Variability of the ice export through Fram Strait in 1993–98: the winter 1994/95 anomaly

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The origin of the large positive anomaly of the Fram Strait sea ice export which occurred in winter 1994/95 is analysed on the basis of a model simulation of the Arctic sea ice cover over the period 1993–98. The overall intra-annual and interannual variability in the model is in good agreement with observational estimates and the 1994/95 anomaly is well reproduced with an amplitude amounting to half of the mean winter value. Model results suggest that, concomitant to anomalous export velocities, larger than usual ice thickness in the strait contributes to the outstanding amplitude of the anomaly. Analysis on the ice thickness evolution in the strait indicates that the thick ice advected in Fram Strait at the end of the fall of 1994 originates in the anomalous cyclonic wind stress which prevailed during the preceding summer. This anomalous wind stress resulted in persistent convergence of the ice flow against the northern coasts of Canada and Greenland and in the formation of a large thickness anomaly north of Greenland. The anomaly then feeds the Fram Strait ice flow during those following winter months when the local wind forcing in the strait favours ice drift from the north-west. Our results suggest that short-term wind stress variations resulting in local thickness changes to the north of Fram Strait can lead to substantial variability of the Fram Strait ice export.

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Fram Strait is the major exit for sea ice out of the Arctic Ocean. A volume export on the order of 0.1 Sv approximately counterbalances the net ice production within the Arctic Ocean. Anomalies of this ice export are likely to impact on the Arctic Ocean sea ice distribution, especially on the multi-year ice area (Vinje 2001), while downstream from Fram Strait such anomalies can result in anomalous volume of melted ice, possibly contributing to large surface salinity anomalies (e.g. the Great Salinity Anomaly; Dickson et al. 1988). When occurring in the Greenland–Icelandic–Norwegian seas or, ultimately, in the Labrador Sea, which are important deep convection areas, such salinity anomalies may have large consequences for the thermohaline circulation of the world ocean.

Observations show large variations in the Fram Strait ice export on time scales from days to years. Area flux variations are primarily attributed to ice velocity changes induced by varying atmospheric forcing. Using ice velocities derived from satellite passive microwave imagery over an 18-year period, Kwok & Rothrock (1999) showed that in winter (October–May) 72 % of the variance of the ice area flux can be explained by the sea level pressure gradient across the strait. According to Vinje et al. (1998), the weakening of this gradient in summer over the period 1990–96 mostly explains the 50 % reduction of the monthly area flux in summer, while the almost doubling of the annual area flux between 1990/91 and 1994/

95 should also be attributed to a change of the gradient between these two periods.

Reliable estimates of the ice volume flux through Fram Strait are sparse due to difficulties in collecting measurements of the ice thickness. The 1990–96 time series reconstructed by Vinje et al. (1998) suggests strong intra- and interannual variability of the volume flux with a standard deviation of about 30% of the mean over that period. The standard deviation of the annual mean ice thickness is only 10% over the same period, implying that interannual variability of the ice flux is largely accounted for by fluctuations of the ice velocity. Some models also reveal strong correlations between the local wind forcing and the ice volume flux through Fram Strait (Hakkinen 1993; Harder et al. 1998).

Still, ice thickness anomalies should contribute as well to part of the volume export variability at Fram Strait. As noticed by Vinje et al. (1998), month-to-month variations of the prevailing wind stress direction are frequently observed at Fram Strait, alternatively bringing into the strait thicker ice from north of Greenland or thinner ice from the eastern Arctic. The shape of the annual cycle of the volume flux may then be altered compared to that of the cross-strait velocity. Thickness anomalies may also be formed in remote areas of the Arctic Ocean and advected across long distances, therefore integrating a complex time history of thermodynamic and dynamic interactions. Several scenarios in which ice thickness anomalies are formed in the Beaufort Sea or the Siberian marginal seas have been proposed to explain interannual variability of the Fram Strait ice export (e.g. Tremblay & Mysak 1998; Venegas & Mysak 2000).

In this study, we focus on the large positive anomaly of the ice volume export observed in winter 1994/95. Model simulations suggest that this anomaly has been one of the largest occurring in the strait during the last five decades (Hilmer et al. 1998; Arfeuille et al. 2000; Vinje 2001); according to observations, it has been the most extreme event over the period 1990–96, with an extra ice export of ca. 0.06 Sv, representing more than 60% of the mean (Vinje et al. 1998). The event has been associated with a concomitant ice thickness anomaly since ice draft measurements reveal monthly mean thickness values up to 4 m at that time. Ice thickness changes may have contributed to the export variability on other large export events (Arfeuille et al. 2000) but the 1995 event is the only one for which draft measurements are available. In this study, we use results of a model simulation over the period 1993–98 to try to understand the origin of the winter 1995 anomaly, as well as the mechanisms and time scales involved.

Model design and experiments

The sea ice model used in this study is based on a variable ice thickness distribution following Hibler (1980). Four ice classes are considered, including open water. The ice growth rate is determined from the vertical heat conduction equation which is discretized according to the zero- and one-layer approximation for the snow and ice, respectively. The ice dynamics are characterized by a cavitative rheology (Flato & Hibler 1992) in which shear stress is neglected. The ocean model is based on the primitive equation, z coordinate, rigid lid ocean code developed at the Laboratoire d'Océanographie Dynamique and Climatologie in Paris (Delecluse et al. 1993). The thermodynamic coupling between the ice and the ocean assumes freezing ocean surface temperature in ice-covered areas and implies heat and salt exchanges at the ice–ocean interface. The dynamic coupling is such that the surface forcing viewed by the ocean is the wind stress forcing modified by the internal ice force, while the ocean exerts a tangential friction force at the bottom of the ice.

The domain covers the Arctic and adjacent seas, with the southern limit lying at about 40° N. In the vertical, the grid includes 30 levels, with level spacing increasing with depth from 10 m in the top 100 m to 500 m in the deepest levels. In the horizontal, the resolution is slightly anisotropic due to the grid geometry with the "pole" lying over China to overcome the North Pole singularity. The horizontal resolution is about 80 - 100 km in the Fram Strait area and in the central Arctic and increases eastward to reach 40 km in the zonal direction in the Kara Sea. All model boundaries are treated as closed boundaries. On the southern boundary in the North Atlantic sector the temperature and salinity fields are restored to climatology.

The model has been forced by daily atmospheric forcing fields from the period 1993–98 extracted from the 40-year NCEP reanalysis (Kalnay et al. 1996). The forcing fields are surface

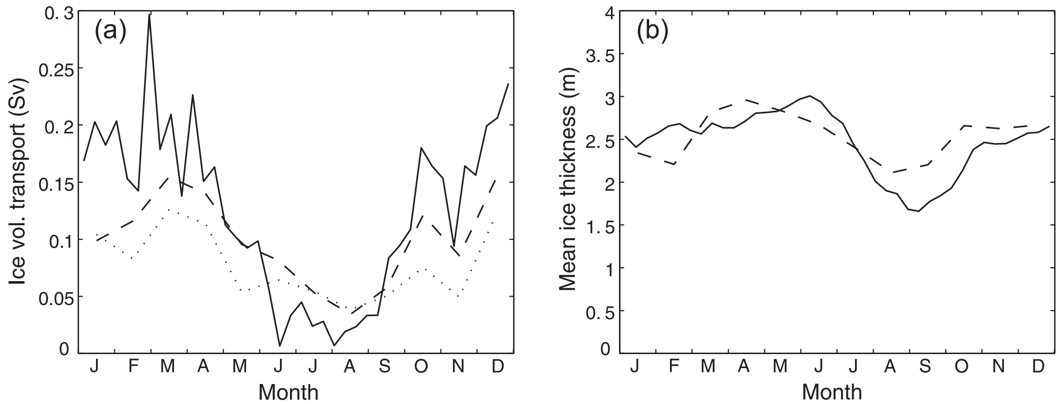

Fig. 1. Mean annual cycle of the Fram Strait (a) ice volume transport and (b) mean ice thickness estimated from the model run (1993–98) (solid line) and from Vinje et al.'s (1998) observations (1993 to July 1996) (dashed line). Also shown in (a) are Kwok & Rothrock's (1999) transport estimates (dotted line).

wind stress, air temperature, specific humidity, pressure and wind speed together with incoming longwave and shortwave radiation. Since the shortwave radiation was revealed to be unrealistically large, it was modified by adding a correction based on the difference between this field and the corresponding field in the European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis (ERA15). Because only the year 1993 was available in the ECMWF data set, the correction was calculated for this particular year and applied identically to the five other years of our NCEP forcing. The model is initialized from rest with ocean temperature and salinity distributions from the PHC global ocean climatology (Steele et al. 2001). The sea ice–ocean coupled system is first spun up for 20 years with a repeated mean annual cycle of the forcing based on the 1993–98 climatology. The model is then run in the interannual mode using the 6-year time series of the forcing fields.

Fram Strait ice export variability during 1993–98

Figure 1a shows the mean annual cycle of the ice volume transport through Fram Strait as estimated from 9-day averages of the model transport. The section runs parallel to a meridian of the model grid, approximately from 16° W, 78.5° N to 12.5° E, 80° N. There is a strong seasonal cycle in the transport with a minimum monthly mean of 0.03 Sv occurring in July and a maximum of 0.23 Sv in March. The winter maximum has, in fact, a two-peak structure with a secondary maximum occurring in December as a result of the weakening of the transport in February. Over the period 1993–96 overlapping with Vinje et al. (1998), the overall structure of the model annual cycle bears a strong resemblance with the data, although the model shows less weakening of the transport in January and a more rapid decrease of the transport in June–July. The amplitude of the annual cycle is also larger in the model due to higher winter values, especially when considering Kwok & Rothrock's (1999) estimates. The model 6-year mean transport of 0.12 Sv is therefore overestimated when compared with the 0.09 Sv (1 Sv = 0.317×10^5 km^3 yr^1) of Vinje et al. (1998) or with the 0.075 Sv of Kwok & Rothrock (1999), both calculated over a slightly different period (1990–96). The model transport estimate falls in the upper limit of previous model estimates obtained in different periods (e.g. Harder et al. 1998; Hilmer et al. 1998).

The transport shows considerable variability at time scales from weeks to years (Fig. 2a). Year-to-year transport variations, obtained after removing the mean annual cycle, exhibit very similar time evolution and magnitude as compared with the data. Over the overlapping 1993–96 years, significant correlations of 0.72 and 0.69 are found between the low-pass filtered (1 month running mean) model anomalies and the data estimates by Vinje et al. (1998) and Kwok & Rothrock (1999), respectively. All time series show a positive anomaly of the ice volume flux starting roughly in November 1994, culminating in January 1995 and persisting through the following

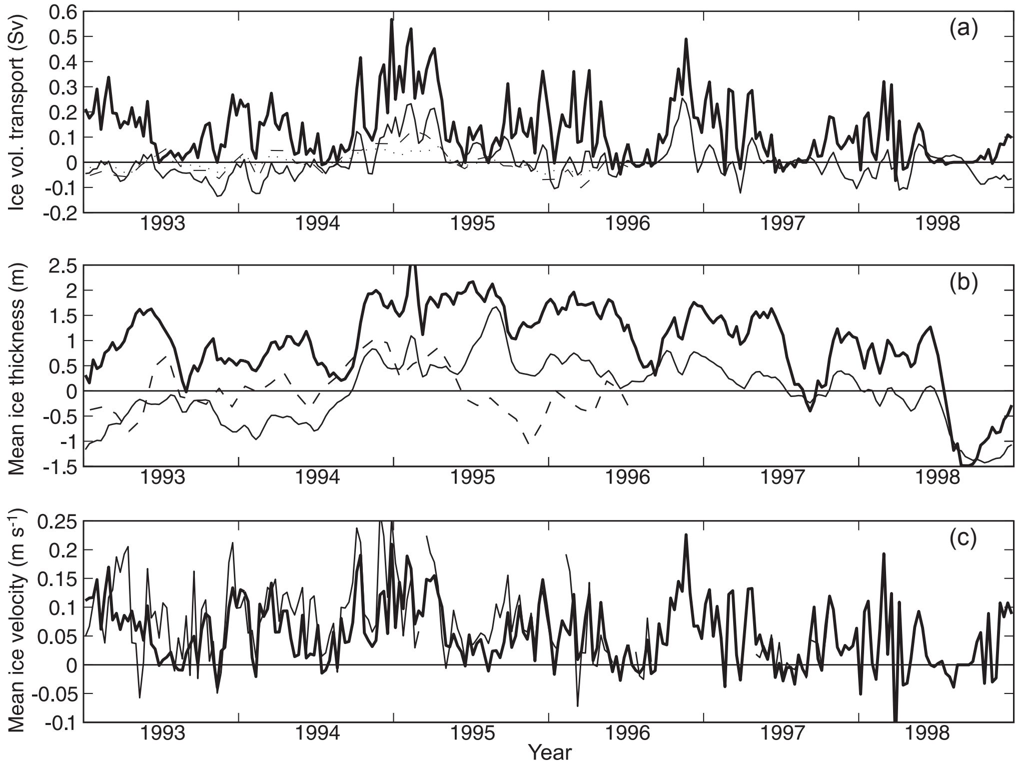

Fig. 2. Time series of the Fram Strait (a) ice volume transport and (b) mean ice thickness estimated from the model run (1993–98) (solid line) and from Vinje et al.'s (1998) observations (1993 to July 1996) (dashed line). Thick lines represent the raw time series of the model while light lines are anomalies with respect to the mean annual cycle. Also shown in (a) are Kwok & Rothrock's (1999) transport estimates (dotted line). (c) Raw time series of the mean ice velocity in Fram Strait for the model (thick line) and the IABP gridded velocities (1993–97) (thin line). Model anomalies have been low-pass filtered with a 1-month running mean. In (b) the scale of the raw time series is to be read on the right axis.

spring. The amplitude of the anomaly averages to 0.06 Sv over the duration of the anomaly, both in the model and in Vinje et al. (1998), but it is much smaller in Kwok & Rothrock (1999). Another positive anomaly occurs in late 1996, but its magnitude is only half of that in 1995, suggesting that the latter is indeed remarkable.

Over the 1993–96 period, the mean ice stream thickness in the strait is 2.71 m. For the same period, Vinje et al.'s (1998) draft measurements give a value of 2.84 m at 5° W, which corresponds to a strait averaged mean ice thickness of 2.54 m. Despite the mean thickness of the ice stream is a bit high in our simulation, its annual variations compare well with observations (Fig. 1b). The decrease in January is not as marked in the model as in the observations, nor are the ice thicknesses measured in summer as small as the simulated ones. The model year-to-year variations show some similarities with the data from January 1993 until the middle of 1995, with the most noticeable feature being the occurrence of a large thickness anomaly in winter 1994/95 (Fig. 2b). The details of the time evolution of the anomalies over that period however differ. In particular, the anomaly starts developing earlier in the data.

Since the width of the winter ice stream varies little from year to year in the model, it has little impact on the year-to-year variations of the ice volume flux. This has been checked by noting that the area flux (not shown) correlates extremely well with the variations of the ice export velocity. However, the width of the ice stream appears to be overestimated in the model and most probably explains the too high simulated winter transports. A possible reason might be that the cavitative fluid rheology, by neglecting shear stress along the Greenland coast, allows for overestimated off-shore component of the ice drift under the effect of the pressure gradient force. Despite an

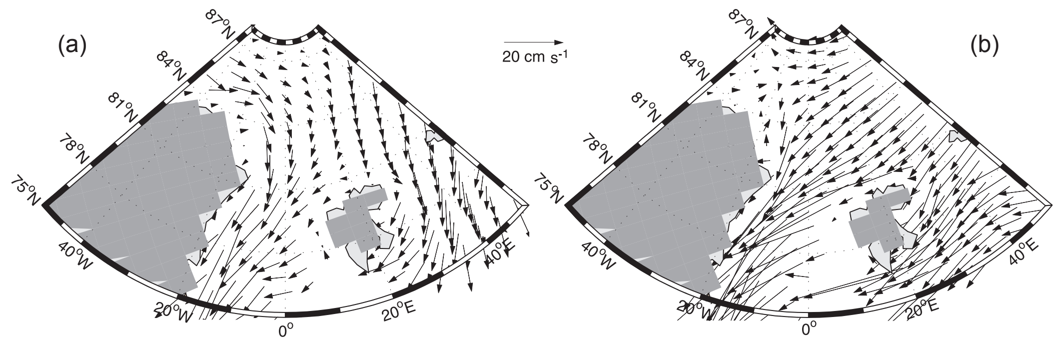

Fig. 3. Ice velocity in Fram Strait in (a) November 1994 and (b) January 1995.

expected discrepancy due to this rheology effect, the mean cross-strait velocity compares very well with IABP gridded buoy velocities (obtained from the Polar Science Center, University of Washington, http://iabp.apl.washington.edu) throughout the year (Fig. 2c). Still, the slightly different orientation (to the south-east) of the model section as compared with the data section (to the south) may hide part of the discrepancy. The winter 1995 event is associated with a strong anomaly of the export velocity which, as for the ice thickness anomaly, occurs earlier in the data than in the model. Note that the comparison covers only the 1993–97 period and that buoy velocities with the variance of the interpolated error greater than 0.5 have been excluded from the comparison.

In view of the above assessment of the model variability, we consider that the outstanding large ice export which occurred in Fram Strait in winter 1995 was indeed associated with the export of abnormally thick ice. In the next section, we analyse the ice thickness variability in order to determine the origin of the 1995 anomaly.

Origin of the winter 1995 thickness anomaly at Fram Strait

Averaged over the November 1994 to February 1995 period, the positive ice thickness anomaly in Fram Strait amounts to 71 cm, with a peak value of 130 cm in mid-February (Fig. 2b). The time evolution of the anomaly reveals two successive events of very thick ice, the first occurring in November and the second in February.

In Fram Strait, the patterns of the ice thickness variations are essentially governed by the advection field, except for the ice edge region where the thermodynamics also play a major role (not shown). The question is whether thickness anomalies in the strait should exclusively be attributed to changes in drift direction advecting the mean ice thickness field or if they should also be related to thickness anomalies formed upwind from the strait. The evolution of the 1994/95 thickness anomaly can partly be explained by changes in the dominant direction of the mean ice drift immediately north of the strait (Fig. 3) which bring ice of different origins into the strait. From the mean ice thickness distribution it can be deduced that, in November, the ice drift favours advection of thick ice coming from northern Greenland, while in December–January, advection from the north-east tends to bring thinner ice from the eastern Arctic. An intermediate situation predominates in February 1995, which is characterized by a strong northerly flow turning north-easterly to the east of the strait. Although such monthly reversals in the drift direction are not exceptional and have been reported in other studies, what makes the 1994/95 winter anomalous with regard to the ice drift are the high velocities associated with the reversal, as revealed by the multi-year velocity time series shown in Fig. 2c.

To identify the possible contribution of upstream ice thickness anomalies to the ice export variability, the distribution of these anomalies at the end of September 1994—that is just before the appearance of the anomaly in Fram Strait—is shown in Fig. 4a. The distribution is characterized by a well-developed positive feature which extends from the Beaufort Sea along the Canadian Archipelago down to the northern coast of Greenland. The feature is attributed to the strong convergence of the ice flux created by a persistent cyclonic circulation in the preceding summer

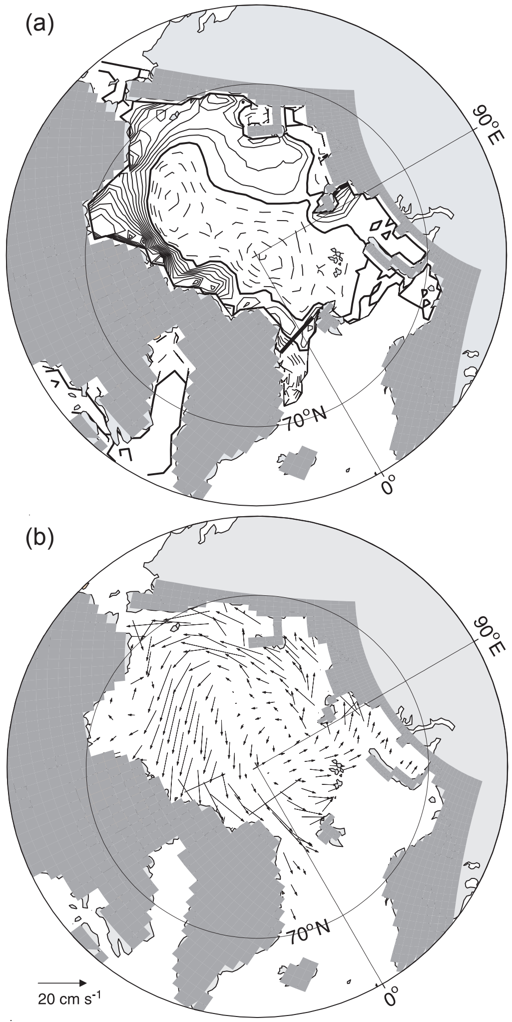

Fig. 4. Arctic (a) ice thickness anomaly (m) at the end of September 1994 and (b) ice velocity in August 1994. In (a) the anomaly is calculated with respect to the mean annual cycle and the contour increment is 0.25 m. Solid isolines indicate positive values; dashed isolines indicate negative values. The bold line is the isoline zero. Also shown in (a) is the model section which has been used for transport estimates in Fram Strait. The dark grey shaded area is the model domain.

(Fig. 4b). To check that this anomaly was indeed advected into Fram Strait and contributed to the thickness anomaly detected in the strait in November, a model experiment was performed in which the daily wind stress in summer (July–September) 1994 is replaced over the entire model domain by the wind stress from the mean annual cycle. Comparing Fig. 5a and c, the ice build-up appears to be greatly reduced to the north of Greenland, while the anomaly disappears in the strait from November through December, indicating that the latter likely originates in the anomalous ice thickness field formed in the western Arctic during the previous summer.

On the other hand, the reappearance of the anomaly in February (Fig. 5b), after the slow decrease in December–January, reflects the change in the drift direction by the end of January. The fact that the anomaly does not disappear entirely in the sensitivity experiment may indicate that some thick ice is being created to the north of the strait in December and January. Indeed, the strong easterly component of the ice velocity during these months (Fig. 3b) prevents ice from being exported to the Greenland Sea. Thick ice may also be advected from quite different regions of the Arctic without being too much affected by changes in the 1994 summer wind stress. The smaller thickness anomaly in the sensitivity experiment at that time (Fig. 5d), however, suggests that some effect of the wind stress change of the previous summer persists through the winter.

Discussion and concluding remarks

The above analysis suggests that large anomalies of the sea ice export through Fram Strait such as the 1994/95 event can be associated not only with large ice export velocities but also with the presence of abnormally thick ice. Several events, in which the contribution due to advection of thicker than usual ice dominates over that due to faster than usual export velocity, have also been identified by Arfeuille et al. (2000) in a model simulation over 1948–1998. In their study, however, the 1994/95 event was not associated with a concomitant thickness anomaly in the strait. This may be due to their model missing part of the ice thickness variability, perhaps for the same reasons it overestimates the mean annual ice export. In view of the good correlation between our model thickness time series and the observations by Vinje et al. (1998), we are somewhat confident that thick ice anomalies were indeed present in Fram Strait in winter 1995. The fact that the northerly wind stress correlates very well with the ice export at that time (see Fig. 3 in Arfeuille et al. 2000) is not contradictory with this idea but only indicates that the anomalous transport is also associated with a velocity anomaly when the ice flow gets

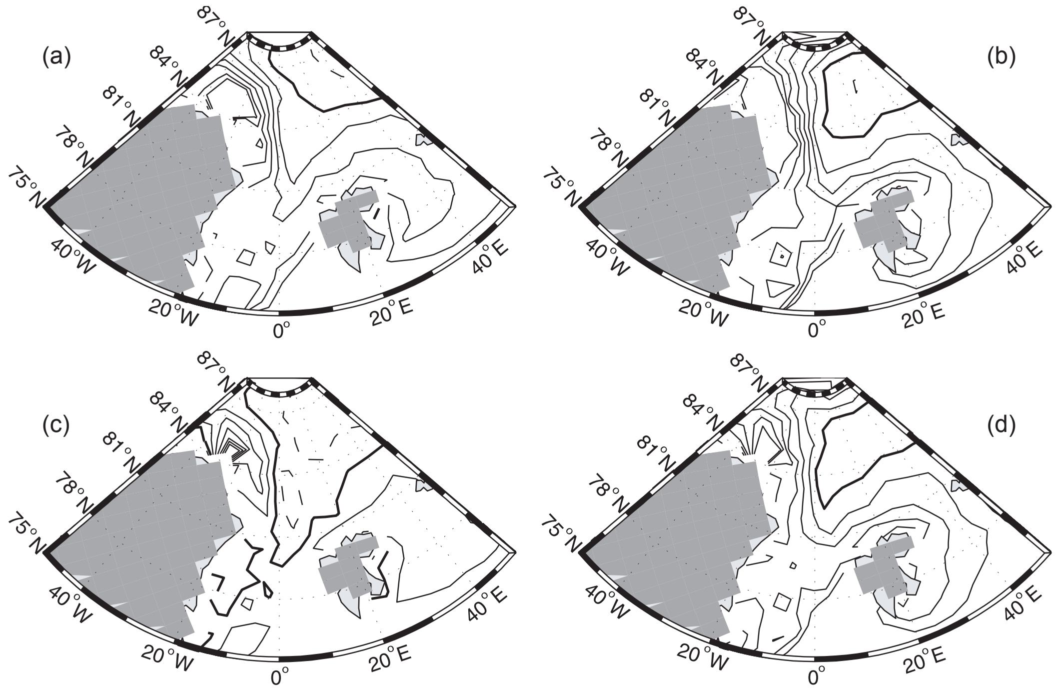

Fig. 5. Ice thickness change (m) in Fram Strait, taking the ice thickness distribution at the end of June 1994 as reference, in the reference experiment in (a) November 1994 and (b) February 1995, and in the sensitivity experiment in (c) November 1994 and (d) February 1995. The contour increment is 0.5 m.

aligned with the north–south strait axis.

Our analysis of the generation of the thickness anomaly observed in 1994/95 suggests that some thickness anomalies in Fram Strait may have a short history, being generated in the area north of Greenland by intra-annual variations of the surface wind stress and then advected towards Fram Strait in a few months. This scenario differs somewhat from those proposed in other studies (Tremblay & Mysak 1998; Mysak & Venegas 1998; Arfeuille et al. 2000) in which Fram Strait ice thickness or concentration anomalies were found to be generated in remote areas of the Arctic (the Beaufort and Chukchi seas or the East Siberian Sea). In these scenarios, the thickness anomalies get advected towards Fram Strait from their source region, clockwise around the Beaufort gyre and/or by the Transpolar Drift. The long time scales involved in these journeys imply that the anomalies must survive a few seasonal cycles before reaching Fram Strait, which may substantially alter their amplitude. In contrast, our simulation implies shorter advection time scales which minimizes the impact of seasonal thermodynamic processes and preserves most of the anomaly integrity.

The build-up of the thickness anomaly is initiated by the anomalous surface wind in summer 1994. The cyclonic wind stress curl anomaly, which first appears north of the Chukchi Sea in July, then gets stronger in August and moves to the North of Canada by the beginning of September. Such cyclonic anomalies are common features of the Arctic summer but the 1994 summer one appears to be particular in terms of strength and duration which altogether lead to anomalous ice motion field. The enhanced impact of summer (as compared with winter) anomalies of the wind stress on the Arctic ice thickness distribution has already been mentioned by Zhang & Hunke (2001) to explain winter anomalies of the ice growth rate in the Canada Basin. Although the impact in the present study is rather of a dynamical nature, the fact that the ice is more responsive to the atmospheric vorticity in summer certainly plays a role in our proposed scenario.

Fram Strait ice volume export anomalies such as the one which occured in winter 1994/95 are potentially very important for climate variability. Melting of the exported ice may impact on the ocean circulation via perturbations in the freshwater flux. This impact depends on the patterns of ice melting and therefore of the ice drift as the ice moves southward towards the Nordic and Labrador seas. The high southward drift speed in winter 1995 apparently favoured the export of most of the ice passing through Fram Strait towards Denmark Strait (e.g. Hilmer et al. 1998), limiting the input of freshwater to the Greenland Sea and inhibiting the Odden formation. In contrast, the Fram Strait ice export anomaly which occurred in 1968 and was assumed to be associated with the export of thicker ice from northern Greenland (Walsh & Chapman 1990) led to the formation of a wide freshwater signal known as the Great Salinity Anomaly. It is possible that other exports of thick ice, not necessarily associated with high drift speed or above normal pressure gradient in the strait, have led to freshwater anomalies in the past.

Due to lack of observations, we do not know the frequency of these Fram Strait ice export anomalies which are associated with thickness anomalies, and our simulation is too short to give insight into this aspect. The mechanism described above, which implies anomalous cyclonic atmospheric circulation in summer, may be linked to the particular period of the study which, according to Proshutinsky & Johnson (1997), corresponds to a cyclonic circulation regime. Venegas & Mysak (2000) recently suggested that time scales on the order of 16 - 20 years characterize Fram Strait ice thickness anomalies when they are associated with anomalous westerly winds north of Canada and Greenland. Other mechanisms, such as ice growth rate fluctuations in response to thermodynamic atmospheric forcing, may also lead to ice thickness anomalies with long characteristic time scales (L'Hévéder & Houssais 2001). This low-frequency variability is likely to impact on the variability of the Fram Strait ice export.

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