Sea ice drift and its relationship to altimetry-derived ocean currents in the Labrador Sea

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Received 10 February 2005; revised 4 May 2005; accepted 6 May 2005; published 11 June 2005.

[1] Low frequency sea ice drift variability and its oceanic and atmospheric forcing are investigated for the Labrador Sea over the period 1979–2002. Our objective is to separate the ocean forced component of ice drift in order to corroborate the changes in the subpolar gyre circulation found by Häkkinen and Rhines (2004). The atmospheric and oceanic forcing components can be approximately separated by comparing the time series resulting from an Empirical Orthogonal Function (EOF) analysis of sea ice motion with local sea level pressure gradients and altimetry-derived oceanic velocities. The first ice motion EOF is found to be associated with wind driven ice drift. The second mode is associated with oceanic forcing, because its time series is similar in its fluctuations to the oceanic velocities derived from altimetry. These two data sets confirm a major weakening of the subpolar ocean circulation between the early 1990s and the latter 1990s.

Citation: Häkkinen, S., and D. J. Cavalieri (2005), Sea ice drift and its relationship to altimetry-derived ocean currents in the Labrador Sea, *Geophys. Res. Lett.*, *32*, L11609, doi:10.1029/2005GL022682.

1. Introduction

[2] High northern latitudes have witnessed a significant decrease in overall sea ice extent and ice thickness during our observational period 1979–2002 [e.g., *Cavalieri et al.*, 2003; *Yu et al.*, 2004]. There is, however, considerable variability within the Arctic sub-regions [*Parkinson and Cavalieri*, 2002]. In this study we focus on the Labrador Sea and its sea ice cover, which (jointly with the Baffin Bay ice cover) has shown a decrease over our study period, although the trend is not statistically significant [*Parkinson and Cavalieri*, 2002]. Besides the changes in the sea ice cover as deduced from satellite microwave radiometry, altimetry platforms like TOPEX/Poseidon and Jason-1 have provided a glimpse of the circulation changes at subpolar latitudes. The 1990s, in particular, showed a decline in the strength of the subpolar upper ocean circulation [*Han and Tang*, 2001; *Häkkinen and Rhines*, 2004]. The decline is difficult to explain by wind driven dynamics alone, so it has to involve large-scale oceanic circulation changes associated with stratification changes. As for the altimetry time series, unfortunately only fragmentary data from current meters are available to validate the altimetry-derived velocities. A goal of this study is to demonstrate the utility of sea ice drift data from the Labrador shelf to complement the open ocean currents derived from the discontinuous altimetry record.

[3] Here we analyze both the altimetry derived ocean currents (NASA Pathfinder Dataset) and sea ice motion data derived from satellite and in situ data sets [*Fowler*, 2003]. The only driving forces for sea ice drift are winds and ocean currents, thus there is a possibility to extract ocean current information from ice drift. We will show that in the Labrador Sea the ice drift can be divided approximately into atmosphere-driven and ocean-driven components. This task will be accomplished by applying EOF analysis to the sea ice motion and altimetry data sets. Links to atmospheric forcing are drawn by using geostrophic wind speed computed from sea level pressure fields. Ties to oceanic forcing are developed from comparisons with altimetric ocean currents and with iceberg drift.

2. Data Sets

[4] The sea ice motion data set used here was developed by *Fowler* [2003] and is available on a 25 km grid from the National Snow and Ice Data Center. The ice motion is derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR), the Nimbus 7 Scanning Multichannel Microwave Radiometer (SMMR), the DMSP Special Sensor Microwave/Imager (SSM/I), and the International Arctic Buoy Programme (IABP) buoy data sets using cross-correlation techniques for the period November 1978 to March 2003. The maximum ice cover in the Labrador Sea is reached in late winter, so to maximize the number of grid points with drift data and to suppress high frequency variability, ice velocities were averaged from February to April retaining only grid points which had a non-zero ice velocity every year during those 3 months for the period 1979 to 2002. The mean February–April drift was removed before the EOF analysis. Another data set that provides potential insight into the changes in ocean circulation is the iceberg count crossing the 48°N latitude. This data set is maintained by the International Ice Patrol (http://www.uscg.mil/lantarea/iip/home.html).

[5] The ocean currents are computed based on the geostrophic balance from sea surface heights measured by altimeters. The altimetry data consist of the archived one-degree resolution TOPEX/Poseidon data, which have been combined with ERS-1/2 data to form the NASA Pathfinder data set. The Pathfinder data set also includes Seasat and Geosat data, which are referenced to TOPEX. The accuracy of the TOPEX/Poseidon altimeter is about 4 cm, whereas the Seasat and Geosat accuracies are of the order of 10 cm or more. Jason-1 data, which were processed similarly to the Pathfinder data set, were appended to the Pathfinder time

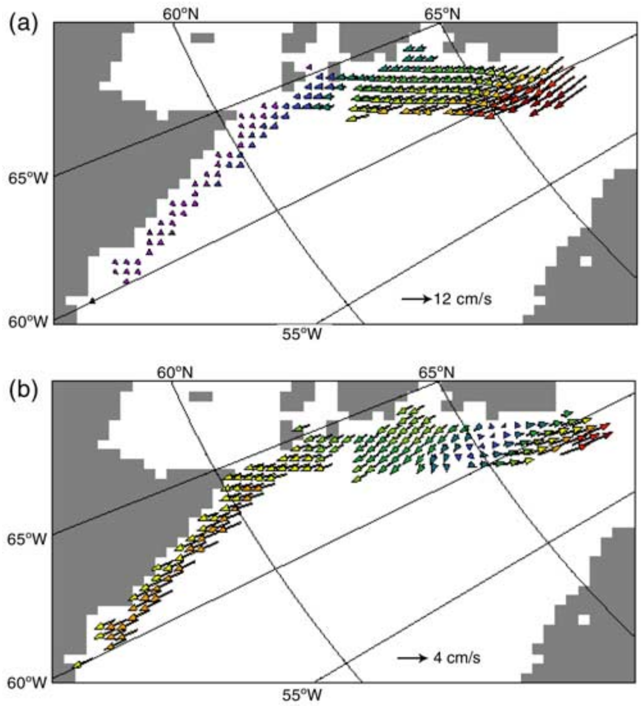

Figure 1. The (a) first and (b) second sea ice motion vector EOF. Colors indicate strength of each vector.

series by blending the two time series over the 7 month period January 2002–July 2002.

3. Results

[6] The interpretation of the Labrador Sea ice drift variability benefits greatly from simplifications in sea ice dynamic balance which, in general, is determined by the wind stress, the ice-ocean interfacial stress, Coriolis, and dissipative forces. The Labrador Sea ice cover is composed mostly of thin first-year ice with large fractions of new and young ice which are associated with weak internal stresses. Also the mean Labrador Sea ice drift is directed towards open ocean and not significantly hampered by land boundaries, thus the oceanic and atmospheric interfacial stresses are the primary forces. Often this type of ice motion is called 'free drift' where equilibrium ice motion can be solved from a simple balance between wind and ocean stress neglecting the Coriolis term (which is an order of magnitude smaller than the interfacial stresses; this balance is achieved within a few hours from initiation of a wind event):

$$\rho_a \, C_{ai} \, W^2 = \rho_w \, C_{wi} (u - ui)^2,$$

(ρ_a and ρ_w density of air and water; C_{ai} and C_{wi} interfacial drag coefficients; W wind speed; u and ui are ocean and ice velocities). The expression for ice velocity can be solved to be:

$$ui = u + W\sqrt{(\rho_a \, C_{ai}/\rho_w \, C_{wi})},$$

which demonstrates the division of atmospheric and oceanic forcing for the simple free drift case. Typical values of $C_{ai} = 1.5 \; 10^{-3}$ and $C_{wi} = 5 \; 10^{-3}$ give ui = u + 2% W. For moderate wind speeds of 7–10 m/s, the wind driven component of ice drift is often larger than the ocean current component (a few cm/s).

[7] With this simplification in mind, we use the EOF analysis to identify the two components of the free drift. The EOF analysis of the February–April ice drift vector fields results in two modes containing more than 90% of the total variance: 85 % and 8.3% for the first and the second modes respectively. We note that EOF analysis using a scalar ice drift gives a similar distribution of variance between the modes (88% and 8.2% respectively) (spatial patterns of scalar modes are not shown but they reflect the amplitudes of the vector modes). Also the principal components (PC's) of the scalar drift speed are nearly identical to the principal components of the vector field. The first mode describes a unidirectional movement of the Labrador Sea/Davis Strait ice field (Figure 1a) while the second mode (Figure 1b) captures opposing ice motions between the Davis Strait region and the rest of the Labrador Sea. The first mode has the largest amplitude in the very northern part of the study region, with greatly reduced amplitude south of 62°N. The first EOF mode of the ice motion is shown to be the atmosphere-driven component.

4. Discussion

[12] We have investigated Labrador Sea ice motion for the last 24 years derived from satellite data sets by *Fowler* [2003]. The accuracy of the Labrador ice drift from satellite data is difficult to assess due to sparse in situ observations. However, we can capture the largest fluctuations by applying EOF analysis which selects dominant features, temporally and spatially, and thereby reduce the impact of inherent uncertainties in the ice motion analysis. Labrador Sea ice motion fields are shown to separate into atmospheric and oceanic driven parts using EOF analysis. Our analysis suggests that the wind driven ice drift in the Labrador Sea explains over 85% of the ice motion variance whereas about 8% can be explained by the ocean driven drift. Together they explain over 90% of the variance which confirms that the free-drift approximation provides a good estimate of sea ice motion in this region. The association of the first mode to wind forcing is based on an east-west SLP gradient over the analysis region. However, no straightforward connection to NAO or AO variability is detected. The ocean driven component of the sea ice drift is determined from comparison of the ice drift PC2 with the first altimetric velocity mode. The two time series contain similar broad features through almost three decades confirming the amplitude variations seen in the altimetric velocity record of *Häkkinen and Rhines* [2004]. Thus, the ice motion data provide an independent data source to support the ocean circulation changes seen from altimetry in the northern North Atlantic Ocean where long term (over decades) current meter data is lacking. Another independent data source is the iceberg count crossing 48°N latitude. Since 90% of iceberg mass is below sea level, it is fair to expect that the ocean currents would dominate the iceberg drift. This relationship can be hampered by the variations in the number of icebergs released from West Greenland. Despite this potential limitation, the iceberg count variability is similar to that observed in the oceanic component of the ice drift and to that of the altimetric velocity mode.