8.3 CAUSE AND EFFECT OF VARIATIONS IN WESTERN ARCTIC SNOW AND SEA ICE COVER

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1. INTRODUCTION

Recent decreases in snow and sea ice cover in the high northern latitudes are indicators of climate change. A radiative perturbation known as the "temperature-albedo feedback" is expected as temperatures rise, snow and ice melt, surface albedo decreases, and solar absorption at the surface increases. This process leads to accelerated warming. Previous studies have documented an advance in the annual date of snow disappearance in northern Alaska. Coincident anomalies over adjacent ocean regions (East Siberian, Chukchi, and Beaufort Seas; hereafter referred to as the western Arctic) suggest physical links between the disposition of sea ice and factors that affect the annual cycle of snow cover. To investigate, passive microwave (PMW) estimates of the onset and duration of the melt season over sea ice were compared with a record of snowmelt from Barrow, Alaska. Normalized Difference Vegetation Index (NDVI) imagery was used to further assess how representative the Barrow record was of other coastal land areas bordering the western Arctic.

2. BACKGROUND

2.1 *Trend Towards an Earlier Date of Snowmelt*

Stone et al. (2002) documented an advance in the date of snow disappearance (melt date) in spring at the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) Barrow Observatory (BRW). The BRW record was shown to be representative of Alaska's North Slope. Factors that influence spring snow melt were identified, and correlations among mechanisms were significant. Variations in melt date were attributable to changing atmospheric circulation patterns that affect the temperature regime of northern Alaska and perturb the radiative balance at the surface.

Figure 1 presents an updated analysis of the BRW melt date time series. Since 1940 the spring melt at BRW has advanced by about 10 days (+/- 4.7 d, 95% CI). Most of the advance occurred after 1976, however. The break in the record coincides with regime shifts in many other climatic as well as biological indicators of change (Hare and Mantua, 2000). Although 1999, 2000, and 2001 were years of moderately late snowmelt at BRW, 2002 was the earliest on record. The 2003 melt was again early, followed by a moderately early melt in 2004. These past three years, when combined with 1990, 1996 and 1998, are unprecedented in the 64-year record as being anomalously early events, and statistically drive the long-term trend. Variations in the annual snow cycle of northern Alaska are attributable, in large part, to changes in atmospheric circulation that involve intensification of the Aleutian Low (AL) in conjunction with fluctuations of the Beaufort Sea Anticyclone (BSA). On this basis, an empirical model was developed to predict melt dates at BRW. Results are shown as a dashed curve in Figure 1. About 75% of the variance in melt dates at BRW can be explained by changes in snowfall during winter, and variations in springtime temperatures and cloudiness (updated from Stone et al., 2002).

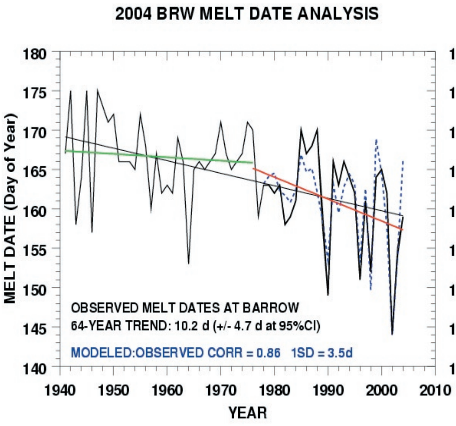

Figure 1. Time series of snow melt dates constructed for the NOAA/CMDL Barrow Observatory. Three linear regressions are plotted; an overall fit for 1941-2004 (thin black line), one for all years prior to 1977 (green), and a third beginning in 1977 (red). Results of an empirical model are also shown (dashed blue line). The time series was compiled from direct snow depth observations, proxy estimates using daily temperature records, and beginning in 1986 on the basis of surface radiometric measurements (updated from Stone et al., 2002).

2.2 *Diminishing Sea Ice in the Western Arctic Ocean*

Since the advent of satellite passive microwave radiometry (1978), variations in sea ice extent and concentration have been carefully monitored. An overall estimated 7.4% decrease in monthly sea ice extent has occurred in the last 25 years (Johannessen et al., 2004). Perennial (multiyear) sea ice has experienced the most

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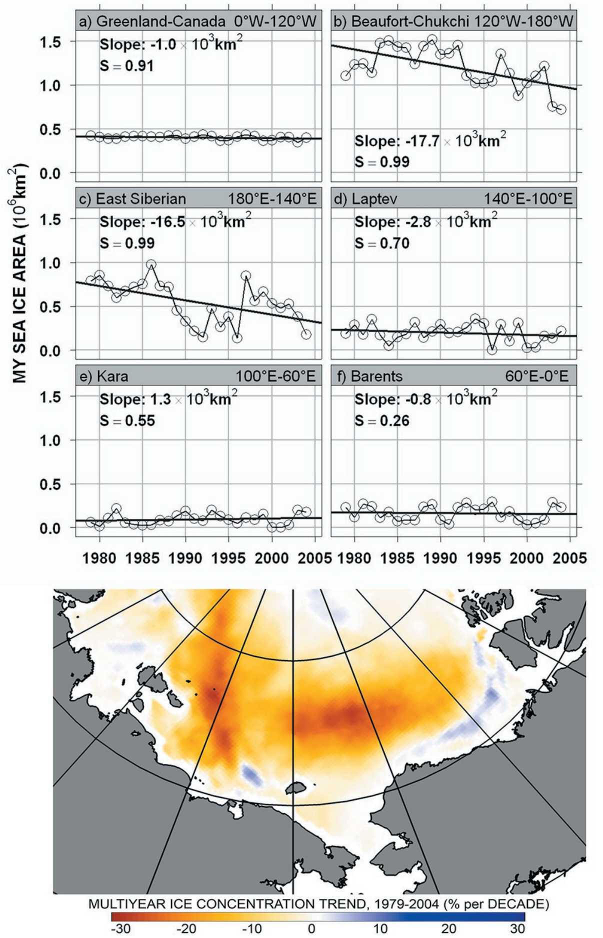

Figure 2. (top) Interannual changes and trends in January multiyear ice area within 6 longitudinal sectors of the Arctic Ocean (updated from Belchansky et al., 2004a); (bottom) 26-year (1979-2004) trend in January multiyear ice concentrations within the western Arctic.

pronounced decline (Comiso, 2002; Belchansky et al., 2004a), especially in the western Arctic (Figure 2). As in the case of the BRW snowmelt record, recent record minima have accounted for much of the decline (e.g., Maslanik et al., 1999; Serreze et al., 2003). Comparisons of time series of Arctic sea ice melt dynamics and snowmelt dates at BRW reveal intriguing correlations that are described below.

3. RELATIONSHIP OF MELT OVER SEA ICE AND ADJACENT LAND AREAS

Melt onset dates over sea ice (Belchansky et al., 2004b) were cross correlated with the melt date time series from BRW (Figure 3a). A relatively large region of high positive correlation (encircled) between melt onset over sea ice and the BRW record of melt dates is apparent. Much of this region also experiences longer melt duration when the snow melts early at BRW as evidenced in Figure 3b. These maps were produced by cross correlating the respective time series of individual 25 km x 25 km pixels of PMW-derived melt onset dates and melt duration with the BRW snowmelt record shown in Figure 1. While variations tend to be correlated, melt onset over sea ice has greater variability than melt dates at BRW, having standard deviations (SD) of about two weeks and one week, respectively. To visualize the respective data on a scale of equal variance, standardized anomalies [(data values - mean)/SD] were computed for each time series. Figure 4 demonstrates the results for a typical pixel within the region of highest correlation. In such an analysis, positive (negative) values represent late (early) events relative to mean conditions. Despite different levels of variance, anomalous events over the encircled region tend to be well-timed with those at BRW.

The area of prominent, high correlation between melt onset over ice and BRW melt date is approximately aligned with the climatological center of the BSA. When present, the BSA induces anticyclonic ice motion in the

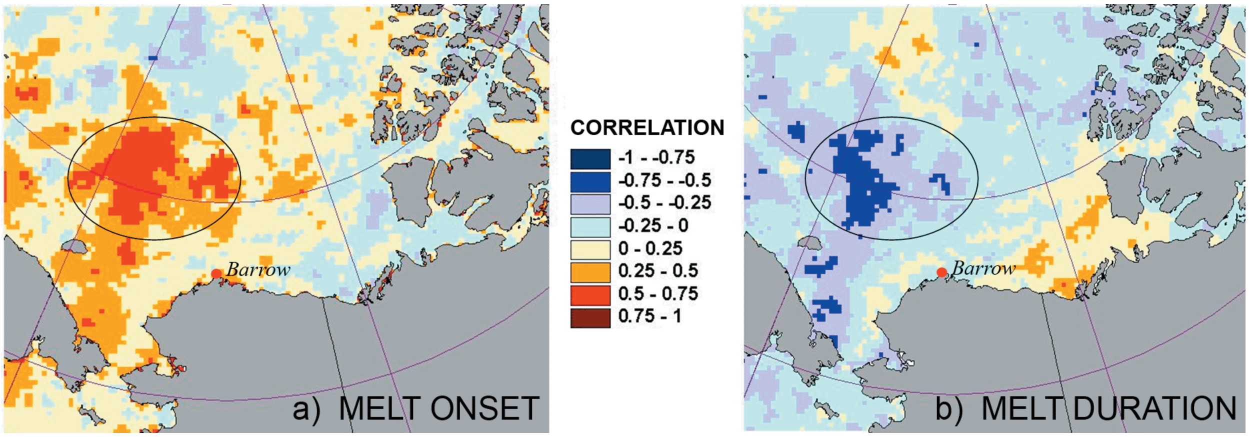

Figure 3. Maps showing correlations between the date of snowmelt at the NOAA/CMDL Barrow Observatory (indicated by the red dot) and a) the onset date of snowmelt over sea ice, and b) the melt season duration (days) over sea ice, for the period 1979-2002.

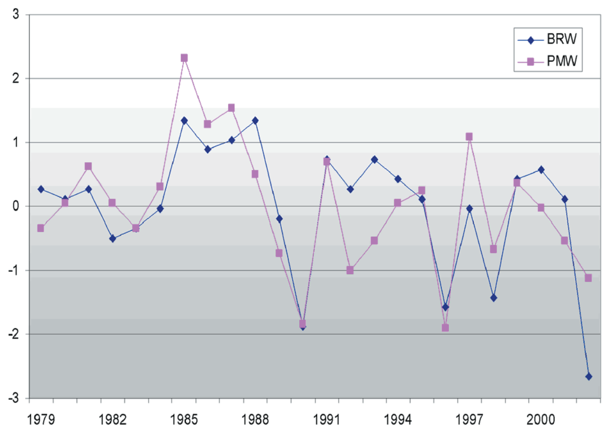

Figure 4. Typical time series of standardized anomalies of BRW melt dates (blue) and a single melt onset PMW pixel (pink) located within the region of high correlation shown in Figure 3a.

region, effectively creating and forcing the Beaufort Gyre. A weak Gyre, caused by a breakdown of the BSA, diminishes transport of multiyear ice into this region (Drobot and Maslanik, 2003). Similarly, the annual snow cycle at BRW varies with the position and intensity of the BSA (Stone et al. 2002, Figure 6). Thus, variations in the BSA appear to have far-reaching effects on the annual accumulation and subsequent melt of snow over a large region of the western Arctic.

By inference, the disposition of the BSA may influence duration of the melt season as well. This is suggested in Figure 3b. In fact, a dramatic increase in melt season duration from the period 1979-1988 to 1989-2001 in the encircled region has been documented (Belchansky et al., 2004b). It is increasingly apparent that dynamical perturbations occurring in the East Siberian-Chukchi-Beaufort sea regions, especially during spring, affect onset and duration of the melt season; and changing environmental conditions there have contributed significantly to the overall decline in the extent and age of multiyear sea ice since about 1990.

4. CAUSE AND EFFECT OF A LENGTHENING SEA ICE MELT SEASON

4.1 *Atmospheric Forcing of Sea Ice Variations*

There is general consensus that the overall decline in Arctic sea ice (since the late 1970s) is due to processes associated with dynamical changes in the atmosphere. Belchansky et al. (2004b) found that the duration of the sea ice melt season was correlated with the phase of the previous winter's Arctic Oscillation (AO) index (Thompson and Wallace, 1998). Following positive index winters, melt onset tends to be early, and the autumn freeze late, especially in the regional "hot spot" indicated in Figure 3. Serreze et al. (2003) cautioned that while much evidence supports this view, there are notable exceptions. The 2002 record minimum ice extent, which was dominated by a negative anomaly in the western Arctic, followed a winter of alternating AO indices. This anomaly was caused by abnormally warm atmospheric temperatures during spring, followed by a summer during which cyclonic surface winds exported ice from the region. The 1998 summer retreat followed a similar pattern (Maslanik et al., 1999). Rigor and Wallace (2004) propose that entrainment of younger and thinner ice anomalies within the Beaufort Gyre during the high-index AO conditions of the 1990s has contributed significantly to the recent extreme summer minima in the western Arctic. Emperically, during the predominately positive phase of the AO since 1989, Belchansky et al. (2004a) clearly document that multiyear ice area has declined most rapidly in the southern Beaufort and Chukchi Seas, and they call for regional-specific analyses to determine "underlying causal mechanisms." The following sections describe regional factors that appear to underlie recent environmental changes in the western Arctic.

4.2 *Synoptic Influences During Spring Transitions*

Spring is a critical transition period in the annual cycles of snow and sea ice. In the recent past, 1985, 1986, 1987 and 1988 were the latest years of melt at BRW, and 1990, 1996, 1998, and 2002 were the earliest (Figure 1). To compare springtime environmental conditions for these "late" and "early" years of melt at BRW, mean March–May synoptic patterns (represented by 850 hPa contours) are superimposed on maps depicting the chronology of melt onset over sea ice and the phenology of vegetation green-up (maximum NDVI) during 21-31 May over land (Figure 5).

Figure 5a represents typical climatological conditions during spring in the Western Arctic. These are characterized as having a well-defined BSA north of BRW, coupled with the AL centered just east of the Aleutian Islands. The mean flow around these pressure centers is indicated schematically by bold vectors; blue representing cold, dry air and red, warm, moist air. The BSA effectively blocks Pacific air from flowing northward into the Arctic basin. Over land, the North Slope of Alaska remains snowbound in late May as does much of eastern Siberia. Melt onset over sea ice does not commence until the first week in June north of BRW, and not until late June north of eastern Siberia. By late September, when ice normally reaches its farthest northerly retreat, a portion of the Siberian coast remains ice bound, and the ice edge (denoted by the white line) is not far north of the Alaskan coastline.

In contrast, Figure 5b composites four anomalously early years of melt at BRW. During spring 1990, 1996, 1998 and 2002 the BSA was absent. Instead, a ridge of high pressure persisted over eastern Alaska. The AL was slightly weaker and centered in the southwest Bering Sea. This pattern results in a persistent northward flow of air during March, April and May (indicated by red arrows) that purges the entire region with warm, moist Pacific air. Transport of southern air masses into the BRW region was found to be 3 times more frequent in spring during years of early snow melt than during years

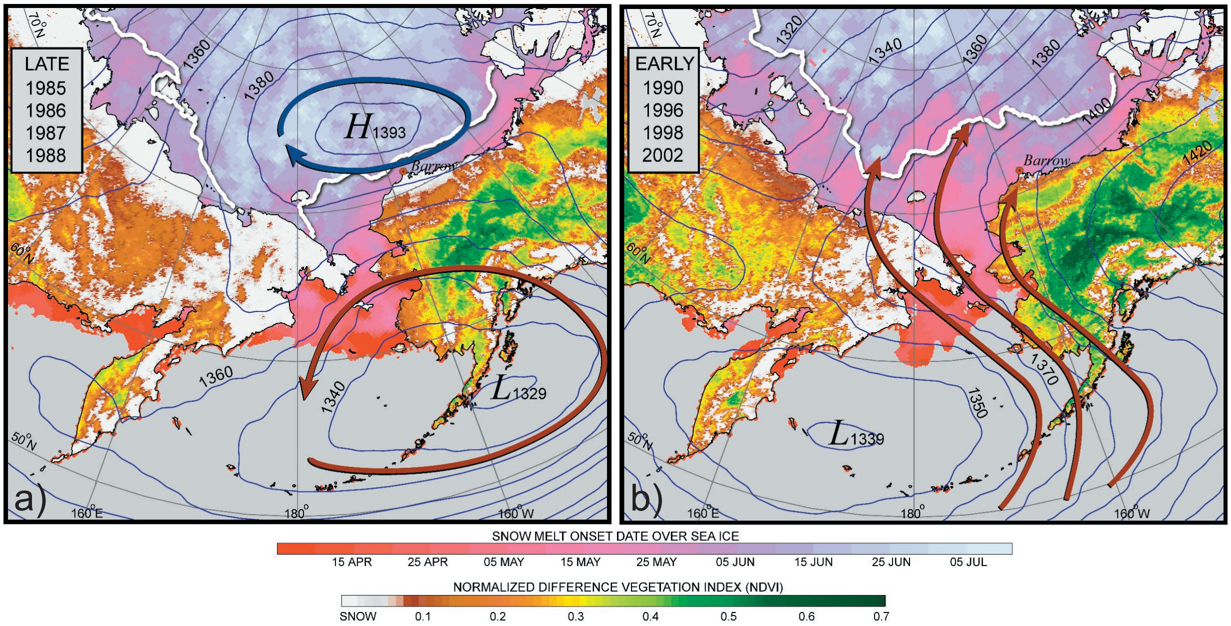

Figure 5. Spring environmental conditions over eastern Siberia and Alaska, averaged for years with (a) late and (b) early snow disappearance dates at Barrow. Blue lines depict 10 m contours of mean March–May 850 hPa geopotential heights from the NCEP/NCAR 40-year Reanalysis Project (Kalnay et al., 1996). Generalized circulation patterns are shown with bold vectors. Mean melt onset dates over sea ice (Belchansky et al., 2004b) are presented for areas where average spring (21–31 May) sea ice concentrations exceed 50% (http://www.nsidc.org/data/nsidc-0079.html). Extent of autumn sea ice retreat is illustrated by the 50% contour of averaged ice concentrations during 21–30 September (bold white line). Vegetation greenness is depicted by the mean annual maximum NDVI during 21–31 May (2002 data missing), adapted from the NOAA/NASA Pathfinder AVHRR Land Program (Maiden and Greco, 1994) data sets (http://daac.gsfc.nasa.gov).

of late melt (Stone et al., 2002). As a consequence, snow melts earlier over western and northern Alaska, resulting in significant greening over the North Slope by late May. East Siberia is mostly snow-free with some greening evident in its central regions. The Pacific air is further warmed as it advects over snow-free regions that have been irradiated increasingly by sunlight.

Similarly, snow melt over sea ice begins earlier when the BSA is absent during spring (Figure 5b). A broad area of melt penetrating north of the Bering Straight is apparent by mid-May. And, by the end of September, a much greater northward retreat of the sea ice edge is observed throughout the western Arctic.

4.3 *Role of Clouds*

Warm air advection associated with the synoptic pattern shown in Figure 5b adds moisture to the Arctic atmosphere, increasing cloudiness. There is evidence that cloud cover in the western Arctic Ocean has in fact increased, especially during spring (J. Key, unpublished results based on the extended AVHRR Polar Pathfinder satellite data product; e.g., Wang and Key, 2003). In winter and early spring, thermal emissions from clouds warm the surface, and may promote loss of snow through enhanced sublimation (e.g., Stone, 1997; Stone et al., 2002). Prolonged effects of warm air advection that enhance boundary layer turbulence, augmented by cloud radiative forcing, can modify the microphysical structure of the overlying snow. This "ripening" may precondition the snow pack such that the melt is accelerated during May/June when solar insolation reaches its annual peak. Ice melt is further accelerated if snowmelt occurs early over sub Arctic regions because air advected northward undergoes enhanced heating (e.g., Aizen et al., 2000).

4.4 *Effect of Snowfall Variations*

The depth of snow on sea ice prior to the onset of melt is also important. Significant ice melt cannot occur until the insulating layer of snow melts first. If snow accumulation on sea ice is low, and conditions favor an earlier ripening of the pack as described above, then the snow cover will melt more rapidly, advancing the onset of ice melt. Warren et al. (1998) produced the most comprehensive, and possibly the only available climatology of snow depth for the Central Arctic. For a period of overlap (prior to 1991), one finds similarities in the annual cycle of snow at BRW and that over the ocean to the northwest. Most notable is a common trend towards decreased snow depth at the end of the accumulation period that Warren et al. attribute to "reduced snowfall" (in winter). Reduced winter snowfall is a primary factor underlying the trend towards earlier snowmelt at BRW. Thus, reduced snowfall over the western Arctic Ocean in recent years may account, in part, for the decline in sea ice in that region.

5. CONSEQUENCES OF ANOMALOUS CIRCULATION IN THE WESTERN ARCTIC

Linkages to the disposition of the BSA (described above) suggest that regional scale climatology can influence broader scale mechanisms and feedbacks that modulate sea ice conditions in the western Arctic. A few important mechanisms/feedbacks are listed below:

1. A weakened BSA diminishes strength of the Beaufort Gyre. Ice is more readily advected into the Transpolar Drift Stream and exported through the Fram Strait (e.g., Drobot and Maslanik, 2003), ultimately reducing average ice age (Rigor and Wallace, 2004) and volume (Belchansky et al., 2004a).

2. A weakened BSA underlies synoptic perturbations, during spring, that promote an earlier and more rapid melt due to thermodynamic and radiative preconditioning of the snow pack by warm, cloudy Pacific air.

3. Earlier melt prolongs the melt season by enhancing the temperature-albedo feedback, and exacerbates summer sea ice retreat that was preconditioned by other dynamic processes (Rigor and Wallace, 2004). Also, under conditions of reduced snowfall, surface snow melt occurs more rapidly and the albedo feedback is prolonged.

4. Longer melt seasons cause reductions in mean sea ice thickness (Laxon et al. 2003, Belchansky et al., 2004a), resulting in amplified warming trends in the Arctic (Holland and Bitz, 2003).

6. CONCLUSIONS

The above analysis supports previous studies that attribute recent declines in Arctic sea ice to dynamic and thermodynamic anomalies. The independent observations suggest that such processes are coupled temporally and are most pronounced in the western Arctic Ocean. Changes in atmospheric circulation underlie variations in the region's annual snow cycle, over land and at sea. Earlier melt onset and longer melt duration reduce summer survival of first-year ice. At the same time, divergence of the pack due to a weakened Beaufort Gyre enhances loss of perennial ice in the western Arctic. As clearly evident in Figure 2 (top), anomalies in this region determine the basin-wide trend.

Concerns arise as to whether or not recent trends resulting from these compounding positive feedbacks (Section 5) are manifestations of natural, low-frequency oscillations, or are anthropogenically forced. Will these mechanisms become self-propagating if the global temperature continues to rise? Answers to these questions have important ecological and cultural implications on a pan-Arctic scale. More detailed investigations of regional scale processes are warranted, especially regarding the behavior and stability of the BSA. Attention should be given to causes and effects of variable cloudiness and snowfall in the Arctic, as well as the mechanisms underlying major shifts in planetary circulation and their associated effects on important synoptic patterns that control regional scale processes.

7. ACKNOWLEDGMENTS

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