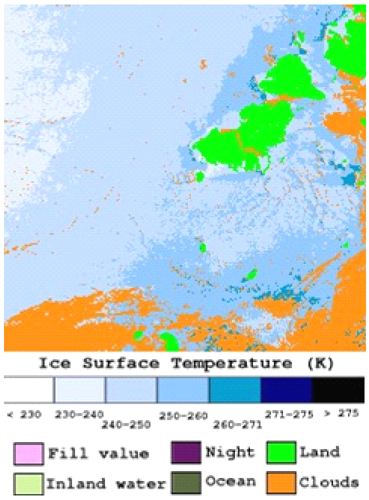

Fig. 2 Original MODIS imagery

3. Methodology

3.1 Sea ice daily-drift velocity

Ice drift velocity is calculated from two consecutive images separated by 24h by adopting the pattern matching technique [Ninnis et al., 1986; Kimura, N., Wakatsuchi, M., 2000]. Prior to the calculation, land, open ocean and cloud are distinguished from the ice field both in template window and search window. In this study, after a comprehensive comparison between different range, a comparatively appropriate resolution 12 × 12 km is selected for ice-drift velocity. The finally obtained vectors are filtered utilizing the maximum cross-correlation coefficient, the sharpness of the correlation peak and the consistency with the surrounding vectors. After this processes, ice-motion data set at a resolution of 12 × 12 km in the period from Feb. 2000 to Aug. 2012 is obtained.

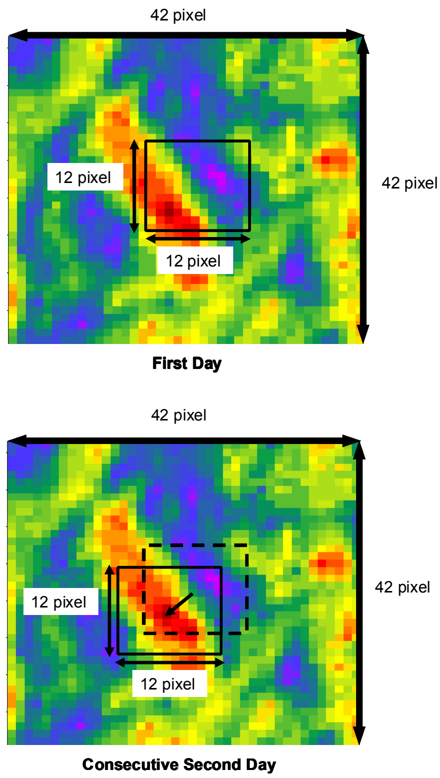

Fig. 3 Pattern Matching Technique

3.2 Gaussian interpolation of wind data

To investigate the correlation between ice motion and 10-meter wind, a grid of 1.5° by 1.5° 10-meter wind data set is employed. Since the resolution of ice motion which is prepared at 12 × 12 km is different from the one of wind data set provided by ECMWF, to match the resolution of two data sets, Gaussian interpolation is adopted.

3.3 Relationship (ice motion & 10-meter wind)

For investigating the relationship between ice motion and the 10-meter wind, the formula (1) is adopted basing on a Least square method [Thorndike and Colony, 1982; Kimura and Wakatsuchi, 2000].

$$\begin{bmatrix} U_i \\ V_i \end{bmatrix} = F \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} u_a \\ v_a \end{bmatrix} + \begin{bmatrix} \overline{U}_w \\ \overline{V}_w \end{bmatrix} \quad (1)$$

Here U_i, V_i denote the sea ice velocity, F represents the speed reduction factor (wind factor), θ means turning angle and u_a, v_a are wind velocity, while $\overline{U}_w, \overline{V}_w$ present the approximate mean ocean current.

By using least square techniques:
$$\theta = \arctan\left(\frac{\sum_{k=1}^{n} u_{akd} V_{ikd} - \sum_{k=1}^{n} v_{akd} U_{ikd}}{\sum_{k=1}^{n} u_{akd} U_{ikd} + \sum_{k=1}^{n} v_{akd} V_{ikd}} \right)$$

$$F = \frac{c_1 - c_2 + c_3 + c_4}{\sum_{k=1}^{n} u_{akd}^{\ 2} + \sum_{k=1}^{n} v_{akd}^{\ 2}}$$

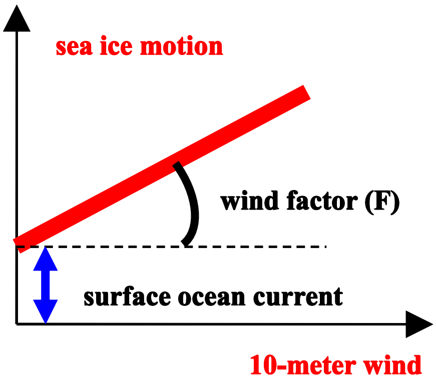

Fig. 4 The 2D linear relationship between ice motion and 10-meter wind

Where:

$$c_1 = \cos\theta \sum u_{akd} U_{ikd};\ c_2 = \sin\theta \sum v_{akd} U_{ikd};$$
$$c_3 = \sin\theta \sum u_{akd} V_{ikd};\ c_4 = \cos\theta \sum v_{akd} V_{ikd};$$

$$u_{akd} = u_{ak} - \bar{u}_a;\ v_{akd} = v_{ak} - \bar{v}_a;$$
$$U_{ikd} = U_{ik} - \bar{U}_i;\ U_{ikd} = U_{ik} - \bar{U}_i;$$

And k is the number of valid data. Overbar denotes the mean value. Additionally, the mean ocean current is obtained after the calculation of θ and F by equation (1).

$$\begin{bmatrix} \bar{U}_w \\ \bar{V}_w \end{bmatrix} = \begin{bmatrix} \bar{U}_i \\ \bar{V}_i \end{bmatrix} - F \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \bar{u}_a \\ \bar{u}_a \end{bmatrix} \quad (2)$$

The correlation coefficient between ice motion and 10-meter wind is defined by normalizing wind factor (F) with ice motion.

$$r = \frac{\cos\theta \sum u_{akd} U_{ikd} - \sin\theta \sum v_{akd} U_{ikd} + \sin\theta \sum u_{akd} V_{ikd} + \cos\theta \sum v_{akd} V_{ikd}}{\sqrt{\sum_{k=1}^{n} u_{akd}^{\ 2} + \sum_{k=1}^{n} v_{akd}^{\ 2}} + \sqrt{\sum_{k=1}^{n} U_{ikd}^{\ 2} + \sum_{k=1}^{n} V_{ikd}^{\ 2}}} \quad (3)$$

4. Calculation results

Due to the adoption of high-resolution MODIS data, small-scale ice motion is obtained, which has not been observed by a passive microwave sensor onboard AMSR-E in some coastal regions. For instance, there is a relatively strong ice drift (around 5-7 cm/s) from Barrow Strait to Lancaster Sound and converge to the Baffin Bay illustrated in Fig. 5. Additionally, the multiyear ice off the northern Canadian Archipelago is drifting towards the Beaufort Sea with a speed of 2-5 cm/s.

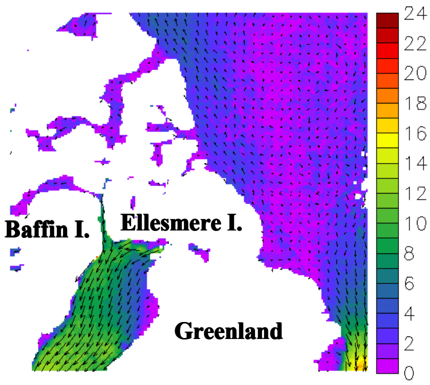

Fig. 5 Mean ice motion of Arctic Archipelago (Unit: cm/s)

In most of the coastal regions of Arctic, Baffin Bay, and Beaufort Sea, the correlation values between ice motion and surface wind are relatively small (<0.7) exhibited in Fig. 8. Relatively low correlation values also exist in the Lancaster Sound and Kane Basin, it indicates that Coriolis force, internal ice stress and sea surface tilt in these areas are relatively more significant than Russian side of the Arctic Ocean which comprises high correlation coefficients (>0.7).

Wind factor, shown in Fig. 9, is well corresponding to the spatial distribution of correlation coefficient (r) while sea ice moves in a range from 1% to 2% and less than 0.8% of surface wind speed in the high-correlation areas and low-correlation areas, respectively. Sea ice motion is strongly controlled by surface wind in the Barents Sea where wind factor reaches the maximum value 2.3%.

For the turning angle (θ), which is defined to be negative when ice vectors lie to the right of the 10-m wind vectors, almost all areas have ranges from -15° to -35° except some coastal regions illustrated in Fig. 10.

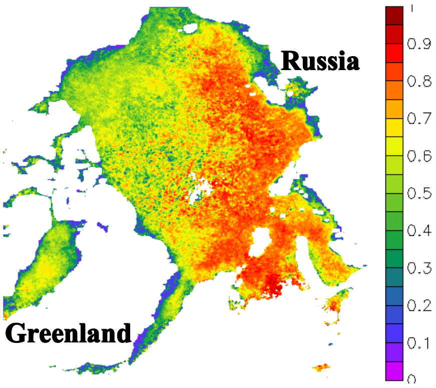

Fig. 6 Correlation coefficient (r) between ice motion and 10-meter wind

5. Variability (2000-2006 & 2007-2012)

Since the original MODIS data is susceptible to cloud, the computable data is limited, the variability of sea ice between 2000-2006 and 2007-2012 is investigated. The difference of correlation between ice motion and surface wind is obtained as well as the difference of wind factor. In addition, Basing on an assumed Arctic Ocean area, the flowing-out sea ice extent is compared between 2000-2006 and 2007-2012.

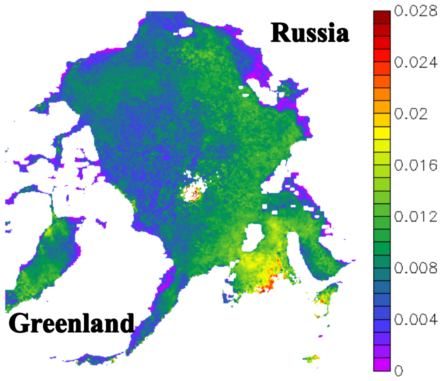

Fig. 7 Wind factor (F) between ice motion and 10-meter wind

6. Conclusions

Significantly small-scale ice motion is revealed. For instance, there exits an eastward mean ice motion in the range around 5-7 cm/s in the Lancaster Sound and a southward motion in the magnitude from 4 to 6 cm/s in the Kane Basin of the Nares Strait. It can be referred as a validation test for the ice motion computed by models to improve the accuracy of forecast.

The thick ice (multiyear ice) is moving out from offshore ice area of northern Canadian Archipelago with so-called Transpolar Drift Stream, and it is prone to be more active in 2007-2012 than in 2000-2006.

Since the more active ice motion in the Lancaster Sound and the Nares Strait, the amount of flowing-out ice of the interior of the Arctic is increasing.

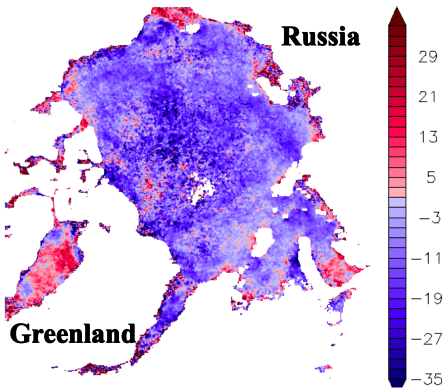

Fig. 8 Wind factor (F) between ice motion and 10-meter wind

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