An ice drift series from the Fram Strait January-March 1992 based on ERS-1 SAR data

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A time series of ERS-1 SAR images is used to estimate ice drift in the Fram Strait January-March 1992 (the ERS-1 mission first ice phase). The images all cover the same area. The sampling interval is three days. The paper shows examples of estimation of ice drift and divergence from this image time series. Divergence is an important quantity in order to estimate ice production and hence mixing of the ocean water masses.

A reference configuration of ice points is defined for each image. These ice points are identified in the successive image giving a set of point pairs. These point pairs are input for statistical analysis.

Upward looking sonars (ULS) and current meters are moored below the scene. A combination of the SAR derived dynamics and the ULS derived ice thickness series will give opportunities to estimate ice mass flux into the Greenland Sea, and to improve ice classification algorithms.

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Introduction

This paper gives results from work demonstrating the feasibility of using ERS-1 SAR imagery data to estimate temporal variations of ice velocities in the East Greenland ice stream. This ice stream represents about 95 percent of all the ice that leaves the Arctic Ocean (Vinje & Finnekåsa 1986) and is therefore an important climatic parameter.

A time series of ERS-1 SAR images covering the same area of 100 × 100 square kilometres and spatial resolution of about 30 metres is used to estimate ice drift in the Fram Strait January-March 1992. Fig. 1 shows the spatial outline for this image time series. The sampling interval is three days.

Analysis method

Let X_t denote the set of all ice particles at time t in the actual region including the frame of observation Z_t that also may depend on the time t. We may regard Z_t and X_t as subsets of the plane R^2 (X_t, $Z_t \subset R^2$). We want a sensible probabilistic and physical interpretation of the transformation T_{t_i,t_j} which maps corresponding ice points between the times t_i and t_j. A first approach may be to represent T_{t_i,t_j} by the shift, stretch and rotation modes as in the Taylor-like expansion:

$$T_{t_1,t_2}(x) = \bar{y} + A(x - \bar{x}) + \varepsilon \qquad (1)$$

where $\bar{x}$ and $\bar{y}$ are mean points of a reference configuration of corresponding ice points at times t_1 and t_2 respectively. A is a 2 × 2 matrix. ε is an

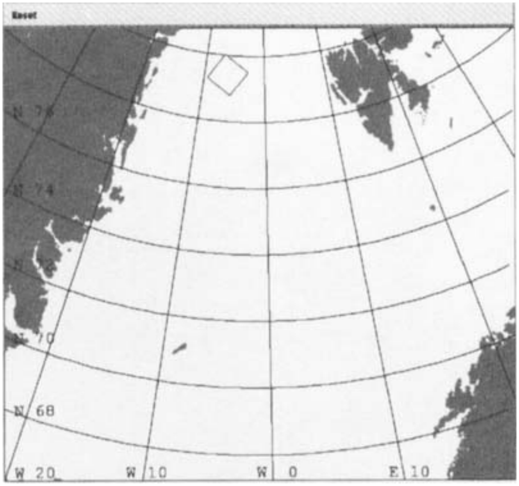

Fig. 1. Spatial coverage of ERS-1 SAR image time series used to estimate ice drift in the Fram Strait January-March 1992 (satellite mission first ice phase).

error or model failure term. Rothrock & Stern (1992) obtained the invariants *vorticity*, *divergence* and *shear* by interpreting the terms of the matrix A as the partial derivatives of a velocity field (a direct use of Equation 1). Their work is based on SEASAT SAR images 19 July–7 October, 1978. Loshchilov et al. (1980) made similar approaches twelve years earlier using SLAR (the author was shown during a stay at the Arctic and Antarctic Research Institute, AARI, in St. Petersburg, June 1992).

The vector $b = \bar{y} - \bar{x}$ reflects ice drift. The transformation A maps a unit circle into an elipsis with axes of length $v_i(A) = \{\lambda_i(A^TA)\}^{1/2}$, $i = 1,2$, where $\lambda_i(A^TA)$ are the eigenvalues with the corresponding eigenvectors e_i of the symmetric, positive semidefinite, matrix A^TA. We assume $\lambda_1 \geqslant \lambda_2$. $v_i(A)$ are in the literature called *singular values* of the matrix A (cf. e.g. Ciarlet 1988, Chapter 3). We can interprete $v_1(A)v_2(A)$ as the increase of area between the image sample times. Let

$$A = CU \tag{2}$$

be the (unique) polar factorization of (the invertible) matrix A where C is a rotation and U is a positive definite matrix (note: we can assume determinant $(A) > 0$). U reflects deformation given by its eigenvalues $v_i, i = 1,2$, and direction θ_1 of the eigenvector e_1.

The measure for approximation in this paper is the common method of least square. A reference configuration $\{x_i\}$ of ice points is defined for each image. Each ice point x_i, is in the successive image

Table 1: Estimates of three days ice drift in the East-Greenland ice stream January-March 1992 based on ERS-1 SAR data (satellite mission first ice phase). Each 3 days period is labeled by its start date. ≈ means analysis performed by eye due to too little common ice in image pair. Blank means missing data. Angles are given relative to north (positive clockwise). ©ESA (1992).

		Drift (b)		Deformation (U)			Rotation	
Date (1992)	Mean velocity (m/s)	Length (km)	Dir (deg)	v_1	v_2	θ_1 (deg)	C (deg)	Prediction error Ē (m)
01.09	.24	61	221	1.00	1.00	102	−1.6	33
01.12	≈.35	≈90	≈200					
01.15	≈.35	≈90	≈200					
01.18	.18	46	200	1.15	.79	112	0.1	715
01.21	.14	36	181	1.01	.91	−33	−6.3	764
01.24	.14	38	194	1.01	.99	−43	6.6	214
01.27	.33	85	205	1.01	.99	−21	3.2	204
01.30	.17	44	196	1.03	.96	124	7.7	241
02.02	.17	44	191	1.00	.97	17	7.4	192
02.05	.19	49	184	1.42	.68	101	−14.6	789
02.08	.27	71	196	1.00	.99	4	9.2	37
02.11	.09	23	177	1.11	1.0	131	3.5	355
02.14	.09	23	184	1.49	1.01	96	7.8	1096
02.17	.10	25	206	1.39	.62	122	−15	1335
02.20	.27	70	224	1.04	.87	49	8.6	323
02.23								
02.26								
02.29								
03.03								
03.06								
03.09	.31	81	199	1.15	.82	127	9.3	801
03.12								
03.15								
03.18	.29	76	186	1.04	.88	112	8.0	285
03.21	.17	44	180	1.01	.97	114	12.4	377
03.24	.22	56	192	1.00	1.00	−12	9.1	39
03.27	.16	41	192	1.00	.99	119	6.1	49

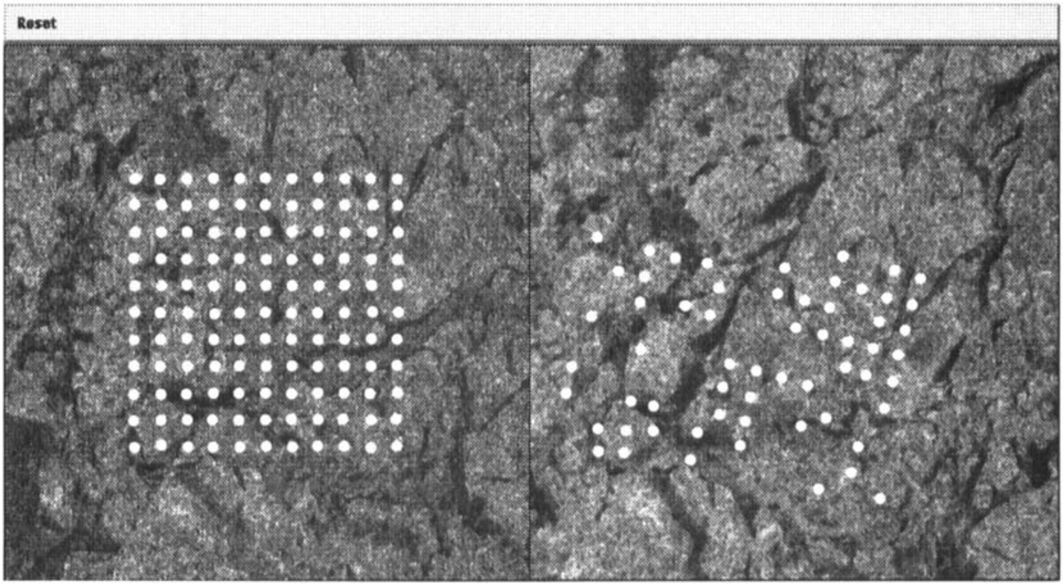

Fig. 2. Development of regular grid of ice points 9–12 March 1992. The images cover 20 × 20 square kilometre subsets of the original ERS-1 SAR scenes. Only the points with significant identification confidence are shown in the right image from 12 March. The image is received and processed at TSS. ©ESA (1992).

identified as y_i with a weight of confidence m_i between 0 and 1. The estimates for A minimize the mean square prediction error:

$$E^{2\,def}\sum_i |y_i - A(x_i - \bar{x}) - \bar{y}|^2 m_i / \sum_i m_i \quad (3)$$

In the present analysis the points y_i were identified by a semi-automatic procedure based on cross correlation. The author manually checked the results. If any doubt about the value of y_i the weight m_i was set to 0 (otherwise 1).

The reference configuration of moving ice points in this case is a regular grid of 121 points covering about 10 × 10 kilometre as illustrated in Figs. 2 and 3. The observation times $t_1 < \ldots < t_n$ have a constant sampling interval $t_{i+1} - t_i = \delta t$ of three days. Table 1 shows the, preliminary, result from this analysis.

Discussion

The aim for the analysis of this paper is to give a representative and general purpose measure for the ice drift in the actual region. Time and spatial aspects are to be considered when setting up an observation code based on physical insight. As such, Equation 1 gives an ad hoc description of ice drift T_{t_1,t_2} without any a priori relevance for significant data reduction.

Decomposition of drift into tidal components and residual drift in principle would give results more independent on ad hoc sampling time

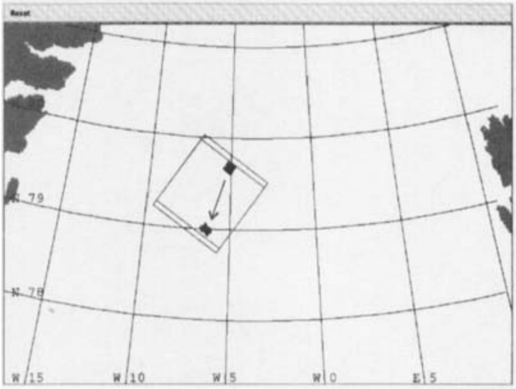

Fig. 3. Development of regular grid 9–12 March 1992 (geocoded) estimated from ERS-1 SAR data. The image coverages are slightly different due to rudimentary data collection timing code (later improved). ©ESA (1992).

schemes. However, tidal estimates for the actual location are minor to the normal mean drift (cf. Schwiderski, 1980).

The estimates of A and b may be sensitive to the choice of the initial reference configuration of ice points $\{x_i\}$. A grid covering a small area often will reflect rigid motion of ice floes and spatial shifts of the grid will give variations of the drift term b reflecting divergence in the ice field. This approach may lead to statistical techniques on ice classification and description based on the identification of rigid sets. A final report with the present approach will include relations between grids of varying size and location in order to provide a general purpose statistical description of the ice dynamics of the region in the freezing season.

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