

合成開口レーダーによる海氷ランダム運動解析

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数10km以上のスケールの海氷野の運動は、氷脈化に伴う弾性体のような空間的になめらかな運動と、乱流のようなランダムな運動、海氷野の割れ目における不連続な運動の総和である。合成開口レーダーにより初めて、海氷野の詳細な速度場が観測できるようになった。本研究に用いた海氷移動データの格子間隔は180mである。本研究では、JERSに搭載された合成開口レーダーによる海氷野の速度場データから、なめらかな運動とそれ以外の運動を分離する一つの手法を提唱した。さらに、なめらかな運動を統計的に解析し、単純な拡散の仮定のもとに、北極海氷移動の拡散係数を見積もった。海氷の拡散には異方性があることがわかった。拡散係数の第一主成分と第二主成分の大きさはそれぞれ毎秒7平方m以下、毎秒3平方m以下である。拡散の第一主成分の方向は合成開口レーダーの1シーン内(75km四方)での海氷の全体的な移動の方向とほぼ一致することがわかった。

キーワード：合成開口レーダー、海氷、JERS、拡散、北極

Analysis of sea-ice motion estimated through SAR

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Ice-displacement data estimated through Japanese Earth Resources Satellite (JERS) with Synthetic Aperture Radar (SAR) is statistically analyzed to examine diffusive coefficients of Arctic sea-ice motion under the assumption of simple diffusion. The grid interval of the ice-displacement data is 180m. The diffusion is not isotropic. The diffusive coefficients of the first and second principal axes are less than 7 and 3 m²/s. The first principal axes are about in the directions of general ice displacement in the scenes (almost the same as the directions of ice displacement at the centers of the scenes).

Key Words : Synthetic Aperture Radar, SAR, Sea ice, JERS, Diffusion, Arctic

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1 Introduction

Sea ice dynamics has been theoretically discussed for its importance on global climate. In the regions of high ice concentration, ice interaction can be influential. Ice interaction is related to the yield curve of pack ice (e.g. Thorndike et al., 1975; Rothrock, 1975). To examine how realistic the elliptical yield curve is, ice displacement data derived through Synthetic Aperture Radar (SAR) is utilized (Stern et al., 1975). Stern et al. mention that the elliptical yield curve is suitable for the SAR-derived data within their observation error range although other yield curves may fit the same data suitably.

For numerical stability, the sea-ice dynamics model of Hibler needs an artificial diffusive term in the equations of ice thickness and concentration continuity (Hibler, 1979). Using the Particle-in-Cell scheme, Flato (1993) eliminates the diffusive term to improve ice-edge calculation. Using buoy-track data, the diffusivity of pack ice is examined (e.g. Thorndike, 1986). Thorndike discusses separation between buoys, proposing a model where random crack slip leads to diffusive mixing of pack ice. In general, the separation rate of two particles is partitioned into that associated with large-scale strain and that due to turbulent diffusion and discontinuous motions. In one-year motion, the large-scale strain of pack-ice fields is more important to net separation than diffusion is (R. Colony, 1996, Personal Communication). The combination of discontinuous motions of pack ice at leads or cracks as shown by the gray hatch lines in Fig. 1 (b) of Stern et al. (1995) is regarded as the main cause of large-scale strain, while the other parts of pack ice (every 5km grid without gray hatch) look slightly zigzag. In this paper, we examined diffusive motions of pack ice with small deformation using SAR-derived ice displacement. Here, we regard spatially high-frequency fluctuations as diffusive or random motions.

2 Data

The resolution of the SAR of JERS is 18m. Before the calculation of ice displacement, the original SAR

images were each averaged over 10 by 10 pixels (180 m by 180m). The grid interval of the ice displacement data is also 180m.

Fig. 1 shows an example of ice displacement data derived from the SAR of JERS. The location is around 73N 147W. The pair of SAR scenes are taken on September 23 and 24, 1992. The surface pressure from the International Arctic Buoy Program is also shown in Fig. 2, which implies southward winds there.

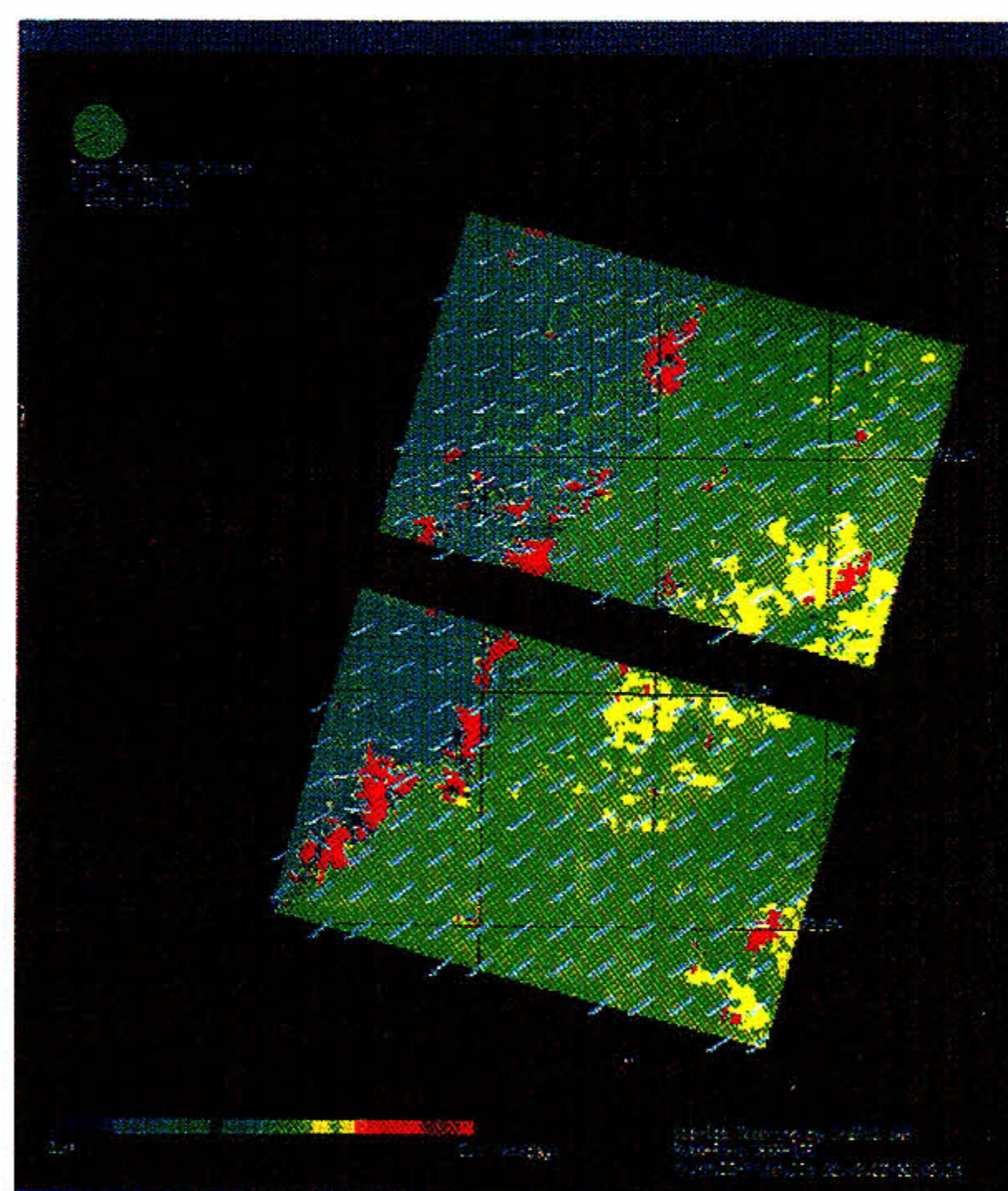


図1 JERSの合成開口レーダーにより観測された1992年9月23日～24日までの海水移動。上方が北。赤色で示されている極端に大きな速さは海水移動の算出におけるエラーであるので、解析の際には除外した。左上の小円はGround Positioning Systemにより測定された付近の漂流ブイの移動である。

Fig. 1 Ice displacement around 73N 147W from September 23 to 24, 1992, estimated through the SAR of JERS. The North is up. The extreme speed shown by red is an error. We eliminated the extreme speed in our analysis. The upper-left small circle shows drifter motion at 73.25N 149.5W determined by the Ground Positioning System.

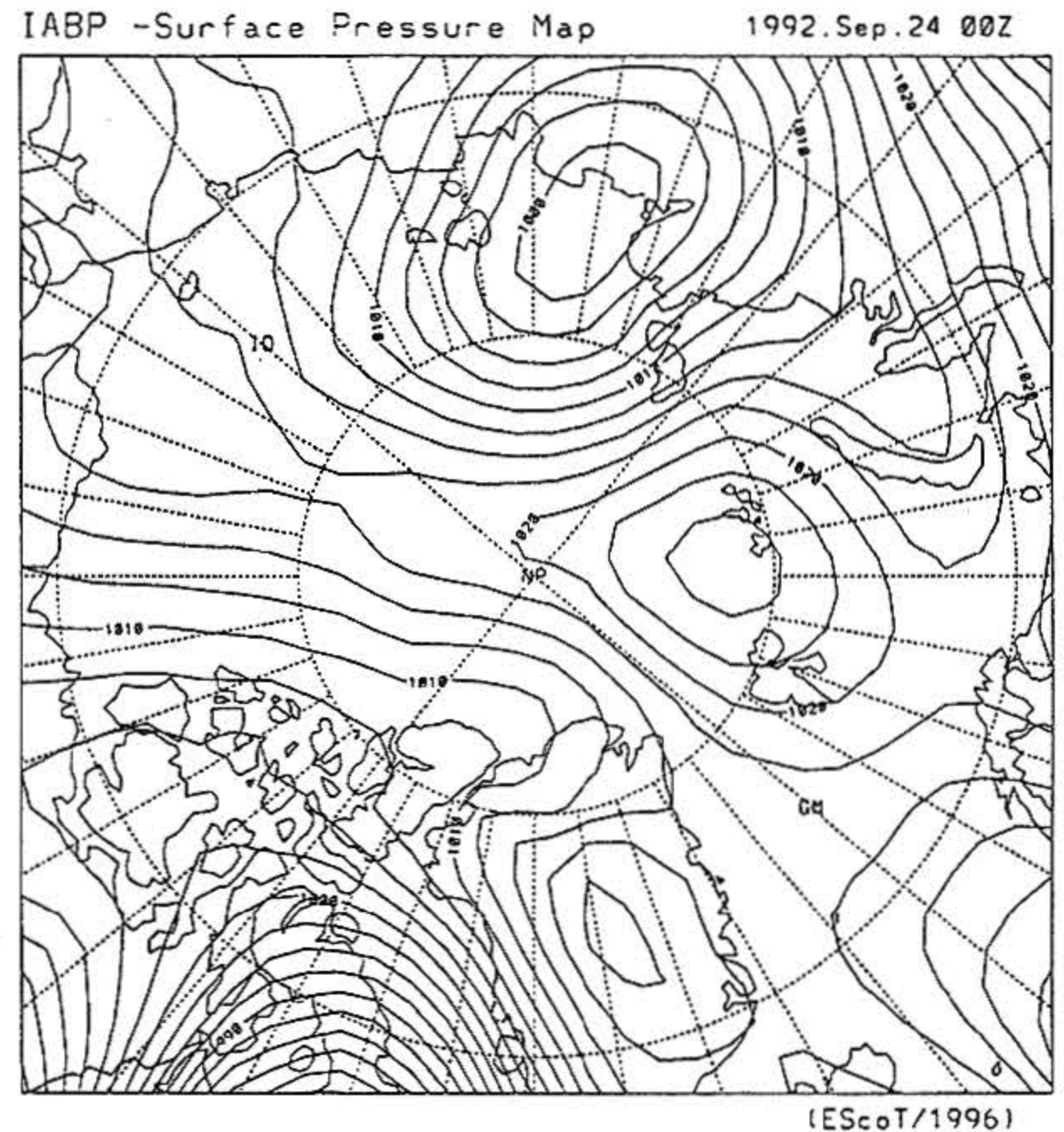
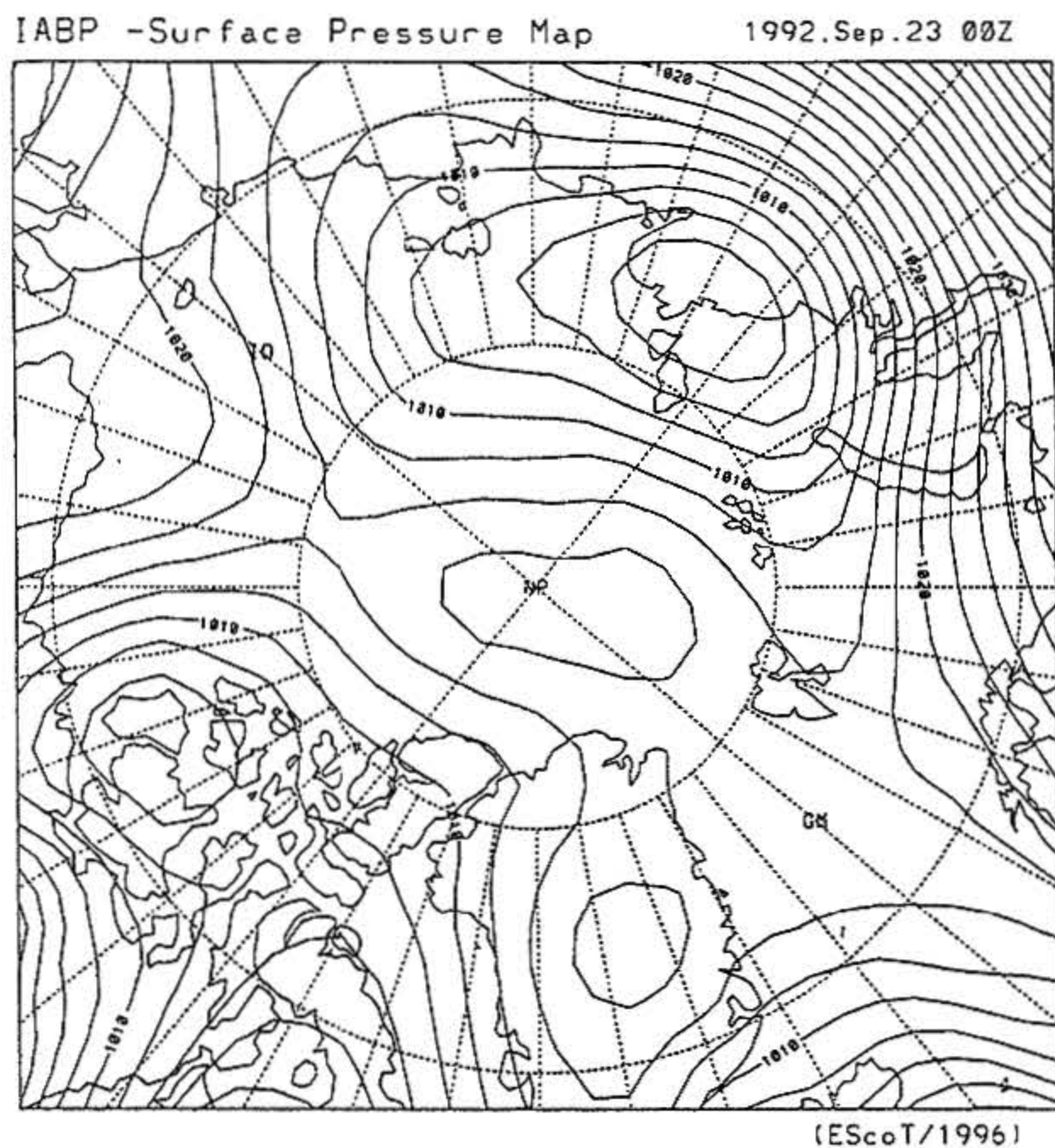


図2 国際北極ブイ計画による1992年9月23日と24日の気圧配置

Fig. 2 Surface pressure on September 23 and 24, 1992 by the International Arctic Buoy Program.

3 Analysis

To discuss turbulent diffusion, we must first define a scale separating turbulent diffusion from large-scale deformation. The spatial increment of the Hibler Model of sea-ice dynamics is about 40-100km. Thus, we paid attention to a scale where the spatial increment is about 75 km, regarding the whole SAR scene as corresponding to a numerical cell of 75 km by 75 km.

To extract spatial fluctuations with high frequencies, regarded as sub-grid fluctuations or turbulent diffusion, we used the polynomials described below. In plastic law, the strain rates (the first order spatial derivative of velocity) of a pack-ice field are related to the stress tensor, whose divergence gives ice interaction:

$$\begin{aligned} F_x &= \frac{\partial \sigma_{11}}{\partial x} + \frac{\partial \sigma_{12}}{\partial y} \\ F_y &= \frac{\partial \sigma_{21}}{\partial x} + \frac{\partial \sigma_{22}}{\partial y} \end{aligned} \quad (1)$$

Here, F_x , F_y , are the x and y component of internal ice stress. Stress tensors, σ_{ij} , are functions of strain rates, $\frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$, where u is velocity. Thus, the spatial patterns of ice interaction are dependent on specifying first and second-order

spatial derivatives of the velocity field. We should be careful not to include this part of the velocity field into the random diffusion. In the Hibler Model, the second-order spatial derivatives of ice velocity gives ice interaction (Equations (5)-(9), Hibler, 1979). To make continuous the second-order spatial derivatives, we adopted the cubic terms in the polynomials. If we used higher and higher-order polynomials, spatially higher and higher fluctuations would be discussed by the polynomials describing the structure of ice-velocity fields on a smaller and smaller scale. Thus, one cannot adopt arbitrarily higher-order polynomials.

Before ice-displacement calculation, we used other cubic polynomials to transform the pixel-line coordinates of an original SAR image into latitudes and longitudes. Thus, the accuracy of positioning of a SAR-derived image depends on the adequacy of the coefficients of the cubic polynomials for the transformation. Therefore, each calculated ice-displacement field may contain systematic errors generated in the cubic polynomial transformation. Such systematic errors can be expressed by cubic polynomials. To extract sub-grid fluctuations from the ice-

displacement fields where transformation by the cubic polynomials may generate systematic errors, we adopt cubic polynomials.

First, we fitted a pair of polynomials of x and y ,

$$\begin{aligned}\Delta x &= a_0 + a_1x + a_2y + a_3x^2 + a_4xy + a_5y^2 + a_6x^3 + a_7x^2y + a_8xy^2 + a_9y^3 \\ \Delta y &= b_0 + b_1x + b_2y + b_3x^2 + b_4xy + b_5y^2 + b_6x^3 + b_7x^2y + b_8xy^2 + b_9y^3\end{aligned}\quad (2)$$

to the data of a two-dimensional ice-displacement field in a pair of SAR scenes of 75km by 75km. Here, we excluded extreme speed shown by red in Fig. 1, because we regard it as false. The fitted polynomials are considered to include SAR-image distortion (which could be as large as 0.5km) caused by the systematic positioning errors. If the SAR images were projected on the tangential planes touching the Earth surface at the center of the images, the distortion would be smaller. However, the polars stereo projection is commonly adopted in sea-ice remote sensing.

The direction of ice displacement (Fig. 1) at the point at 73N 147W is 124 degrees west from North. We obtained ice divergence, shear, and rotation from the fitted polynomial. Since the SAR-image distortion could be as large as 0.5km, $0.5\text{km}/75\text{km} = 0.0067$ of strain could be caused by the distortion. Thus, strain rates of 0.0067 day^{-1} and their linear combination such as divergence, shear, and rotation could be insignificant, because, in this case, the time interval of the pair of SAR scenes is one day. The ice divergence, rotation and shear at the point at 73N 147W are 0.004 day^{-1} (insignificant), -0.042 day^{-1} and 0.071 day^{-1} . The direction of the first principal component of strain rates at the point at 73N 147W is 15 degrees west from North (Fig. 3). Roughly speaking, the ice field is compressed in the direction parallel to the displacement while stretched in the direction orthogonal to the displacement.

Next, we obtained a two-dimensional residual field between the data and the fitted polynomials (Fig. 4). We regard the residual $\Delta\tilde{x}$, $\Delta\tilde{y}$ as a result of random motion. The histogram of the residual is shown in Fig. 4. Rotating the $\Delta\tilde{x}-\Delta\tilde{y}$ coordinate, we find the first principal axis $\Delta\tilde{x}_p$ that maximizes the variance of the residual. This is

an eigenvalue problem. The first principal axis is about in the direction of general ice displacement in the scenes.

Finally, dividing the variances by the time interval (one day in this case) of the pair of SAR scenes, we estimate the diffusive coefficients of ice motion (Fig. 5). Here, we regarded the sub-grid fluctuations, which are on the rotated coordinates, as a result of random walk. The diffusive coefficients of the first and second principal axes are 0.56 and $0.25\text{km}^2/\text{day}$ (6.5 and $2.9\text{m}^2/\text{s}$).

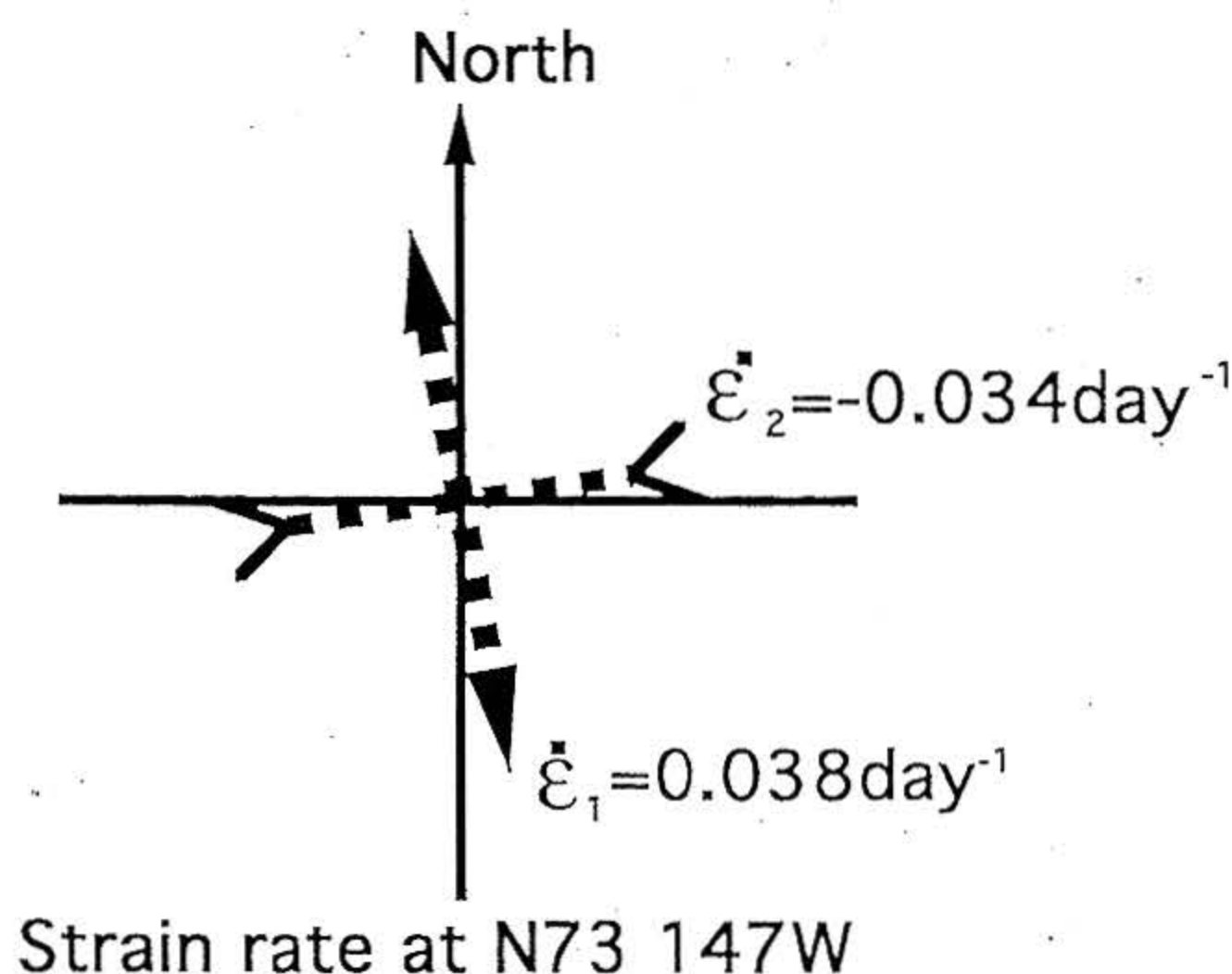


図3 北緯73度西経147度における歪速度の主成分。海水野は海水移動とほぼ一致する方向に圧縮され、それと垂直な方向に伸びている

Fig. 3 The principal components of strain rates at 73N 147W. Roughly speaking, the ice field is compressed in the direction parallel to the displacement while stretched in the direction orthogonal to the displacement.

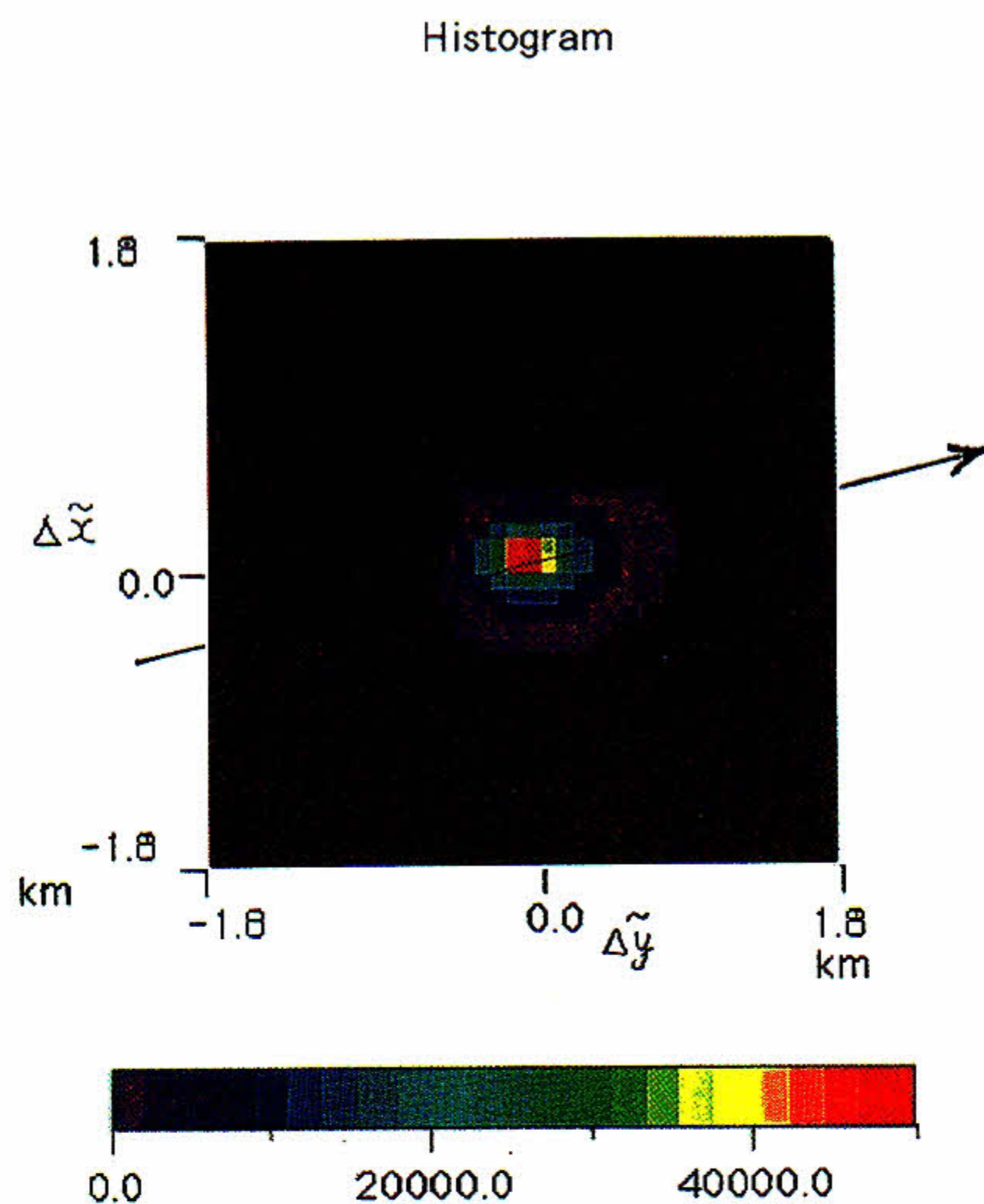
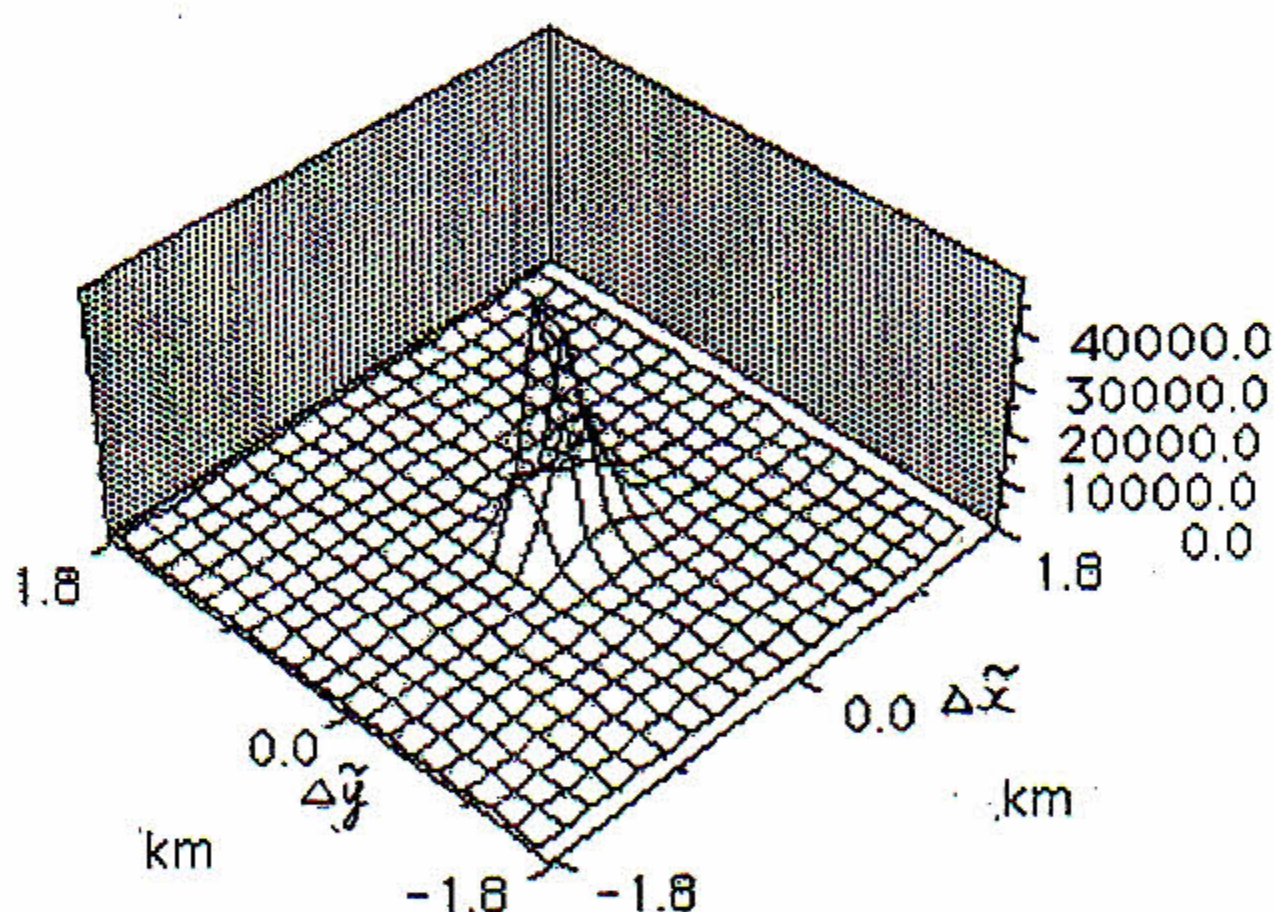


図4 海水移動データとフィットされた多項式の間の残差。
矢印は分散が最大の方角を示す

Fig. 4 Residual field between the data and the fitted polynomials. The arrow shows the direction in which the variance is the largest.



$$f(\Delta \tilde{x}, t) = \frac{\exp\left(-\frac{\Delta \tilde{x}^2}{2Dt}\right)}{\sqrt{2\pi Dt}}$$

$f(\Delta \tilde{x}, t)$: probability density function

D : diffusive coefficient

t : time

Dt : variance

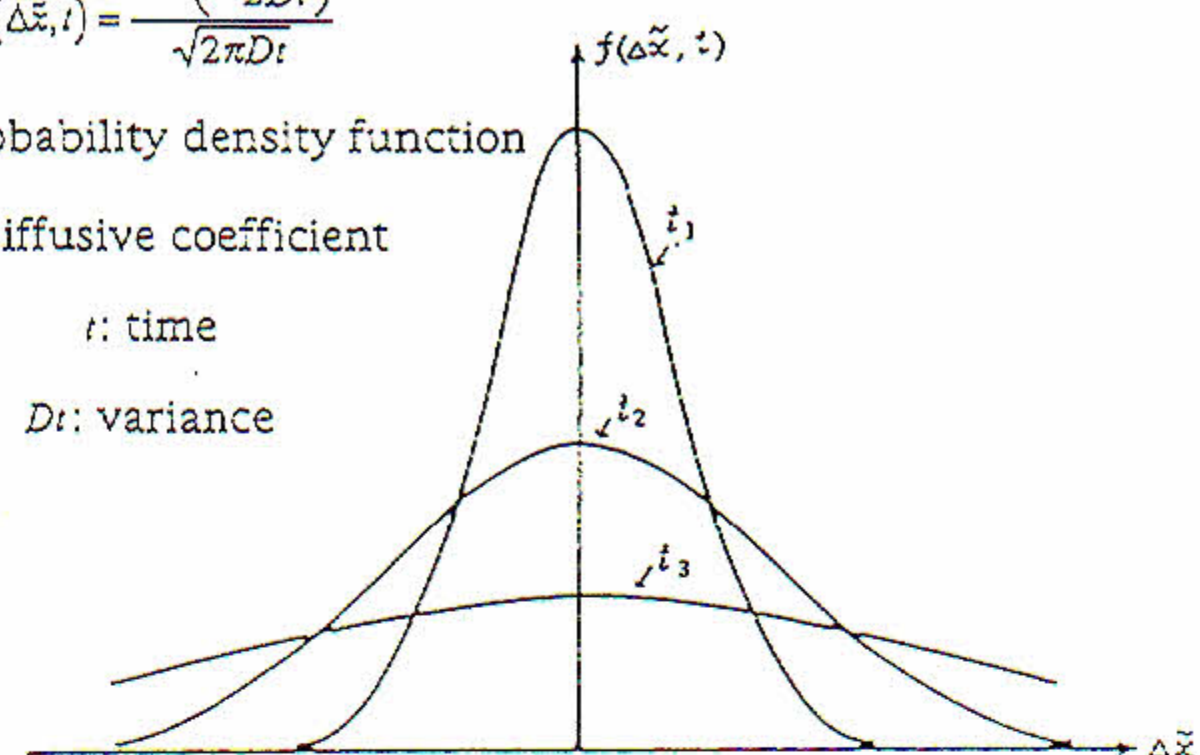


図5 分散と拡散係数の関係。 $t = 0$ においては確率密度関数はデルタ関数である

Fig. 5 Relationship between variance and diffusive coefficient. At $t=0$, the probability density function is a delta function.

4 Discussion

We made the same analysis as described above on other samples. The dates and locations of the samples are listed in Table 1 as well as the diffusive coefficients we determined. The diffusion is not isotropic. The main drive of sea ice motion is wind stresses. The variance of wind fields may not be isotropic. Even if wind fields are uniform, the wind drag coefficients of ice pieces may vary. As a result, the reaction of ice pieces to wind varies, more diffusive in the direction of ice displacement. The diffusive coefficients of the first and second principal axes are less than 7 and 3 m^2/s . These values are on the order of one thousandth of the artificial diffusive coefficients in traditional numerical sea-ice models. The first principal axes are about in the directions of general ice displacement in the scenes (almost the same as the directions of ice displacement at the centers of the scenes).

The divergence, shear, and rotation at the centers of SAR scenes are also listed in Table 2. The divergence is negative except for the sample at 73N 147W. This sample also shows the largest diffusive coefficients. It may be because the sample is closer to an ice margin than the others are. Each ice piece may move more freely near an ice margin to be more diffusive. The rotation is negative except the sample at 81N 137.5W.

表1 拡散係数

Table 1 Diffusive coefficients.

Dates	Location	Diffusive coefficients km ² /day (m ² /s)	
		first	second principal axis
26&28 Jun.'92	80.3N 135.5W	0.49 (5.7)	0.18 (2.1)
3 & 5 Jul.'92	81N 137.5W	0.13 (1.5)	0.01 (0.1)
3 & 5 Jul.'92	81.7N 136W	0.25 (2.9)	0.04 (0.4)
23&24 Sep.'92	73N 147W	0.56 (6.5)	0.25 (2.9)
29&30 Mar.'93	79N 121.5W	0.03 (0.4)	0.01 (0.1)
29&30 Mar.'93	78N 123.5W	0.13 (1.5)	0.06 (0.7)

表2 シーンの中心における発散, シアー及び回転

Table 2 Divergence, sheer & rotation at the centers of scenes.

Location	Divergence day ⁻¹	Sheer day ⁻¹	Rotation day ⁻¹
80.3N 135.5W	-0.085	-0.25	-0.17
81N 137.5W	-0.045	0.10	0.07
81.7N 135.9W	0.000	-0.012	-0.042
73N 147W	0.004	0.071	-0.042
79N 121.5W	-0.009	0.094	-0.031
77.9N 123.5W	-0.056	0.047	-0.012

Ice displacement was derived from averaged values over 10 by 10 original pixels (180 m by 180 m) each. Thus, variance less than $180\text{ m} \times 180\text{ m} = 32400\text{ m}^2$ is not significant. (If the sampling errors are uniformly distributed, the significant level of variance is smaller (2700 m^2). However, we take the maximum possible value for the significant level for security because there is no guarantee that the sampling errors are uniformly distributed.) Since one day is 86400 seconds, diffusive coefficients less than $32400\text{ m}^2/86400\text{ s} = 0.375\text{ m}^2/\text{s}$ are not significant for a pair of images with a one-day interval, and those less than $32400\text{ m}^2/86400\text{ s} / 2 = 0.1875\text{ m}^2/\text{s}$ are not for a pair of images with a two-day interval.

What we saw by SAR is area. We did not use the velocity of each ice piece but of each square of 180m by 180m for the two following reasons. One reason

is the technical complexity in determining the velocity of each ice piece. The shapes and sizes of ice pieces are irregular. The other is that we must think about the rotation of each ice piece if we deal with the velocity of each ice piece. However, the rotation is already taken into consideration when we deal with each square of 180m by 180m.

5 Conclusions

The diffusive motion of pack ice is not isotropic. The diffusive coefficients of the first and second principal axes are less than 7 and 3 m²/s. The first principal axes are about in the directions of general ice displacement in the scenes (almost the same as the directions of ice displacement at the centers of the scenes).

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