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Sea ice velocity in the Fram Strait monitored by moored instruments

K. Widell,[1,3] S. Østerhus,[1,2,4] and T. Gammelsrød[1,3]

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[1] The Fram Strait sea ice velocity was measured by means of a new method using moored Doppler Current Meters in the period 1996–2000. Almost 3 years of ice velocity observations near 79°N 5°W are analyzed. The average southward ice velocity was 0.16 m/s. The correlation between the ice velocity and the cross-strait sea level pressure (SLP) difference was R = 0.76 for daily means and R = 0.79 for monthly means. The same cross-strait SLP difference exhibits a positive trend since 1950 of 10% of the mean per decade. By a simple linear model we compute mean sea ice area flux to 850 000 km^2/year for the period 1950–2000. Ice thickness, monitored by means of Upward Looking Sonars since 1990, is also discussed. The combined data gave a monthly ice volume flux of 200 km^3 during the last decade with no significant trend. *INDEX TERMS:* 4540 Oceanography: Physical: Ice mechanics and air/sea/ice exchange processes; 4207 Oceanography: General: Arctic and Antarctic oceanography; 4594 Oceanography: Physical: Instruments and techniques. **Citation:** Widell, K., S. Østerhus, and T. Gammelsrød, Sea ice velocity in the Fram Strait monitored by moored instruments, *Geophys. Res. Lett.*, *30*(19), 1982, doi:10.1029/2003GL018119, 2003.

1. Introduction

[2] The Fram Strait is the main gate for Arctic ice export, and the magnitude of the flux is thus thought to provide a measure of the net ice production in the Arctic Ocean. In addition the transport of ice and liquid freshwater through the strait constitutes the largest freshwater input to the Nordic Seas [*Aagaard and Carmack*, 1989] where it plays an important role for the local convection. By its variability, the Fram Strait ice and freshwater outflow is considered both to influence global climate and provide a climate signal itself, and it has received increasing interest in the light of the reported climate changes in the Arctic. Satellite data, drifting buoys, numerical models and budget considerations have been used in literature to construct estimates of the ice flux through the strait (see e.g., *Vinje et al.* [1998], *Kwok and Rothrock* [1999]). In this paper we present the first direct measurements of ice velocity obtained by moored instruments. Based on these observations we examine the relation between ice velocity and atmospheric pressure. Ice thickness recordings for 1990–1999 from moored instruments are used to estimate the ice volume flux during the 1990s.

[1]Geophysical Institute, University of Bergen, Norway.
[2]Bjerknes Centre for Climate Research, University of Bergen, Norway.
[3]University Centre on Svalbard, Norway.
[4]Norwegian Polar Institute, Norway.

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2. Data

[3] In 1995 a new method to measure the sea ice velocity by moored Doppler Current Meters (DCM12) was introduced in the Fram Strait. The DCM12, manufactured by Aanderaa Instruments (www.aanderaa.no), utilizes Doppler shift principles to measure ice velocity in addition to the water velocity at five levels between the instrument and the sea surface. It uses an acoustic sinusoidal pulse at 607 kHz and has a 60 m range. A pressure sensor enables the DCM12 to detect the water surface and the uppermost depth velocity can be interpreted as the ice velocity, or the surface current in case of open water. The stated accuracy is ±0.03 m/s. Instrumented moorings carrying a DCM12 at nominal depth of 30–50 meters have been deployed annually at the shelf break at around 79°N 5°W, see Figure 1.

[4] This study includes three near yearlong DCM12 ice velocity series from near 79°N 5°W during 1996–2000, Table 1. Ten minutes vector averages were stored each hour.

[5] Ice thickness has been monitored since 1990 by the Norwegian Polar Institute by means of one to three moored Upward Looking Sonars (ULS) manufactured by Christian Michelsen Research (www.cmr.no). The instrument and the first six years of observations were described in *Vinje et al.* [1998]. Here an additional three years (1996–1999) from 4–7°W are included.

[6] The atmospheric data sets used in our analysis are (1) NCEP/NCAR reanalysis from www.cdc.noa.gov (global, 1948-present, 2.5° × 2.5° grid, *Kalnay et al.* [1996]), and (2) reanalysis data from Norwegian Meteorological Institute (DNMI) (regional, 50–90°N and 40°W–40°E, 1955–2000, 75 × 75 km grid, *Reistad and Iden* [1998]).

3. Results

[7] The monthly means of ice velocity are shown in Figure 2a. Ice velocity was generally in the south-southwesterly direction and aligned to the shelf break. The mean southward component was 0.16 m/s, (Figure 2b). The water velocity at the lowest depth cell was near parallel to the surface velocity during the whole period with magnitudes around 1/3 of the surface value (Figure 2c).

[8] Monthly mean ice thickness (Figure 3) during 1990–1999 varied between 0.5 m and 5 m in a sawtooth manner with an apparent period of 3 years. The average for the whole period was 2.8 m, which is identical to the value presented for 1990–1996 in *Vinje et al.* [1998].

[9] The monthly averages of meridional velocity and ice thickness are shown in Figure 4. There was a seasonal

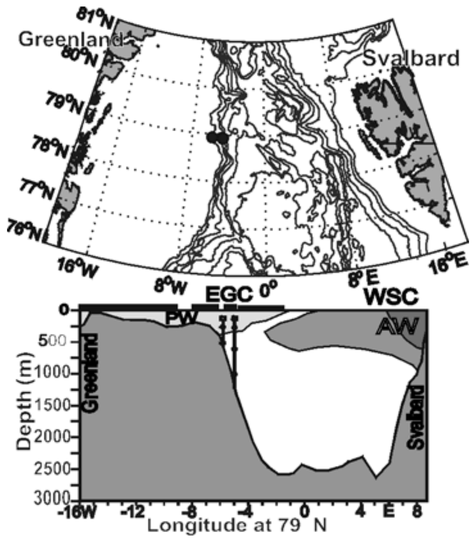

Figure 1. Upper: ULS and mooring positions in Fram Strait. Lower: Vertical transect of moorings along 79°N. EGC: East Greenland Current, WSC: West Spitsbergen Current, PW: Polar Water, AW: Atlantic Water. The DCM12 was positioned near 5 W.

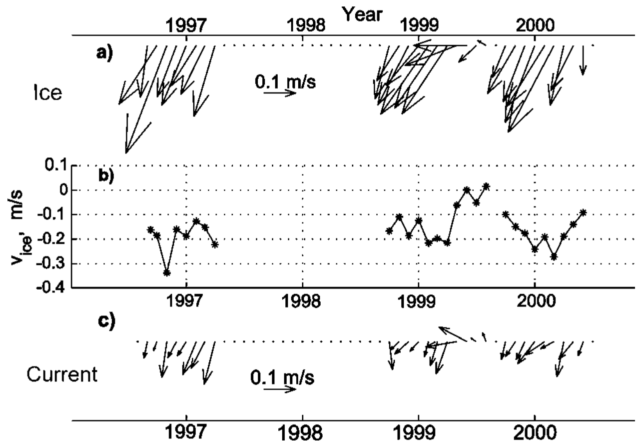

Figure 2. Results from DCM12, 1996–2000 except 1997/98. a) Monthly mean ice velocity. b) Meridional ice velocity component, v_{ice}. Negative values indicate southward velocity. c) Velocity at instrument depth, lowermost depth cell of the DCM12.

signal in meridional ice velocity with a maximum during March to April of around 0.2 m/s and a minimum during the summer of less than 0.05 m/s, or even northward velocity. Note that the months of July and August are covered only once. The ice was thicker during the summer months, presumably as a result of thicker ice originating from north of Greenland [*Vinje et al.*, 1998]. The seasonal variation of ice thickness and (modelled) ice transport was recently discussed in *Vinje et al.* [2002].

4. Discussion

4.1. Atmospheric Forcing

[10] Away from coastal boundaries sea ice moves mainly in response to wind stress, stress from the water below and the Coriolis force. For instance, *Thorndike and Colony* [1982] found that in the central Arctic more than 70% of the variance in ice motion is explained by the geostrophic winds.

[11] Since the atmospheric hindcast records cover a much longer period than the ice velocity observations, it is expedient to relate the ice velocity to the atmospheric pressure field. *Vinje et al.* [1998] suggested parametrization of the ice flux through the strait by the difference in atmospheric SLP between 81°N 10°W and 73°N 20°E (ice velocity from drifting buoy and satellite data). In *Kwok and Rothrock* [1999], a cross Fram Strait ΔP is used for computing the summer area fluxes (ice velocity from satellite data). Here we used observed ice velocity and NCEP/NCAR reanalysis SLP. By systematically calculating the correlation coefficient (R) between a large number of ΔP and the southward component of observed ice velocity on monthly and daily means, we found local east-western pressure differences to be the most appropriate choice for a parametrization based on our DCM12 data. Indeed, this is also intuitive regarding the northerly geostrophic wind over the strait, which results from-and is proportional in strength to-the zonal pressure gradient between the Greenland High and the northeastern part of the Northeast Atlantic Trough. The ΔP between the two points 80°N 15°W and 80°N 5°E (ΔP_{FS}, see Figure 6) correlated by $r^2 = 0.58$ for daily means and $r^2 = 0.62$ for monthly means to the velocity observations.

[12] The linear regression between daily means of southward velocity$-v_{ice}$ at 5°W and ΔP_{FS} reads:

$$-v_{ice} = 0.021\Delta P_{FS} + 0.09 \qquad [\mathrm{m/s}]. \qquad (1)$$

The response of the ice motion to day-to-day changes in the local pressure field is well described by equation (1), see Figure 5. An exception is May to July 1999 when westerly and northerly components in the ice velocity were observed. This episode coincides with a period of northwestward component in the current observed at around 30 m depth (Figure 2) and even by a current meter at 260 m depth (not

Table 1. Ice Velocity Data Sets Used in this Study[a]

start	end	sn[b]	position	days[c]	depth[d]
11 Sep 1996	07 May 1997	63	78.93N 5.00W	239	50
17 Sep 1998	16 Sep 1999	47	78.97N 5.31W	365	53
27 Sep 1999	04 Aug 2000	47	78.95N 5.35W	313	32

[a]1997/1998 series is excluded due to instrument malfunction.
[b]Serial number of DCM12.
[c]Days from deployment to recovery.
[d]Depth of DCM12 [m].

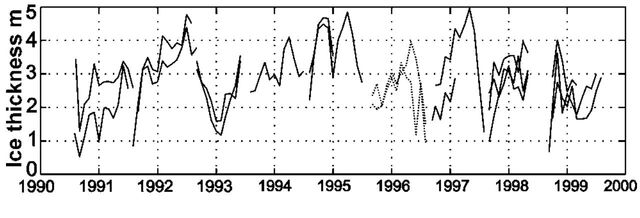

Figure 3. Monthly mean ice thickness 1990–1999. 1–3 instruments annually, presented as separate lines. Stippled lines in 1995/96 to indicate a more southerly position of the moorings that year, at 77.5°N.

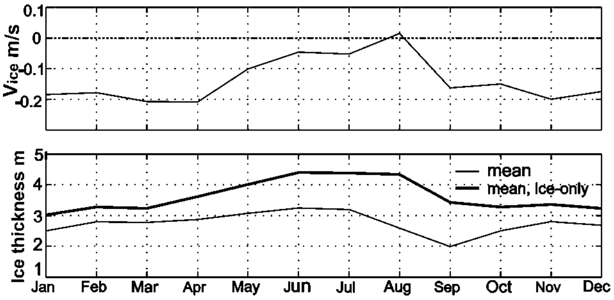

Figure 4. a) Seasonal variation in meridional velocity component. b) Seasonal variation in ice thickness, 1990–1999. Effective mean ice thickness and means when open-water measurements are excluded ('ice-only').

shown here). Such events are not accounted for by equation (1) which assumes a constant contribution from the underlying current of 0.09 m/s.

[13] The NCEP/NCAR reanalysis data exhibits a significant positive trend in ΔP_{FS} of 10% of the total mean per decade since 1950. This increase stems from a shift in atmospheric pressure pattern also present in the reanalysis record from the Norwegian Meteorological Institute, as illustrated in Figure 6. Although the records differ to some extent on the spatial pattern of the change, both show a greater pressure decrease in the eastern part of Fram Strait.

4.2. Ice Area Flux

[14] Although relation (1) explains only about 60% of the variance, it is tempting to assume that it also holds beyond the monitoring period and may be used to make estimates of ice flux for the years prior to the observations. Assuming: (i) constant ice stream width across the interval 0–15°W (318 km); according to *Vinje et al.* [1998] less than 3% of the southward transport of ice takes place east of the 0°W, (ii) no temporal variation in the contribution from the baroclinic part of the current, assuming that wind-induced variability in upper current is included in equation (1), (iii) there is no zonal variation in wind speed across the strait, (iv) a jet-like structure in the East Greenland Current with a maximum at around 3–5°W [*Foldvik et al.*, 1988].

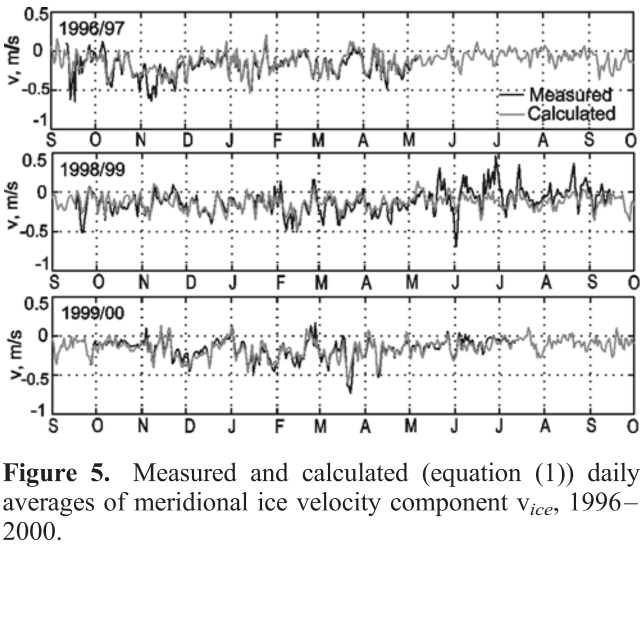

Figure 5. Measured and calculated (equation (1)) daily averages of meridional ice velocity component v_{ice}, 1996–2000.

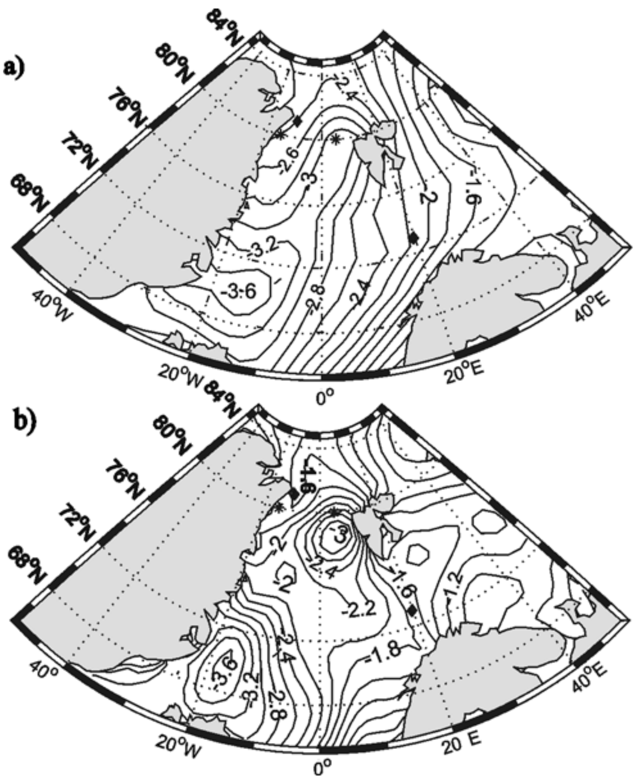

Figure 6. a) Difference between decadal means in sea level pressure from NCEP/NCAR (hPa, 1960s minus 1990s) and b) same for the higher spatial resolution DNMI reanalysis record. Stars show ΔP_{FS}, diamonds show pressure difference used in *Vinje et al.* [1998] and *Vinje* [2001].

Fahrbach et al. [2001] presented the vertical structure of the velocity in the East Greenland Current, and from their Figure 4 we estimated the mean current velocity between 0–15°W to be proportional to the velocity at 5°W by $U_{0-15^\circ W} = 0.6\ U_{5^\circ W}$. Only the constant term in equation (1) was multiplied by this factor.

[15] The estimate of monthly mean southward area flux F_A is by these assumptions given as

$$F_A = 17200\Delta P_{FS} + 44400 \qquad \left[\mathrm{km}^2/\mathrm{month}\right]. \qquad (2)$$

The area estimates from equation (2) correlate by $r^2 = 0.52$ to the estimates derived from satellite passive microwave

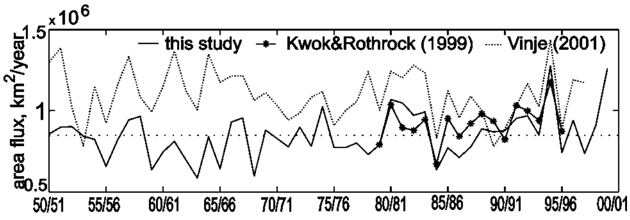

Figure 7. Cumulative area flux (sum of August–July monthly means) 1950/51–1999/2000 by use of equation (2), compared to *Vinje* [2001] and *Kwok and Rothrock* [1999]. The series by *Kwok and Rothrock* [1999] includes summer values derived by their parametrization.

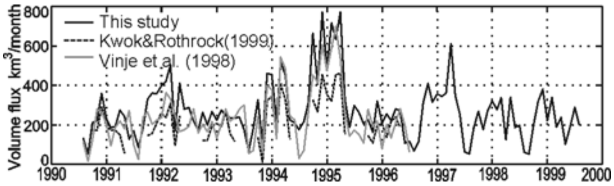

Figure 8. Monthly mean ice volume flux 1990–1999, in comparison with the results by *Vinje et al.* [1998] and *Kwok and Rothrock* [1999], both using *Vinje et al.* [1998] ice thickness.

imagery (SMMI/SMMR) in *Kwok and Rothrock* [1999] for October–May values during 1978–1996, indicating the quantitative skill of equation (2).

[16] The results from equation (2) for the NCEP/NCAR period are shown in Figure 7. The 50-year mean was 850 000 km^2/year and the trend caused by the increasing ΔP 3 100 km^2/year, or 4% of the total mean per decade. The minimum area flux was found during the 1960s, and the 1990s decadal mean was by our model 24% higher. The constant term (44 400 km^2/month) in equation (2) made up around 60% of the total flux. By varying the constant term (0.09 m/s) in equation (1) over the interval [0.06 0.12], the 50-year mean of ice area flux varied by ±21%.

[17] Figures 7 and 6 show the importance of the choice of ΔP when assessing trends in the area flux by simple parametrization to atmospheric data. The ΔP used in *Vinje* [2001], exhibited no trend during the analyzed period, since the locations of their pressure readings experienced the same decrease, see Figure 6. By our choice of pressure readings the increased atmospheric forcing in the strait is captured.

4.3. Ice Volume Flux

[18] The quantity of major interest is not ice area, but ice volume flux. We obtained this by multiplying the monthly area flux estimates from equation (2) with the monthly means of ice thickness data, see Figure 8. As *Vinje et al.* [1998], we assumed a mean cross-stream ice thickness related to the observed thickness at 5°W by $h_{0-15^\circ W} = 0.9\, h_{5W}$. Using these assumptions, monthly mean volume flux during 1990–1999 was 200 km^3 (±20%). There was a maximum in 1994/95 resulting from strong atmospheric forcing combined with relatively thick ice. We found no trend in ice volume flux during the 1990s.

[19] The lack of observations of ice thickness in the Arctic prior to the relatively well-monitored 1990s hinders the construction of long term ice volume flux series. The main source of ice thickness information is ice draft recordings from submarine surveys, offering only limited spatial and temporal coverage. *Rothrock et al.* [1999] and *Wadhams and Davis* [2000] reported a decrease in ice thickness of more than 40% over 20 years, while other authors, e.g. *Tucker et al.* [2001], *Shy and Walsh* [1996] and *Winsor* [2001] found less or no decrease from different compositions of draft data. *Holloway and Sou* [2002] pointed out that some of the dominant modes of variability may not be resolved by the submarine data, and that observed trends may be an effect of under-sampling. Improved 'ice thickness models are necessary in order to assess the long-term variability of the ice volume flux through the Fram Strait.

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K. Widell, S. Østerhus, and T. Gammelsrød, Geophysical Institute, University of Bergen, Allegaten 70, 5007 Bergen, Norway. (karolina.widell@gfi.uib.no)