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Interannual variations in the opening date of the Prudhoe Bay shipping season: links to atmospheric and surface conditions

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ABSTRACT: This paper examines interannual variability in the opening date for the Prudhoe Bay shipping season (1953–2005), considers how variations in antecedent sea-ice and atmospheric conditions influence the opening date, and then develops a forecasting technique to predict whether the opening date will be early, normal, or late. Analysis of antecedent sea ice and atmospheric conditions indicates that there are significant differences in the Bering Sea ice cover as early as February in years preceding early *versus* late opening dates. In particular, prior to early opening years, the sea-ice cover in the southern Bering Sea is reduced in February, and as the season progresses, sea-ice concentrations in the central and northern Bering Sea remain lower in years preceding early opening dates. Analysis of accumulated freezing degree days (FDDs) also suggests that temperatures are warmer over a broad area, ranging from the Bering Sea through the Chukchi Sea and the Beaufort Sea, in winter and spring months preceding early opening dates. Although the warmer temperatures may be related to reductions in sea ice in the Bering Sea, our results suggest that 500 hPa flow patterns and sea level pressure (SLP) patterns play are a larger role in controlling accumulations of FDD in the Chukchi and Beaufort seas. Finally, an ordinal regression model is presented to forecast whether the opening date will be early, normal, or late. On the basis of April sea-ice concentrations and accumulated FDD, the model correctly forecasts the opening date class in 32 of the 53 years. Copyright © 2008 Royal Meteorological Society

KEY WORDS sea ice; climate change; shipping; Arctic climatology; remote sensing

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1. Introduction

There is considerable evidence that Arctic sea ice has undergone significant changes in the last few decades, including an increase in the length of the summer open-water season (Smith, 1998; Belchansky *et al.*, 2004). Projections of future sea-ice conditions consistently suggest a continued decline in sea-ice and a longer open-water season (Holland *et al.*, 2006; Zhang and Walsh, 2006), likely equating to increased opportunities for maritime shipping operations (Brigham and Ellis, 2004). Additionally, there is some evidence that ice conditions are already changing faster than previously expected (Stroeve *et al.*, 2007), with a new record low observed in 2007 (Comiso *et al.*, 2008; Stroeve *et al.*, 2008), as forecast before the summer by Drobot (2007). However, a reduction in sea ice might also be accompanied by greater interannual variability, at least in the early part of the 21st century (Atkinson *et al.*, 2006). The potential combination of increased maritime traffic and high-interannual variability in the ice cover will require national and regional governments to provide improved sea-ice information to maritime operators.

One of the main US areas of Arctic maritime shipping operations is along the coastal waters of the Alaskan North Slope. Since 1953, the opening date for the navigable ice season to Prudhoe Bay has been monitored by the US National Ice Center (NIC) and its predecessors. However, little research has examined interannual variability in the opening date, nor is there a clear picture of which environmental conditions drive interannual variability in the opening date. Yet such information is key to achieving a better understanding of how the shipping season may vary in the future and developing predictive models for the opening date.

Although research has not examined interannual variability in the opening date directly, considerable research has examined interactions between sea ice and environmental conditions. Within the Beaufort Sea, the general consensus is that low-frequency atmospheric variability, such as described by the Arctic Oscillation (AO), strongly influences ice conditions (Barnett, 1976, 1980; Maslanik *et al.*, 1999; Tucker *et al.*, 2001; Rigor *et al.*, 2002; Drobot and Maslanik, 2003; Rigor and Wallace, 2004). Near-surface temperatures and wind patterns are also associated with interannual variability in ice conditions

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Table I. Opening date statistics for Prudhoe Bay shipping season.

	Early year category	Normal year category	Late year category	All years
Number of years	18	20	15	53
Earliest opening date	196	210	222	196
Latest opening date	28	220	256[a]	256[a]
Average opening date	201	215	232	215
SD (days)	3.8	3.0	11.5	13.8

[a] excluding 1975, when there was no official opening or closing date

(Rogers, 1978; Drobot and Maslanik, 2003). Although these previous studies provide clues to how environmental conditions might influence interannual variations in the opening date, most of them examined sea-ice conditions averaged over large areas, or integrated sea-ice conditions over long time periods (i.e. months, seasons). As a result, it is not clear how well previous results will translate to an examination of the opening date. Therefore, the objectives of this paper are to examine interannual variability in the opening date of the Prudhoe Bay shipping season (Table I); assess how interannual variations in atmospheric and surface forcing conditions affect the opening date of the shipping season; and examine to what extent the opening date can be forecast several months in advance.

2. Data processing

The study period extends from 1953 through 2005, and the types of data used to define the opening date have varied over the 53-year period. Prior to 1972, the data were based mainly on available aerial reconnaissance. Beginning in 1972, data used to compute the shipping season are based on the NIC ice charts. Owing to improvements in remote sensing technology and changes in NIC policy, different methods have been used to examine the ice conditions since 1972, as discussed by Dedrick *et al.* (2001) and Partington *et al.* (2003). Beginning in 1979, the ice charts have relied heavily on satellite data, incorporating the scanning multichannel microwave radiometer (SMMR) (1978–1987), the advanced very high resolution radiometer (AVHRR) (1982–), the special sensor microwave imager (SSM/I) (1987–), the operational linescan system (OLS) (1992–); and RADARSAT (1995–). According to Partington *et al.* (2003), the NIC charts are '... possibly the most informative and reliable record of sea-ice conditions available across the Northern Hemisphere as a whole during the satellite era, almost certainly during summer when the passive microwave algorithms underestimate ice concentrations significantly.'

The NIC data provide opening date information every year except for 1975; as reported by Barnett (1976, 1980), ice conditions in 1975 were especially severe and the ice never left the coast. As a result, there is no official opening date for 1975. Given this, and that data used to generate the shipping metrics varied over time, we decided to classify the opening date into early, normal, or late opening dates based on the standardized opening date index value, which is a ratio of the open date in a given year minus the 1953 through 2005 mean open date, divided by the standard deviation in the open date over the 1953 through 2005 timeframe (1)

$$Std.Index = \frac{Opendate_{\text{year}} - Opendate_{\text{mean}(1953-2004)}}{Opendate_{\text{stdev}(1953-2004)}} \quad (1)$$

Early opening years incorporate all years where the standardized index is <-0.44, normal years occur when the standardized opening date ranges from -0.44 to 0.44, and late years occur with values >0.44. Additionally, 1975 is classified into the late years. Over the study period, there were 18 early, 20 normal, and 15 late opening years (Figure 1).

The linear trend from 1953 through 2005 (excluding 1975) is -2.47 days/decade (p-value $= 0.05$), suggesting that the opening date is almost 2 weeks earlier today in comparison with the 1950s. A closer examination of the opening dates (Figure 1) also provides some interesting contextual features. For example, the earliest opening dates occurred during two time frames: the 1950s to 1960s and since the mid-1990s. One of the key differences between these two eras is the years that were not early opening date cases. In the 1950s and 1960s, early years were mixed with very late years, as the opening date was in late August or September several times in the 1950s and 1960s (Figure 1). However, the opening date has not been later than the middle of August since the extreme conditions in 1975. Thus, two notable features of the opening date in the last 15 years are (1) a remarkable run of record or near-record early

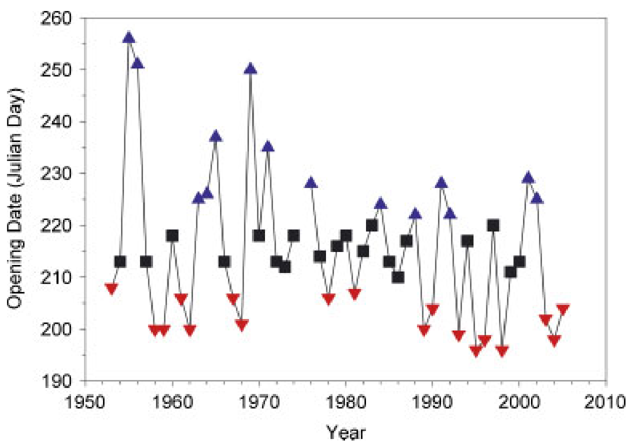

Figure 1. Interannual variability in the opening date for the Prudhoe Bay shipping season, 1953–2005. Each year is also coded into early (upside down triangle), normal (square), and late (triangle) opening seasons. In 1975 there was no official opening date. This figure is available in colour online at www.interscience.wiley.com/ijoc

opening dates and (2) a lack of extremely late opening dates.

To assess how environmental conditions influence the shipping season, mean monthly total sea-ice concentrations (CTs), accumulated freezing degree-days (FDDs), sea level pressures (SLP), and 500 hPa heights were investigated. Through 1996, the CT data are from the UK Meteorological Office HadISST 1.1 – global sea-ice coverage and sea surface temperature (SST) (1870 to the present) dataset, discussed in Rayner *et al.* (2003). The data are on a 360 × 180, 1° by 1° grid, and the CT data increment in 1% steps from 0 to 100%. Prior to 1997, the HadISST developers used the standard NASA Team algorithm for passive microwave data, but this data was not initially available after 1996 when the HadISST data set was being constructed. As noted by Stroeve *et al.* (2007), this led to a significant inconsistency pre- and post-1997. As a result, for CT data from 1997 onwards, we solely used the NASA Team algorithm to improve consistency in the data series. The other data are based on the NCAR/NCEP reanalysis (NNR). The base temperature to calculate the FDDs is set to −1.8 °C. Andreas and Ackley (1982) determined that melt of Arctic sea ice may initiate at a surface air temperature around −1.8 °C based on common relative humidity and radiation flux values for the Arctic in spring. For example, if the NNR surface temperature at a given pixel was −5.8 °C, then 4.0 FDDs would be accumulated. The annual FDDs are accumulated from 1 October of a given year through 30 April of the next year.

3. Environmental forcing conditions

Clues to whether the opening date will be classified as early, normal, or late are available several months preceding the actual opening date. Although there are no significant differences in the Bering Sea ice conditions in January (not shown), there is evidence to conclude sea-ice conditions in the southern Bering Sea have lower concentrations in February preceding early opening years and higher concentrations in years preceding later opening dates (Figure 2(a)). The hatch marks on the right-hand images in Figure 2(a) indicate locations where the difference between early and late years is significant (i.e. p-values less than 0.05) based on t-tests. Through April (Figure 2(b)), there is significantly less sea ice extending from west Bristol Bay into the Bering Sea prior to early opening dates. By June, the Bering Sea typically has little ice coverage, yet there is still significantly less sea-ice coverage in the Bering Strait, Chukchi Sea, and Beaufort Sea preceding early opening dates (Figure 2(c)). Overall, these results are consistent with previous research suggesting that antecedent ice conditions play a role in defining future ice conditions, and hence the opening date (e.g., Maslanik *et al.*, 1999; Tucker *et al.*, 2001; Drobot and Maslanik, 2003; Lindsay and Zhang, 2005).

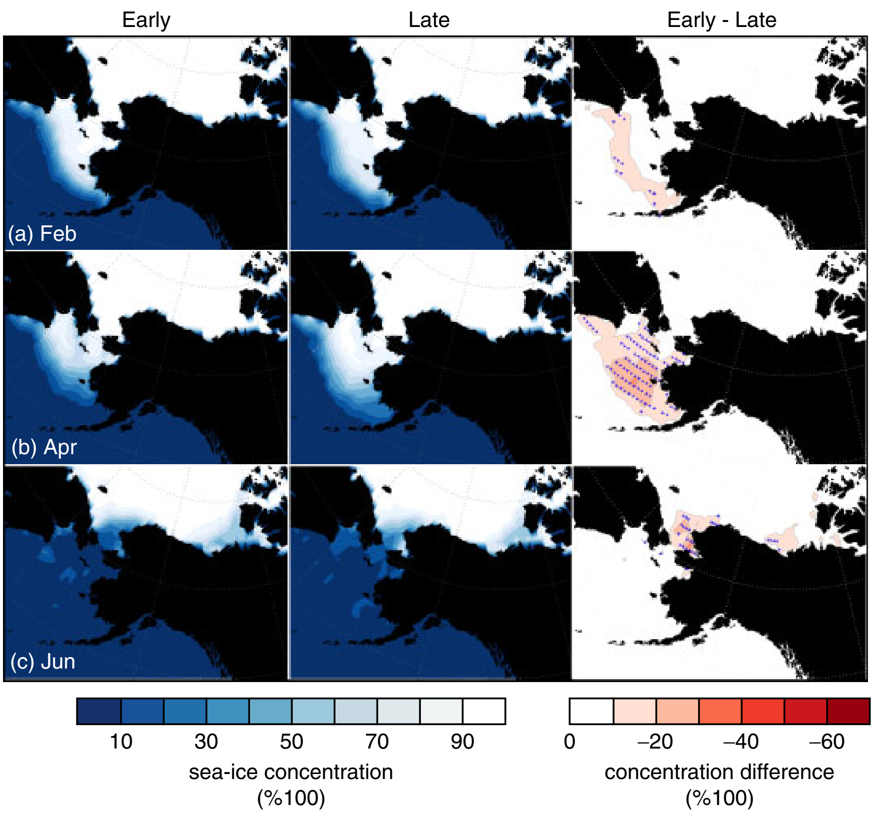

Figure 2. Composites of mean monthly sea ice conditions during early (left), late (middle), and early minus late (right) opening dates for (A) February; (B) April; and (C) June. Hatches on the right hand image indicate statistically significant differences between early and late years. This figure is available in colour online at www.interscience.wiley.com/ijoc

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The condition of the sea-ice cover is in turn related to near-surface temperature conditions. Early opening-date years with below-normal Bering Sea ice cover are associated with smaller accumulations of FDDs (i.e. warmer near-surface temperatures; Figure 3) over most of the study region. The difference in FDDs in the southern Bering Sea by February is likely related to a reduction in ice cover, through the ice-albedo feedback mechanism discussed in Curry *et al*. (1995). However, of particular interest is the difference in FDDs between early and late composites in the Beaufort Sea by February, exceeding 375 FDDs (Figure 3(a)). With smaller accumulations of FDDs, the ice would not grow as thick, and therefore the reductions in FDDs preceding early opening dates 'pre-condition' the pack for more rapid loss of ice cover due to melt. By April, the greatest differences in FDDs are concentrated in two areas: the central Bering Sea, with composite differences of more than 375 FDDs, and a region just west of Barrow, AK, where differences exceed 525 FDDs (Figure 3(b)). Through the end of June, the area of the differences in FDDs composites becomes larger (Figure 3(c)). These FDDs composites highlight the importance of near-surface air temperatures within the Beaufort Sea on the opening date. Changes in the accumulations of FDDs at the ice margin would be associated with changes in the ice cover; however, temperatures further north within the ice pack also provide crucial hints as to whether the opening of the shipping season will be early, normal, or late.

Although the ice-albedo feedback mechanism partly explains the reduction in FDDs in the Bering Sea early in the year, the ice pack fully covers the Beaufort and Chukchi Seas at this time, and thus another explanation is needed to account for the large reduction in FDDs in these areas preceding early opening years. Analysis of atmospheric flow patterns provides a possible link. In years with early opening dates, the composite 500 hPa height flow pattern favours southerly flow, which would lead to warm-air advection and reductions in FDDs (Figure 4). In contrast, the composite 500 hPa pattern leading to late opening dates is associated with advection of air masses from Chukotka and the Russian ocean areas, which would promote colder air advection. In addition to the advection patterns, there are also some zones of significant height differences preceding early and late opening dates; higher heights suggest warmer air in the atmospheric column and are associated with earlier opening dates.

To complement the upper-atmosphere analysis, relationships between accumulated FDDs and larger-scale atmospheric circulation patterns were studied by correlating the accumulated FDDs at each grid cell with the frequency of dominant SLP patterns identified by Maslanik *et al*. (2007) using self-organizing maps (SOMs). In that study, SOM analysis was used to classify daily NNR SLP fields for the Arctic into 99 separate synoptic maps, using daily mean SLP data for 1948–2004. Those results also showed that the SOM patterns more closely matched

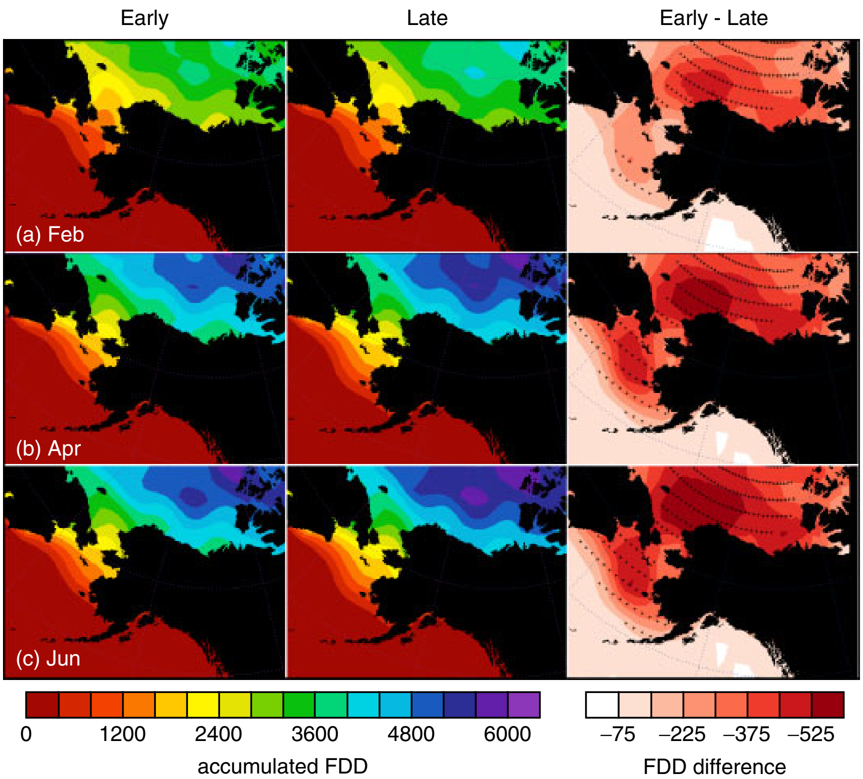

Figure 3. Composites of accumulated FDD conditions during early (left), late (middle), and early minus late (right) opening date years for (a) October through February accumulations; (b) October through April accumulations; and (c) October through June accumulations. Black hatches on the right-hand image indicate statistically significant differences between early and late years. This figure is available in colour online at www.interscience.wiley.com/ijoc

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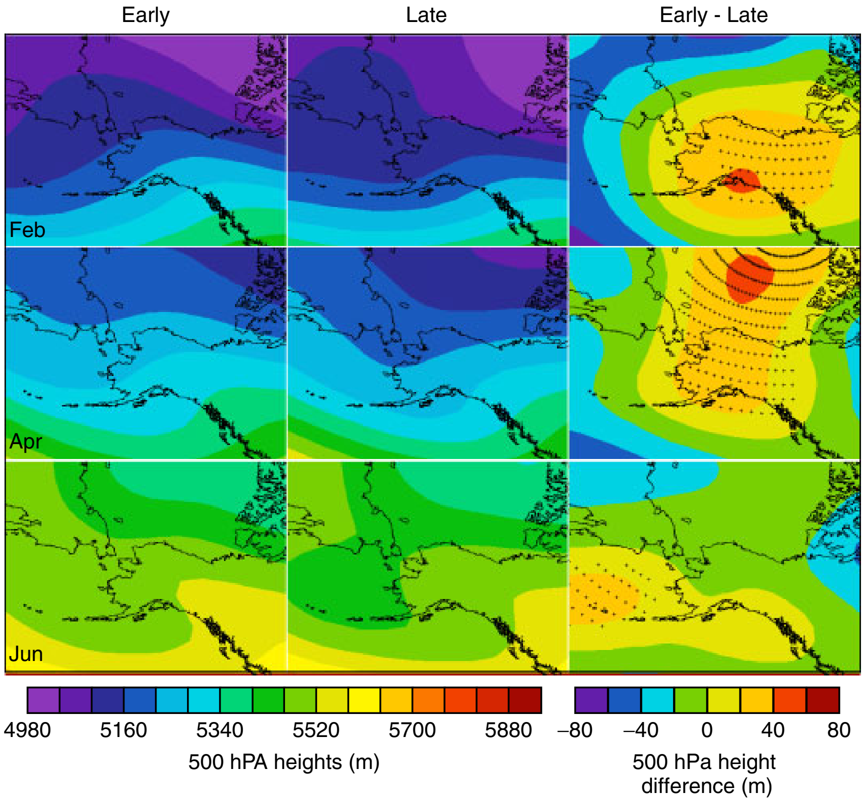

Figure 4. Composites of 500 hPa height patterns during early (left), late (middle), and early minus late (right) for February; April; and June. Black hatches on the right-hand image indicate statistically significant differences between early and late years. This figure is available in colour online at www.interscience.wiley.com/ijoc

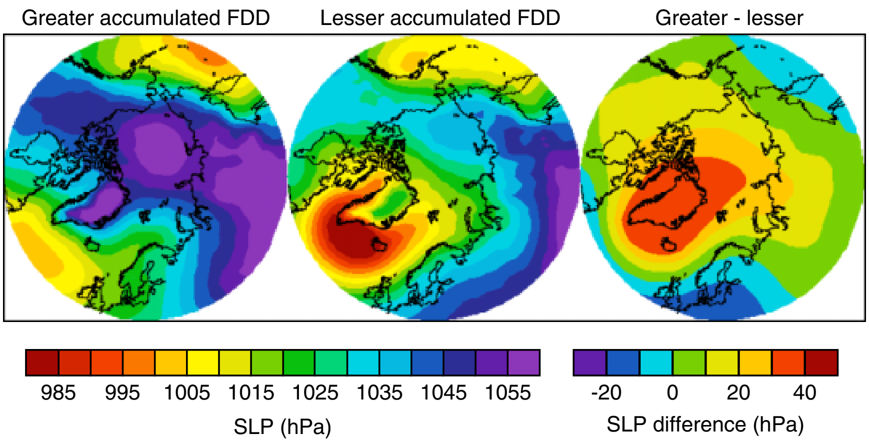

Figure 5. Composite SLP patterns of SOMs associated with greater (left) and lesser (middle) accumulated FDDs; the difference in SLP between the left and middle maps is shown on the right. This figure is available in colour online at www.interscience.wiley.com/ijoc

interannual variability in the western Arctic sea-ice cover than the more traditional AO/NAO approach, which is not well-correlated with sea-ice conditions in the last few years.

To investigate relationships between SLP patterns and FDDs, we performed a linear regression between the total annual FDDs and the frequency of occurrence of each of the 99 SOM SLP patterns for each of the years from 1982 through 2004, the time period of overlapping data. The resulting correlation maps indicate which SLP patterns correlate most closely with FDDs at each grid point. The most notable result from the regression analysis is that accumulated FDDs in the Beaufort Sea correlate with SOMs that show a general pattern of cyclonic and anti-cyclonic atmospheric circulation (Figure 5). The composite SLP of the SOMs that are related to above normal accumulations of FDDs in the Beaufort Sea demonstrate that enhanced FDD accumulations are linked to the formation of strong high-pressure cells in the Canadian Basin (Figure 5, left). Additionally, the high-pressure cell would promote northerly winds in the Beaufort Sea, which in turn would push ice against the north coast of Alaska. As a result, increased ridging and perennial ice close to the coast will likely work in combination

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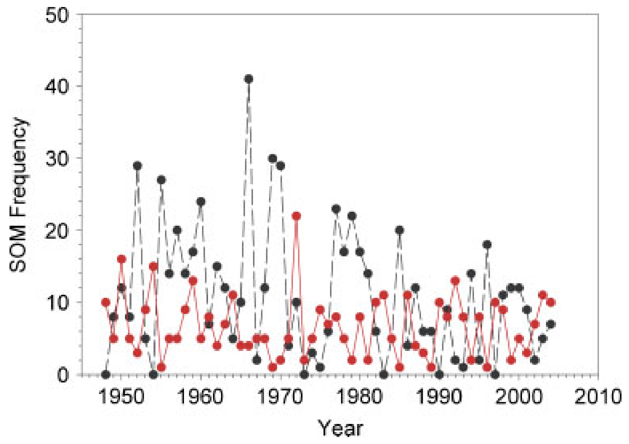

Figure 6. Time series of the frequency of occurrence of the SOM patterns associated with colder Beaufort Sea conditions (triangles) and warmer Beaufort Sea conditions (upside down triangles). There has been a drop in the occurrence of cold conditions since the 1960s. This figure is available in colour online at www.interscience.wiley.com/ijoc

with the colder temperatures to delay the opening date. These results are consistent with previous studies finding that anti-cyclonic atmospheric circulation in the Arctic is generally a cold pattern producing northerly winds in the Beaufort Sea (Barnett, 1980; Maslanik *et al*., 1999; Drobot and Maslanik, 2003). In contrast, composites of the SLP patterns associated with the below normal FDD accumulations indicate that small amounts of accumulated FDDs occur when the SLP pattern favours reduced frequency of northerly winds, with a greater influence of low pressure in the Gulf of Alaska (Figure 5, middle). These winds also promote advection of ice away from the coast, helping lead to an earlier opening date. The composite difference in the SLP fields indicates that FDD accumulations in the Beaufort Sea are greater when SLP is higher over much of the Arctic (Figure 5, right). The time series of the frequency of occurrence of the SOM patterns in Figure 6 for 1948–2004 (Figure 6) shows that the most prevalent change over time has been a decrease since the 1960s in the frequency of the anti-cyclonic, northerly wind SLP patterns discussed above that are well correlated with large FDD values (e.g., low temperatures in the study area).

4. Long-range forecasting of the opening date

The SLP and FDD results offer promise for the development of forecasting schemes using atmospheric and ice data available at the end of April. Because we classified the opening dates into three categories, which have a rank order, ordinal regression is an appropriate method for forecasting. The first step in developing an ordinal regression is to define our predictor (also termed independent or exogenous) variables. We therefore define the sea-ice data as the mean April sea ice area in the Bering Sea, since results from the preceding section noted that this was the region where large changes in ice conditions occurred before early and late opening dates (Figure 2). The accumulated FDD data are based on the mean accumulated FDDs over ocean pixels from the northern part of the Bering Sea into the Chukchi Sea, where the differences between early and late opening dates are greatest (Figure 3). For the SOM predictor, we simply use the frequency of occurrence of the SOM patterns, which is shown in Figure 6.

Results from the ordinal regression model indicate that two of the three predictors (sea ice and accumulated FDDs) are valuable in forecasting whether the opening date will be early, normal, or late (Table II). The SOM predictor was not significant, likely because variations in the SOM frequency correspond closely to changes in accumulated FDDs; in other words, the SOM frequencies did not provide enough unique information in addition to the other predictors to be retained. The overall model fit is significant ($\chi^2 = 20.41$; p-value <0.0001) and the goodness-of-fit ($\chi^2 = 105.94$; p-value $= 0.39$) indicates that the observed and expected cell counts are similar, and that we can reject the null hypothesis that the regression model is not fitting the observed data appropriately (note that for ordinal regression, good models have non-significant p-values for goodness-of-fit).

Using the ordinal regression equation, the correct class was predicted in 32 of the 53 years (i.e. 60% of the time; Table III). At no time did the model ever predict a late opening date when in actuality it was an early opening year, but there were four cases where an early predicted class turned out to be actually a late year. Nevertheless, these are reasonable results given the several month lead time, and overall, this scheme would provide stakeholders with some information on whether the upcoming season will open in early, normal, or late.

Table II. Ordinal regression results.

Predictor	Estimate	Std. error	Wald	df	p-value
Ice	0.76 ± 0.40	0.22	12.30	1	0.00
AFDD	0.40 ± 0.38	0.20	4.23	1	0.04

Table III. Classification matrix.

		Predicted class		
		Early	Normal	Late
Actual class	Early	11	6	0
	Normal	3	14	3
	Late	4	5	6

5. Summary and conclusions

As sea ice continues to decline, opportunities for shipping in the Arctic coastal waters should increase. However, some research indicates that reductions in sea ice will also

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be accompanied by increased variability in the ice cover. Therefore, to take advantage of potential long shipping seasons, and to prepare for shorter shipping seasons, studies examining whether antecedent ice and atmosphere conditions influence the opening date are needed, in order to assess predictive capabilities. Focussing on the Prudhoe Bay shipping season, results from this paper indicated:

- Linear trend analysis from 1953 through 2005 indicate that the opening date is about 2 weeks earlier now as compared to the start of the data record. Additionally, the opening dates in the last 15 years have shown a remarkable run of record or near-record early opening dates and a lack of extremely late opening dates.
- Clues as to whether the shipping season will be early, normal, or late are apparent in the spring ice cover, which is influenced by accumulated FDDs and atmospheric flow patterns. Variations in FDDs with the ice margin are expected, however, a key finding was that reductions in FDDs further north within the Beaufort Sea ice pack are also indicative of early opening dates.
- Interannual variations in the April Bering Sea ice area and the April accumulated FDDs in the Bering and Chukchi Seas are both significant predictors of the opening day class. Using these two predictors, the opening classes correctly predicted in 32 of the 53 years

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References

Andreas EL, Ackley SF. 1982. On the differences in ablation seasons of the Arctic and Antarctic sea ice. *Journal of the Atmospheric Sciences* **39**: 440–447.

Atkinson DE, Brown R, Alt B, Agnew T, Bourgeois J, Burgess M, Duguay C, Henry G, Jeffers S, Koerner R, Lewkowicz AG, McCourt S, Melling H, Sharp M, Smith M, Walker A, Wilson K, Wolfe S, Woo M-k, Young K. 2006. Canadian cryospheric response to an anomalous warm summer. *Atmosphere-Ocean* **44**: 347–375.

Barnett DG. 1976. *A Practical Method of Long-range Ice Forecasting for the North Coast of Alaska*. Technical Report to the Fleet Weather Center: Suitland, MD.

Barnett DG. 1980. A long-range ice forecasting method for the north coast of Alaska. In *Sea Ice Processes and Models*, Pritchard R (ed.). University of Washington Press: Seattle, WA.

Belchansky GI, Douglas DC, Platonov NG. 2004. Duration of the Arctic sea ice melt season: regional and interannual variability, 1979–2001. *Journal of Climate* **17**: 67–80.

Brigham L, Ellis B. 2004. *Arctic Marine Transport Workshop*. Institute of the North/Arctic Research Commission/International Arctic Science Committee: Anchorage, AK.

Comiso JC, Parkinson CL, Gersten R, Stock L. 2008. Accelerated decline in the Arctic Sea ice cover. *Geophysical Research Letters* **35**: L01703, DOI:10.1029/2007GL031972.

Curry JA, Schramm JL, Ebert EE. 1995. Sea Ice-Albedo climate feedback mechanism. *Journal of Climate* **8**: 240–247.

Dedrick K, Partington K, Van Woert M, Bertoia C, Benner D. 2001. U. S. National/Naval Ice Center digital sea ice data and climatology. *Canadian Journal of Remote Sensing* **27**: 457–475.

Drobot SD. 2007. A 92 chance of setting a new record minimum in 2007. Available at http://ccar.colorado.edu/arifs/.

Drobot SD, Maslanik JA. 2003. Interannual variability in summer Beaufort sea ice conditions: relationship to spring and summer surface and atmospheric variability. *Journal of Geophysical Research* **108**: 3233, DOI:10.1029/2002JC001537.

Holland MM, Bitz CM, Tremblay B. 2006. Future abrupt reductions in the summer Arctic sea ice. *Geophysical Research Letters* **33**: L23503, DOI:10.1029/2006GL028024.

Lindsay RW, Zhang J. 2005. The thinning of Arctic sea ice, 1988–2003: Have we reached the tipping point?. *Journal of Climate* **18**: 4879–4895.

Maslanik J, Drobot SD, Fowler C, Emery W, Barry R. 2007. On the Arctic climate paradox and the continuing role of atmospheric circulation in affecting sea ice conditions. *Geophysical Research Letters* **34**: L03711, DOI:10.1029/2006GL028269.

Maslanik JA, Serreze MC, Agnew T. 1999. On the record reduction in western Arctic sea-ice cover in 1998. *Geophysical Research Letters* **26**: 1905–1908.

Partington K, Flynn T, Lamb D, Bertoia C, Dedrick K. 2003. Late twentieth century Northern Hemisphere sea-ice record from U.S. National Ice Center ice charts. *Journal of Geophysical Research* **108**: 3343, DOI:10.1029/2002JC001623.

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research* **108**: 4407, DOI:10.1029/2002JD002670.

Rigor I, Wallace JM. 2004. Variations in the age of Arctic sea-ice and summer sea-ice extent. *Geophysical Research Letters* **31**: L09401, DOI:10.1029/2004GL019492.

Rigor IG, Wallace JM, Colony RL. 2002. Response of sea ice to the Arctic Oscillation. *Journal of Climate* **15**: 2648–2663.

Rogers JC. 1978. Meteorological factors affecting interannual variability of summertime ice extent in the Beaufort Sea. *Monthly Weather Review* **106**: 890–897.

Smith DM. 1998. Observation of perennial Arctic sea ice melt and freeze-up using passive microwave data. *Journal of Geophysical Research* **103**: 27,753–27,769.

Stroeve J, Holland MM, Meier W, Scambos T, Serreze M. 2007. Arctic sea ice decline: faster than forecast. *Geophysical Research Letters* **34**: L09501, DOI:10.1029/2007GL029703.

Stroeve J, Serreze M, Drobot S, Gearhead S, Holland M, Maslanik J, Meier W, Scambos T. 2008. Arctic sea ice extent plummets in 2007. *EOS-Transactions-American Geophysical Union* **89**: 13.

Tucker WB, Weatherly JW, Eppler DT, Farmer LD, Bentley DL. 2001. Evidence for rapid thinning of sea ice in the western Arctic Ocean at the end of the 1980s. *Geophysical Research Letters* **28**: 2851–2854.

Zhang X, Walsh JE. 2006. Toward a seasonally ice-covered Arctic Ocean: scenarios from the IPCC AR4 model simulations. *Journal of Climate* **19**: 1730–1747.