A link between Fram Strait sea ice export and atmospheric planetary wave phase

Donald J. Cavalieri

NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Received 7 January 2002; revised 2 February 2002; accepted 6 March 2002; published 29 June 2002.

[1] A link is found between the variability of Fram Strait sea ice export and the phase of zonal wave 1 in SLP for the period 1958–1997. Previous studies have found that the link between ice export through Fram Strait and the NAO is inconsistent over time scales longer than the last two decades. Inconsistent and low correlations are also found between Fram Strait ice export and the AO index. The phase of zonal wave 1 explains 60%–70% of the simulated ice export variance after the removal of two anomalous phases in 1966 and 1967. Unlike the NAO and AO links, these high variances are consistent for both the first and second halves of the 40-year period. This consistency is attributed to the sensitivity of wave-1 phase to the presence of secondary low pressure systems in the Barents Sea that serve to drive Arctic sea ice southward through Fram Strait. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4207 Oceanography: General: Arctic and Antarctic Oceanography; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620)

1. Introduction

[2] Arctic sea ice export through Fram Strait is an important climate parameter that serves to modulate the North Atlantic thermohaline circulation [*Mauritzen and Häkkinen*, 1997]. The link between the ice export through Fram Strait and the North Atlantic Oscillation (NAO) has received considerable attention recently [e.g., *Kwok and Rothrock*, 1999; *Dickson et al.*, 2000; *Hilmer and Jung*, 2000; *Jung and Hilmer*, 2001;*Vinje*, 2001], but the mechanism by which the atmosphere drives the ice export on time scales longer than the last two decades remains in question.

[3] Over a 5-year period, *Kwok and Rothrock* [1999] found a correlation of 0.56 between the volume flux of ice through Fram Strait and the winter NAO, while for the 20–year period 1976–1995, *Dickson et al.* [2000] found that the NAO explains about 60% of the variance in the Fram Strait ice flux, but they suspect that the high correlation breaks down for longer periods. On the other hand, *Hilmer and Jung* [2000] discovered no significant correlation between Arctic sea ice export and the NAO from 1958 to 1977, but for the period 1978–1997 the correlation increased to 0.7. Most recently, *Vinje* [2001] obtained a correlation of only 0.1 between the Fram Strait ice export and the NAO index from an analysis of a 50-year time series (1950–2000) of parameterized monthly ice volume flux through Fram Strait. *Hilmer and Jung* [2000] found the same low correlation for the 40-year period 1958–1997. Over the period 1976–1996, *Dickson et al.* [2000] obtained a correlation of 0.77 from parameterized ice volume flux. *Vinje* [2001] found a negative correlation of -0.32 for the period 1962–1978 and also discovered that only for certain periods is there a significant correlation between the NAO and the Arctic ice flux. *Vinje* [2001] sums up the situation by stating that recent

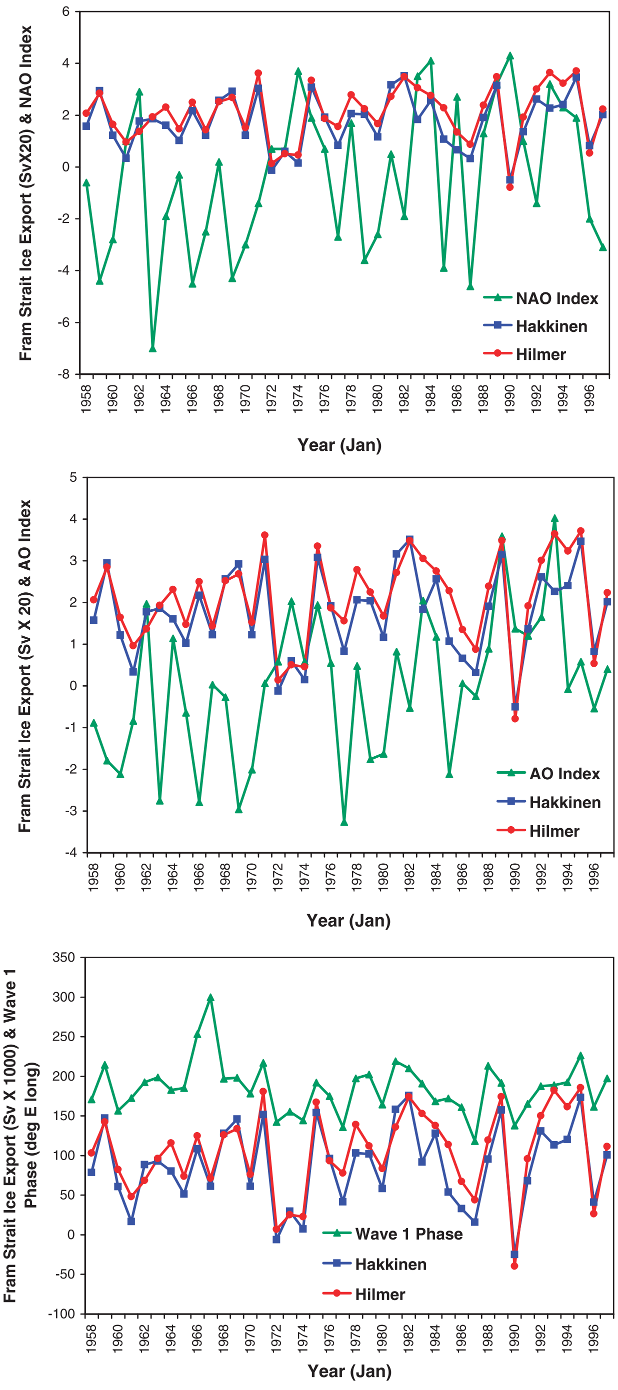

Figure 1. Time series of simulated January Fram Strait ice export from both the Häkkinen and Hilmer models with January NAO index (top), January AO index (middle), and January wave-1 phase (bottom) for the period 1958–1997.

0094-8276/02/2002GL014684$05.00

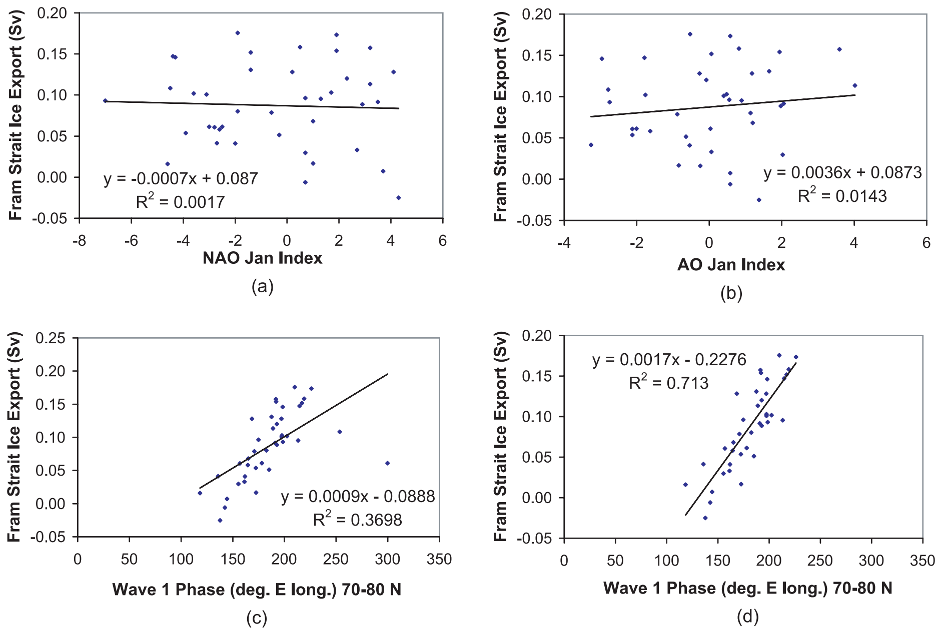

Figure 2. Scatter plots of the January Fram Strait ice export from the Häkkinen model for the years 1958–1997 versus (a) NAO January index, (b) AO January index, (c) wave-1 phase, and (d) wave-1 phase minus data for 1966 and 1967. Linear least squares fit and explained variance are provided for each plot.

observational and modeling studies provide evidence of an unstable link between the NAO and ice export through Fram Strait.

[4] In this study, comparisons are made between the January Fram Strait ice export and corresponding values for (a) the NAO index, (b) the Arctic Oscillation (AO) index, and (c) the phase of the longest planetary-scale SLP wave, zonal wave 1, for the period 1958–1997. Based on the results of these comparisons, we conclude that fluctuations in the phase of zonal wave 1 provide a

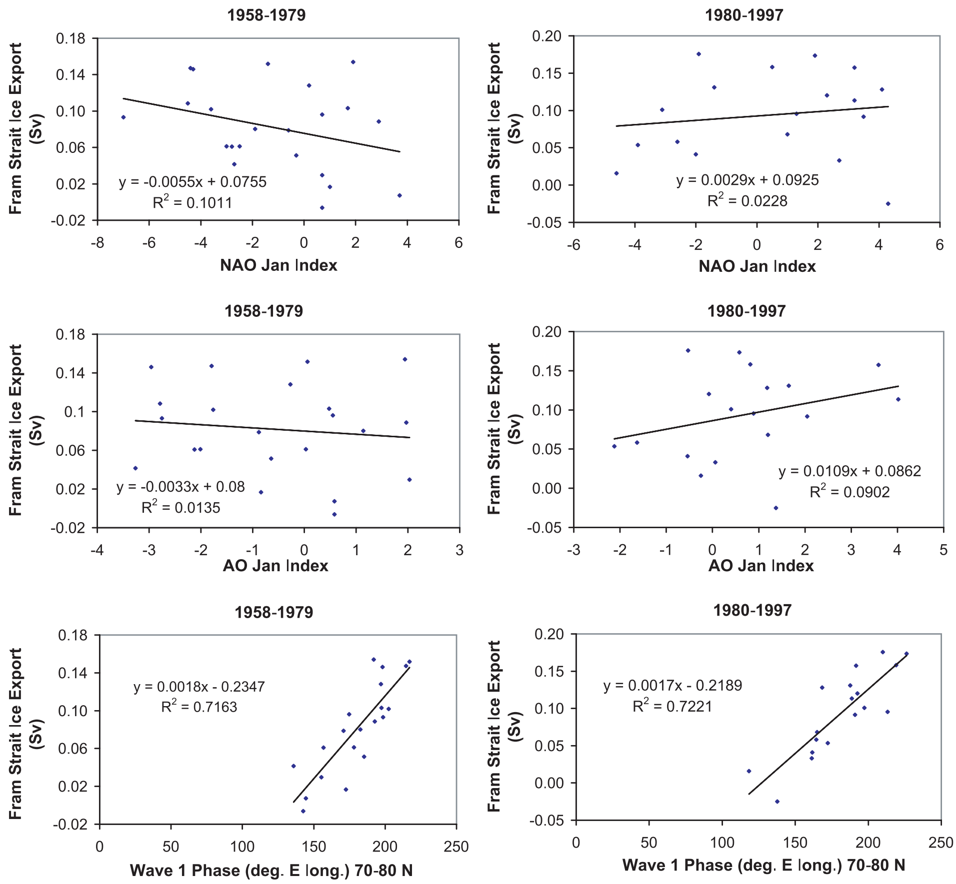

Figure 3. Scatter plots similar to those shown in Figure 2, but for the periods 1958–1979 and 1980–1997. The plots involving wave-1 phase data do not include data for 1966 and 1967.

Table 1. January Fram Strait Ice Export Variance Explained by the January NAO index, the January AO Index, and the January Wave-1 Phase Both for the Entire 40-Year Period and for the First and Second Half Periods From a Linear Regression Analysis

Period	NAO		AO		Wave 1 Phase	
	Häkkinen	Hilmer	Häkkinen	Hilmer	Häkkinen	Hilmer
1958 – 1979	0.10 (−0.32)	0.10 (−0.31)	0.01 (−0.12)	0.01 (−0.12)	0.72 (+0.85)	0.62 (+0.79)
1980 – 1997	0.02 (+0.15)	0.03 (+0.17)	0.09 (+0.30)	0.11 (+0.34)	0.72 (+0.85)	0.60 (+0.77)
1958 – 1997	0.0 (−0.04)	0.00 (0.00)	0.01 (+0.12)	0.03 (+0.18)	0.71 (+0.84)	0.59 (+0.77)

The phase values for years 1966 and 1967 were not included. Corresponding correlations are within parentheses. Results obtained using both the Häkkinen and Hilmer simulations are shown for each case. All wave-1 phase correlations are significant at better than the 0.01 level.

reasonable mechanism by which most of the Fram Strait ice flux variance can be explained over the 40-year period.

2. Results

[5] Simulated ice volume transport through Fram Strait was obtained for the 40-year period 1958–1997 from two dynamic-thermodynamic ice models. The reason for using simulations from two different ice models is to show that the results presented are not model specific. The first model is a coupled ice-ocean model forced by monthly surface wind and air temperature data derived from the NCEP/NCAR reanalysis project and is described by *Häkkinen and Geiger* [2000]. The second model is forced by daily surface wind and air temperature data also derived from the NCEP/NCAR reanalysis project [*Hilmer*, 2001]. Trenberth's Northern Hemisphere monthly sea level pressure (SLP) grids obtained from the NCAR website http://dss.ucar.edu/datasets/ds010.1/) were analyzed for the same 40-year period to obtain phase and amplitude information of the longest planetary-scale waves for the latitude band 70°N to 80°N following the procedure described by *Cavalieri and Häkkinen* [2001]. The monthly NAO indices were obtained from Jim Hurrell's website at NCAR (http://www.cgd.ucar.edu/~jhurrell/nao.html) and the monthly AO indices were obtained from the atmospheric science website at Colorado State University http://www.atmos.colostate.edu/ao/Data/ao_index.html). Comparisons are made for the month of January when the wintertime atmospheric circulation is well developed. This analysis will eventually be redone using more recent SLP data compilations (e.g., the NCEP reanalysis SLP product) and possibly with spatially and temporally varying indices [e.g., *Portis et al.*, 2001].

[6] Time series of the January Fram Strait simulated ice export from both models versus the January NAO index, the January AO index, and the January phase of zonal wave 1 for the 70°–80°N latitude band are shown in Figure 1. Examination of this figure shows that both the NAO and AO indices exhibit a negative correlation from 1958 until the mid 1970's when the correlation then becomes positive for the remainder of the period. In contrast, the association with the phase of wave 1 is positive for the entire 40-year period except for 1966 and 1967 when there was a rapid eastward shift in phase preceding the reduction in amplitude of the dominant wave 1 high-latitude circulation pattern [*Cavalieri and Häkkinen*, 2001]. Examination of Figure 1 also shows the high correlation between the ice export simulations from the two models. For this reason, the January Fram Strait ice export data shown in the scatter plots of Figure 2 are from the *Häkkinen and Geiger* [2000] model only. Figure 2 shows the Fram Strait ice export for 1958 – 1997 versus (a) the NAO index, (b) the AO index, (c) wave-1 phase, and (d) wave-1 phase without the inclusion of 1966 and 1967. The wave-1 phase for these two years appears to be anomalous and as mentioned previously preceded the breakdown of the high-latitude wave-1 atmospheric circulation in the mid 1960's [*Cavalieri and Häkkinen*, 2001]. The ice flux variance explained by the NAO index is 0.00 over this period, a result consistent with *Hilmer and Jung* [2000]. Similarly, the variance explained by the AO index is also insignificant, but the variance explained by the wave-1 phase at a latitude of 70° – 80°N is 37% and increases to 71% when the two anomalous years, 1966 and 1967, are removed.

[7] The 40-year period 1958–1997 is next divided into two halves to examine the consistency of the relatively high correlation between the Fram Strait ice export and the phase of wave 1. The results are shown in Figure 3. The correlations reverse sign for both the NAO and AO indices going from negative during the first period to positive for the second period, while the correlation involving the wave-1 phase is consistently positive. Table 1 provides a summary of the variances explained as well as the correlations for each index and the wave-1 phase for the entire 40-year period and for the first and second half periods. The results for both sets of simulated ice flux are included. The findings reveal generally small variances and correlations for the NAO and AO indices for the individual periods and even smaller overall correlations resulting from the change in signs between the two halves. The negative correlation between the simulated Fram Strait ice fluxes and the NAO index for the first half is −0.32 and −0.31 for the Häkkinen and Hilmer simulations respectively, in agreement with the negative correlation (−0.32) obtained by *Vinje* [2001] for the period 1962–1978. In contrast, the correlations obtained using the phase of wave 1 are consistently about 0.8 for both simulated ice flux data sets for all three time periods.

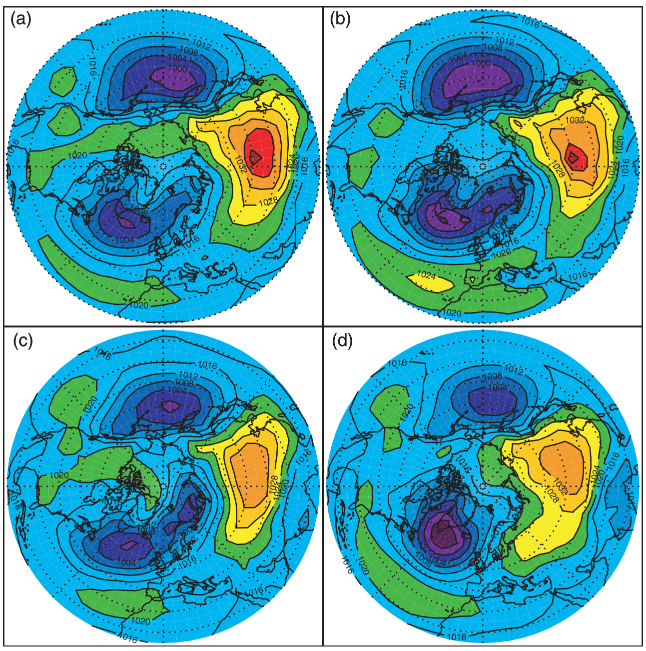

Figure 4. Mean January SLP maps for the years (a) 1958–1979, (b) 1980–1997, (c) when wave-1 phase is greater than the mean plus 1 standard deviation, and (d) when wave-1 phase is less than the mean minus 1 standard deviation. The contours range from 996 hPa (purple) to 1040 hPa (red) with an interval of 4 hPa.

3. Discussion

[8] A comparison of a 40-year record of simulated Fram Strait ice export with both the NAO and AO indices reveals poor correlations both for the overall period as well as for the first (1958–1979) and second (1980–1997) periods separately. The results for the NAO index agree with previously reported correlations [e.g., *Vinje*, 2001] and reasons for the poor correlations have been discussed previously by *Häkkinen and Geiger* [2000], *Jung and Hilmer* [2001], and *Vinje* [2001]. Mean SLP maps for the first and second periods are shown in Figures 4a and 4b, respectively. The mean SLP pattern for the second period (Figure 4b) is indicative of a high NAO pattern. This and the presence of a secondary low in the Norwegian Sea (the mean SLP in the region was 8 hPa lower on average than during the first period) explain the positive correlations for the second period. This result is consistent with the findings of *Jung and Hilmer* [2001]. They suggest that the positive correlations reported result from an eastward shift in the NAO's center of interannual variability during this period. They also suggest that this NAO pattern and the high correlation for 1978–1997 are unusual at least in the context of natural climate variability. In a study of the atmospheric variability over the Norwegian and Barents Seas and its relationship to the AO, *Skeie* [2000] defines a Barents Oscillation (BO) in terms of the second EOF of monthly winter SLP anomalies, but finds that the BO is not well correlated to the NAO index. On the other hand, *Tremblay* [2001] asks whether the BO is independent of the AO. Using a toy model of North Atlantic atmospheric variability, *Tremblay* [2001] finds that an EOF analysis decomposes a non-stationary process (in this case, the secular shift of the NAO pattern in the mid 1970's) into orthogonal modes; thus, the BO appears in his analysis "as a way to represent the non stationarity of the AO spatial pattern." In contrast, by using a zonal wave decomposition approach, the secular shift in the North Atlantic atmospheric circulation in the 1970's appears simply as a shift in the phase of the two longest planetary waves in SLP [*Cavalieri and Häkkinen*, 2001].

[9] The phase of wave 1 explains 60%–70% (correlation is about 0.8) of the simulated Fram Strait ice export variance. The variances and positive correlations are consistent for the first and second periods examined as well as for the entire 40-year period. This consistency is attributed to the variation of the wave-1 phase between two extreme modes [*Cavalieri and Häkkinen*, 2001]. The extreme eastward mode is shown in Figure 4c and is characterized by the extension of the Icelandic Low into the Barents Sea, whereas the extreme westward mode shown in Figure 4d is characterized by a deeper Icelandic Low that does not extend into the Barents Sea. The latter mode is somewhat similar to the positive NAO pattern. As discussed by *Cavalieri and Häkkinen* [2001] and also noted by others [*Häkkinen*, 1993; *Hilmer et al.*, 1998], the extension of low pressure into the Barents Sea provides the forcing for ice export through Fram Strait. The results presented show that the phase of zonal wave 1 at high latitudes is a highly consistent measure of this extension of low pressure into the Barents Sea and as such provides a useful index for monitoring ice export through Fram Strait.

[10] **Acknowledgments.** The author thanks both Sirpa Häkkinen and Michael Hilmer for supplying the simulated Fram Strait ice export data sets. Sirpa also provided many valuable suggestions during the preparation of this paper. Xiaoping Zhang and Alvaro Ivanoff provided programming and graphics support. The author also thanks two anonymous reviewers for their very helpful comments. This work was supported by the Cryospheric Sciences Research Program at NASA Headquarters.

References

Cavalieri, D. J., and S. Häkkinen, Arctic climate and atmospheric planetary waves, *Geophys. Res. Lett.*, *28*, 791–794, 2001.

Dickson, R. R., T. J. Osborn, J. W. Hurrell, J. Meincke, J. Blindheim, B. Adlandsvik, T. Vinje, G. Alekseev, and W. Maslowski, The Arctic Ocean response to the North Atlantic Oscillation, *J. Climate*, *13*, 2671–2696, 2000.

Häkkinen, S., An Arctic Source for the Great Salinity Anomaly: A Simulation of the Arctic Ice-Ocean System for 1955–1975, *J. Geophys. Res.*, *98*, 16,397–16,410, 1993.

Häkkinen, S., and C. A. Geiger, Simulated low-frequency modes of circulation in the Arctic Ocean, *J. Geophys. Res.*, *105*, 6549–6564, 2000.

Hilmer, M., A Model Study of Arctic Sea Ice Variability, Thesis, Institüt fur Meereskunde of the Christian-Albrechts-Universität Kiel, Germany, 2001.

Hilmer, M., and T. Jung, Evidence for a recent change in the link between the North Atlantic Oscillation and Arctic sea ice export, *Geophys. Res. Lett.*, *27*, 989–992, 2000.

Hilmer, M., M. Harder, and P. Lemke, Sea ice transport: A highly variable link between Arctic and North Atlantic, *Geophys. Res. Lett.*, *25*, 3359–3362, 1998.

Jung, T., and M. Hilmer, The link between the North Atlantic Oscillation and Arctic sea ice export through Fram Strait, *J. Climate*, *14*, 3932–3943, 2001.

Kwok, R., and D. A. Rothrock, Variability of Fram Strait ice flux and North Atlantic Oscillation, *J. Geophys. Res.*, *104*, 5177–5189, 1999.

Mauritzen, C., and S. Häkkinen, Sensitivity of thermohaline circulation to sea-ice forcing in an Arctic-North Atlantic model, *J. Geophys. Res.*, *24*, 3257–3260, 1997.

Skeie, P., Meridional flow variability over the Nordic seas in the Arctic Oscillation framework, *Geophys. Res. Lett.*, *27*, 2569–2572, 2000.

Tremblay, L. B., Can we consider the Arctic Oscillation independently from the Barents Oscillation?, *Geophys. Res. Lett.*, *28*, 4227–4230, 2001.

Portis, D. H., J. E. Walsh, M. El Hamly, and P. J. Lamb, Seasonality of the North Atlantic Oscillation, *J. Climate*, *14*, 2069–2078, 2001.

Vinje, T., Fram Strait ice fluxes and atmospheric circulation 1959–2000, *J. Climate*, *14*, 3508–3517, 2001.

D. J. Cavalieri, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.