Evidence for atmospheric control of sea-ice motion through Nares Strait

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[1] Satellite observations of ice motion are combined with model estimates of low-level winds and surface wind stress to provide evidence for atmospheric control of sea-ice motion through Nares Strait, between Ellesmere Island and Greenland, during two periods in 2004. The results suggest that ice flux through the strait, and its shutdown through the formation of a landfast ice mass in the strait, can be controlled by wind stress and atmospheric cooling. Analysis of the model results during these two periods also suggest that the intense, low-level, along-strait winds are strongly ageostrophic, and may be usefully estimated from pressure differences along the Strait. **Citation:** Samelson, R. M., T. Agnew, H. Melling, and A. Munchow (2006), Evidence for atmospheric control of sea-ice motion through Nares Strait, *Geophys. Res. Lett.*, *33*, L02506, doi:10.1029/2005GL025016.

1. Introduction

[2] The ice and freshwater balance in the Arctic Ocean has importance for the maintenance of perennial Arctic pack ice, a critical element of the global climate system. The general flow of seawater through the Arctic from Pacific to Atlantic brings sensible heat and freshwater (in the form of relatively fresh seawater) into the Arctic via Bering Strait and removes freshwater and sea ice from the Arctic via the channels of the Canadian Arctic Archipelago (CAA) and Fram Strait [*Melling*, 2000]. This general flow has been attributed to higher sea level (as much as 0.5 m) in the Pacific than the Atlantic [*Wijffels et al.*, 1992], which is in turn the steric manifestation of the lower salinity of Pacific surface waters. This low-frequency, hemispheric forcing is modulated by regional, time-dependent influences of comparable magnitude: changing wind-driven circulation of the Beaufort and Baffin gyres, seasonal steric anomalies associated with the freeze-thaw cycle, annual and semi-annual tides, and fluctuating atmospheric pressure gradients and along-channel winds.

[3] *Kwok et al.* [2004] and *Vinje* [2001] have studied the export of sea ice through Fram Strait, but little is known about the control on ice flux through Nares Strait (Figure 1), the main eastern channel of the CAA [*Melling*, 2000]. A sea-level drop across the CAA of 0.1–0.3 m [*Muench*, 1971] is likely the primary driver of the persistent flux of seawater and ice through Nares Strait into Baffin Bay. In narrow, high-latitude channels, the oceanic response is strongly constrained by the pack ice. In Nares Strait, high ice concentration and low ice temperature during the freezing season may be sufficient to halt ice drift, despite strong forcing. Pack ice often consolidates in winter behind an ice bridge near Smith Sound [*Agnew*, 1998]. Consolidation can occur any time between November and April, and may occur in stages, with bridges forming consecutively in Robeson and Kennedy Channels and Smith Sound, and collapsing a few weeks later or persisting as late as mid-August. Evidently, the land-fast ice regime of Nares Strait is near marginal stability in the present climate, between the permanent mobility of pack ice in Fram Strait and the more persistently static conditions in the western CAA.

[4] We hypothesize that local atmospheric forcing contributes to the intermittent instability of land-fast ice in Nares Strait. The purpose of this note is to provide direct support for this hypothesis, using model estimates of atmospheric forcing and satellite observations of ice motion. We focus here on periods in January–February and November–December 2004, which were chosen because of distinctive ice-motion events noted during ongoing continuous observation of Nares Strait. During these periods, extremes in atmospheric forcing are implicated in a reversal and in a cessation of ice drift in Nares Strait.

2. Observations and Model Configuration

2.1. Satellite Observations

[5] Advanced Microwave Scanning Radiometer (AMSR-E) data were obtained from the National Snow and Ice Data Center (NSIDC). Ice motion through Nares Strait was estimated using the daily averages of images acquired by the 89-GHz horizontally polarized radiometer on all descending orbits, projected onto a polar grid with 6.25-km pixel spacing. Because this resolution is coarse relative to the 40-km width of the narrower channels that comprise Nares Strait, ice motion was determined by tracking identifiable ice floes at 3 to 5 locations along the Strait from day to day. The main sources of uncertainty are the geolocation error of the images each day, and the tracking error for the floes in each image, each estimated to be half a pixel (roughly 3 km). Assuming these errors are independent and normally distributed yields a combined uncertainty in estimated ice drift speed of roughly 4 km d^{-1}. Higher resolution satellite-based synthetic aperture radar (e.g., Radarsat) data would be potentially useful to supplement the AMSR-E motion estimates

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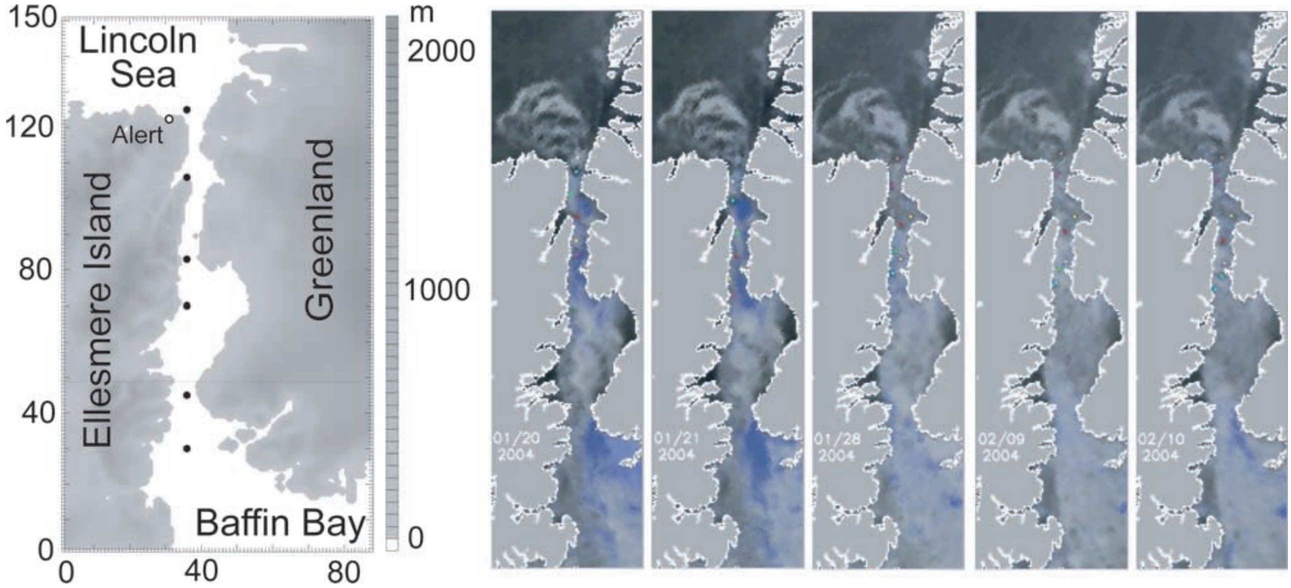

Figure 1. Left panel: Inner-nest atmospheric model domain (axis labels: grid-point numbers) and topography (grey shading). Locations of analyzed model time series, cited in the text by grid-point abscissa, are indicated (black dots). From north to south, Nares Strait is comprised of Robeson Channel (roughly grid points 110–125), Hall Basin (105–110), and Kennedy Channel (80–105). The domain also covers Kane Basin (50–80) and Smith Sound (30–50). Right panels: False-color AMSR/E satellite images of Nares Strait on (from left) 20, 21, 28 January and 9, 10 February 2004. Areas of ice cover (grey shading; darker color indicates thicker ice) and open water (blue), and features used for ice-motion estimates (colored dots) are indicated. From 20 to 21 January, Nares Strait ice moves roughly 60 km southward, and the North Water polynya on the east side of Smith Sound is open. From 28 January through 9 February, a period of weak or reversed wind forcing, the ice is nearly stationary. The North Water polynya, mostly closed during 28 January through 9 February, has begun to re-open on 10 February.

[*Kwok*, 2005], but were not available for the corresponding time periods at the time of this analysis.

2.2. Regional Atmospheric Model

[6] Continuous, long-term in-situ measurements of atmospheric forcing are not currently available in the remote and logistically challenging Nares Strait region. A regional mesoscale atmospheric model is instead being used to simulate local meteorological conditions during 2003–2007, as part of an on-going oceanographic observational program (A. Münchow et al., Observational estimates of volume and freshwater fluxes leaving the Arctic Ocean through Nares Strait, submitted to *Journal of Physical Oceanography*, 2005, hereinafter referred to as Münchow et al., submitted manuscript, 2005). The model used for these simulations is the Polar MM5 [*Bromwich et al.*, 2001] version of the Pennsylvania State University/National Center for Atmospheric Research MM5, a non-hydrostatic, primitive-equation, terrain-following model with full moist physics. The Polar MM5 is optimized for the polar environment and has been used successfully to simulate meteorological conditions in both polar regions [e.g., *Cassano et al.*, 2001; *Guo et al.*, 2003]. It is implemented here in a triply-nested configuration, with 54-km, 18-km, and 6-km grid resolutions in the outer, intermediate, and inner nests, respectively (Figure 1), and run in a daily 36-hr forecast mode. Initial and time-dependent outer boundary conditions are taken from the operational global National Center for Environmental Prediction AVN model. Hourly model fields from the simulations were concatenated into continuous time series, and analyzed at six grid locations in the channel (Figure 1). In the region of interest, radiational cooling and surface fluxes cause frequent development of a stable planetary boundary layer, in which wind direction and speed are strongly affected by the steep coastal orography. Mesoscale models nested in operational global atmospheric forecast models have previously been shown capable of reproducing observed low-level wind structure arising from the interaction of a stable lower atmosphere with coastal orography at mid-latitudes [e.g., *Perlin et al.*, 2004]. The regional model should reproduce similar effects in the Nares Strait region with similar accuracy. During each of the time periods considered below, the correlation of hourly model sea-level pressure at grid 125 (Figure 1) with hourly observed surface pressure at Alert, on the adjacent northern coast of Ellesmere Island, is 0.98. Verification of model performance in other regions of the domain is in progress and will be reported on elsewhere.

3. Ice Motion Events

3.1. January–February 2004

[7] Animations of satellite imagery revealed a brief reversal of the generally southward movement of ice in Nares Strait during several days in late January to early February 2004 (Figure 1). Model estimates of low-level winds and surface wind stress showed a simultaneous weakening and reversal of the prevailing southward (northerly) airflow. Average daily ice motions during 15 January to 15 February 2004 are well correlated with daily averages of modeled wind stress at grid-point 83 (Figure 2). From 15–22 January (day-of-year 15–22), the daily average stress was southward, with

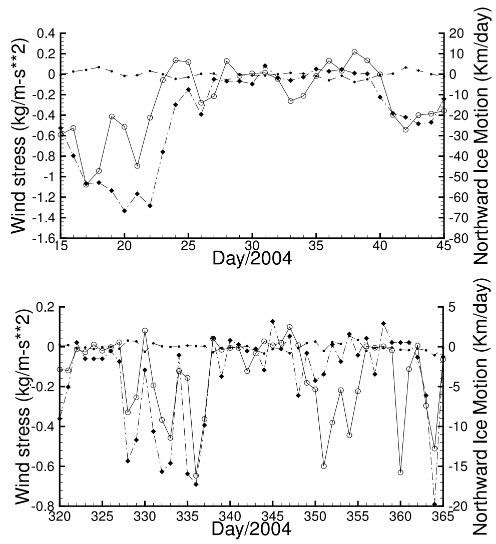

Figure 2. Daily averaged ice motion (solid diamonds) and grid-83 (see Figure 1 for location) along-strait (open circles) and cross-strait (solid circles) wind stress vs. year day during (upper panel) 15 January–15 February 2004 and (lower) 15 November–31 December 2004. The corresponding correlations of along-strait stress and ice motion are 0.77 and 0.54, respectively.

magnitude greater than 0.4 N m^{-2}. During this period, ice motion was southward at 30–70 km d^{-1}. From 24 January through 8 February (day-of-year 24–39), wind stress was less than 0.4 N m^{-2}, and positive (northward) roughly half the time. During this period, ice motion was less than 10 km d^{-1} southward on all but two days, and northward on 31 January and during 4–8 February. Strong southward winds developed again on 9 February (day-of-year 40) and southward ice motion resumed at roughly 40 km d^{-1}. The opening and closing of the North Water polynya on the east side of Smith Sound, and the fraction of open water within Nares Strait, which are both clearly visible in the satellite images, are also correlated with the wind stress (Figure 1).

3.2. November-December 2004

[8] In a typical year, ice becomes fast in Nares Strait in mid to late January. However, in 2004 satellite images revealed an unusually early freeze-up on 4 December. This event coincided with an interlude of weak atmospheric flow as simulated by the model (Figure 2): stress was less than 0.1 N m^{-2} for the 12-day period 4–15 December (day-of-year 338–349). Simultaneous sustained abnormally low temperatures of 240–245 K evidently facilitated complete freeze-up of the strait. The ice remained essentially stationary despite subsequent southward wind stresses of 0.4–0.6 N m^{-2} during 17–21 December (day-of-year 351–355) and on 27 December (day-of-year 361). The bridge across Smith Sound collapsed briefly on 30 December (day-of-year 364), permitting much of the ice in Kane Basin and Kennedy Channel to move about 50 km southward. However, the ice cover of Hall Basin and Robeson Channel remained fast. Continued monitoring via AMSR/E, Radarsat and other means revealed no further ice movement for the remainder of the winter. Ice movement re-commenced in Kennedy Channel in July.

[9] Numerical modeling [*Padman and Erofeeva*, 2004] and direct current observations (Münchow et al., submitted manuscript, 2005), which agree to better than 10% (Münchow et al., submitted manuscript, 2005), suggest strong tidal currents and large spatial gradients of tidal properties in Nares Strait. During spring tides, current amplitudes reach 0.4 m s^{-1} and semi-diurnal tidal excursions exceed 5 km, while neap-tide currents are less than 0.2 m s^{-1}. The neap tide, and weak tidal stress, on 6 December 2004 coincided with the low wind stress and high freezing rate to create optimal conditions for fast-ice formation. The temporary collapse of fast ice in the southern half of the channel on 30 December occurred shortly after the spring tide on 28 December. Tides increasing toward the spring phase may have prevented fast-ice formation in late January 2004, despite model air temperature was as low as in December 2004. The sensitivity of fast ice in the CAA to the spring-neap cycle of tides has been documented by *Topham et al.* [1983].

4. Ageostrophic Winds and Wind-Pressure Correlations

[10] The model along-strait wind and wind stress during the January-February and November-December 2004 periods discussed above are well correlated with the model sea-level pressure difference along Nares Strait between the Lincoln Sea and northern Baffin Bay, with correlations −0.96 and −0.92 during the first period and −0.88 and −0.84 during the second, respectively, and the signs consistent with flow from high to low pressure (Figure 3). This suggests that the low-level atmospheric jet and strong surface stresses arise from an ageostrophic response to orographic channeling of winds in the stable lower atmosphere, similar to that found in some midlatitude coastal marine regions [e.g., *Winant et al.*, 1988; *Samelson and Lentz*, 1994]. During both periods, daily-averaged model sea-level pressure differences from north to south along the Strait reached values as

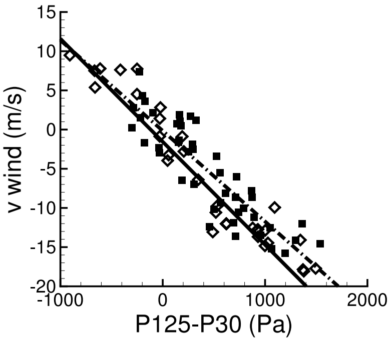

Figure 3. Daily averaged grid-83 (see Figure 1 for location) northward along-strait 10-m wind vs. north-to-south (grid-125 minus grid-30) sea-level pressure difference along Nares Strait during 15 January–15 February (open diamonds) and 15 November–31 December (solid squares) 2004. The corresponding linear regression lines (solid and dashed, respectively) $y = aG + b$, where y is wind speed and G is pressure difference, have $a = -0.013$ and $b = -0.72$, and $a = -0.011$ and $b = -0.30$, respectively.

large as 15 mb (Figure 3), and daily-averaged model wind stress reached values of 0.7–1.0 N m^{-2}.

[11] These results suggest that, in the absence of in-situ meteorological observations, it may be possible to obtain a useful estimate of along-channel winds and stress in the Strait from measurements of sea-level pressure at or near the north and south ends of the Strait. A more complete analysis of this correlation and the associated dynamics is in progress and, along with a two-year model climatology of winds in the Strait, will be presented elsewhere. If successful, a method based on this correlation would allow reconstruction of wind and stress time series in Nares Strait from historical pressure records, and provide a method for estimating Nares Strait winds from robust and relatively low-cost surface meteorological observations.

5. Summary

[12] Satellite observations of ice motion and model estimates of low-level winds and surface wind stress provide evidence for atmospheric control of sea-ice motion through Nares Strait, between Ellesmere Island and Greenland, during two periods in 2004. The results suggest that ice flux through the Strait, and its shutdown through the formation of a landfast ice mass in the strait, can both be controlled by wind stress and atmospheric cooling. Analysis of the model results during these two periods also suggest that the intense, low-level, along-strait winds are strongly ageostrophic, and may be usefully estimated from pressure differences along the Strait.

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