The Advancing Date of Spring Snowmelt in the Alaskan Arctic

R. S. Stone and D. Longenecker
Cooperative Institute for Research in Environmental Sciences
University of Colorado
Boulder, Colorado

E. G. Dutton, J. M. Harris, and D. Longenecker
National Oceanic and Atmospheric Administration
Climate Monitoring and Diagnostics Laboratory
Boulder, Colorado

Abstract

Since the mid-1960s the spring snowmelt has advanced by about 8 days in northern Alaska because of decreasing snowfall in winter and warmer spring conditions. This is attributed to shifting synoptic patterns that favor northerly airflow during winter but southerly flow in spring. Early snowmelt enhances the seasonal NET surface radiation budget dramatically, especially when the snow first disappears. At Barrow, Alaska, NET radiative forcing can exceed 150 Wm^{-2} on a daily basis at the time of snowmelt, and as a result of the 8-day advance we estimate an increase of $\approx$2 Wm^{-2} annually. Our results are in general agreement with earlier analyses that suggest a pan-Arctic reduction in snow cover has contributed to a warming over northern hemispheric land areas because of a temperature-albedo feedback.

Introduction

An important process that occurs every spring over high-latitude continental regions is the melting of the snow pack. Variability in the date when the Arctic tundra becomes snow free is expected to affect the net energy budget of the region. If the global mean temperature continues to increase, the Arctic may experience enhanced warming because a positive radiative feedback will result when the surface albedo decreases in response to accelerated ice and snow melt (e.g., Houghton et al. 1996). Lower albedo will increase solar absorption by the surface and promote further warming. This “temperature-albedo feedback” is one reason observers look to the Arctic for early indications of global warming. Much of the Arctic has already warmed significantly, decreases in Northern Hemisphere (NH) snow cover have been documented, and sea ice has also diminished (Serreze et al. 2000; and references therein). It is not yet known if these changes are anthropogenically forced or result from natural variations of the climate system. Because any long-term change in the distribution of snow will perturb the Arctic energy budget, a better understanding of why snow cover varies is needed. In this paper some of the physical processes Changes in key climate variables are found to underlie a trend towards an earlier spring snowmelt. The consequences that influence the annual cycle of snow on the North Slope of Alaska (NSA) are identified and evaluated. Changes in key climate variables are found to underlie a trend towards an earlier melt date are also discussed. A more detailed analysis is given in Stone et al. (2001), from which the figures presented here are taken.

Background of Snowmelt Analyses

On the basis of snow depth measurements Foster (1989) found that the spring melt at the Barrow National Weather Service (NWS) had occurred progressively earlier since the 1940s. He speculated that this was a manifestation of global warming. Dutton and Endres (1991), however, suggested the trend was attributable to local effects related to development near the NWS site. They used radiometric data (albedo measurements) from the National Oceanic and Atmospheric Administration (NOAA) Climate Monitoring and Diagnostics Laboratory (CMDL)-Barrow Observatory (BRW), combined with historic observations, to show that the NWS trend was not representative regionally. BRW (71.3°N, 156.6°W; elev. 8 m) is located on open tundra several kilometers upwind of town where any effects of development are minimal. Foster et al. (1992) then analyzed NOAA satellite images and found evidence of a pan-Arctic trend in the date of spring snowmelt.

Figure 1 illustrates how the disappearance of snow can be determined from surface albedo (α) derived from measurements of upwelling (SU) and downwelling (SD) solar irradiance (α = SU/SD). A daily average threshold of $\alpha \leq 0.30$ (30 percent) is used to determine the date of melt at BRW, where during the final few days α falls rapidly from $\geq$0.75 to $\approx$0.17$\pm$0.03. Once the daily average albedo drops below 0.30, it seldom increases again until snow accumulates the following autumn. This fact makes monitoring the spring melt relatively straightforward and provides a useful indicator of climate change. Although the final melt occurs in a matter of a few days, the timing of this event is highly variable year to year, depending on many factors, especially temperature and the amount of snow that accumulates prior to the melt. Climate variations that cause a shift in the spring melt date cause a perturbation in the regional energy budget because the melt occurs during the peak of the solar cycle (Figure 1). At this time of year, a dramatic decrease in albedo greatly enhances the NET surface radiation budget (e.g., Stone et al. 1996).

Figure 2 compares time series of melt dates from the NWS and the BRW locations. The records show further divergence since earlier assessments were made (Foster 1989, Dutton and Endres 1991). It is now known for certain that the NWS record has been contaminated because of new construction and a dramatic increase in traffic directly upwind of that site. Rapid growth began in the late 1960s in conjunction with developing the NSA oil reserves. The effects of "urbanization" cannot be quantified so it is not possible to detect a natural climate signal in the NWS record. Instead the BRW time series is analyzed. This is shown in Figure 2 as a merged record of NWS observations, albedo-determined melt dates, and proxy observations (see Stone et al. 2001 for details). A linear fit of the BRW time series shows an advance of 7.7 days ($\pm$4.6) over 60 years, significant at the 95 percent confidence level (CL). Overall the melt has advanced by more than a week since the mid-1960s, but the record is characterized by significant interannual variability. The most pronounced change occurred during the

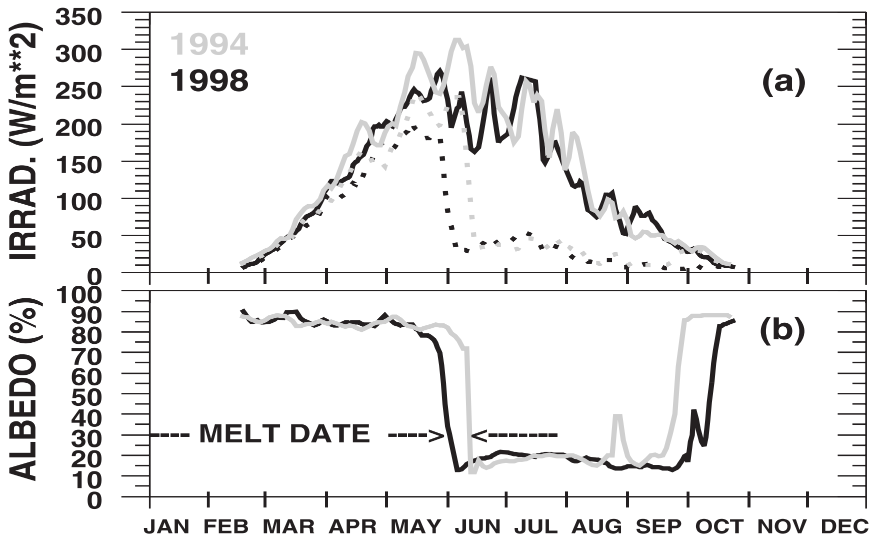

Figure 1. Seasonal cycles of (a) downwelling (SD, solid) and upwelling (SU, dashed) solar irradiance at NOAA/CMDL-BRW, representing late (1994, gray) and early (1998, black) spring melt seasons, and (b) derived albedos (α = SU/SD) for the same 2 years. A 30 percent albedo threshold is used to determine the annual date of snowmelt at BRW.

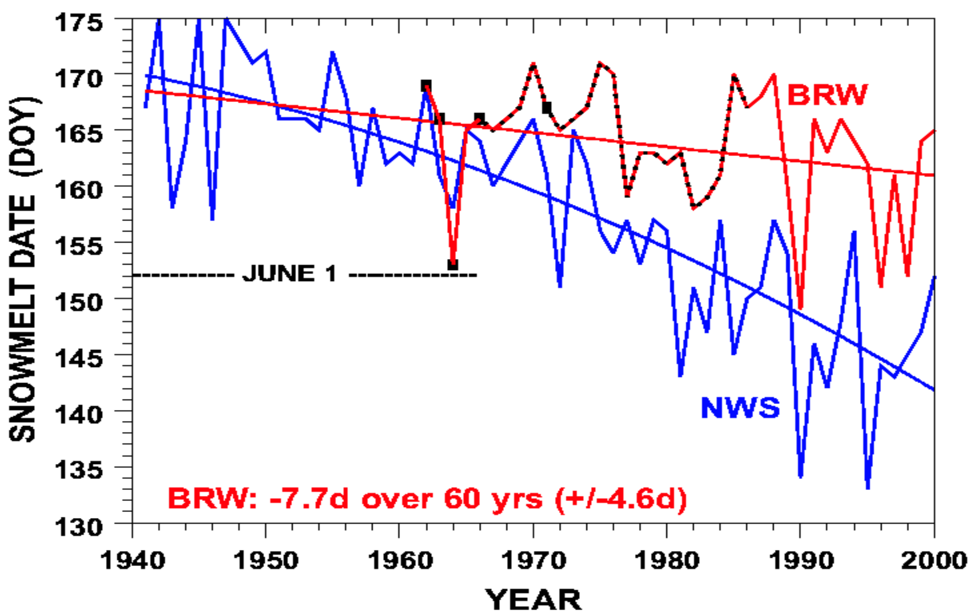

Figure 2. Time series of melt dates at the Barrow National Weather Service (NWS, blue) compared with a BRW record composed of historic (squares) and NOAA/CMDL-BRW radiometric observations (solid, red) and proxy estimates determined from temperature records (dashed). The BRW time series, merged with the 1941 to 1961 NWS record, was fitted linearly to yield the trend indicated in the legend, significant at the 95 percent confidence level (details are given in Stone et al. 2001).

last decade, with the melt dates of 1990, 1996, and 1998 being anomalously early. Analyses (not shown) of six similar records from other NSA sites show equivalent trends, suggesting that a regional-scale climate change has occurred.

Figure 3 shows time series of melt dates and proxy observations from six other NSA sites that are correlated with the most recent 35 years of the BRW record. The locations of these sites are indicated on the map, Figure 4. Yearly data were analyzed to determine trends and correlation coefficients, but only 5-year-smoothed data are presented. The Sagwon (69.4°N, 148.8°W; elev. 351 m) and Franklin Bluffs (69.9°N, 148.1°W; elev. 76 m) melt dates were determined using a 0.30 albedo threshold (e.g., Figure 1). Both sites are within the Kuparuk River Watershed located southeast of Barrow. Barter Island (70.1°N, 143.6°W; elev. 15 m) was another NWS station where, until 1987, melt dates were determined from snow depth data. The series labeled satellite was derived from visible satellite images of a strip of tundra about 150 km south of Barrow, Alaska. Though this record begins in 1976 (Foster et al. 1992), we discovered that prior to 1982 the satellite observations showed a significant late bias when compared with concurrent records that, in recent years, are well correlated with the satellite observations. In the early years there were fewer polar orbiters, analyses were made only weekly, and observers did not have the benefit of multi-spectral data now used to help distinguish clouds from snow (J. Foster, NASA-GSFC, personal communication 2000).

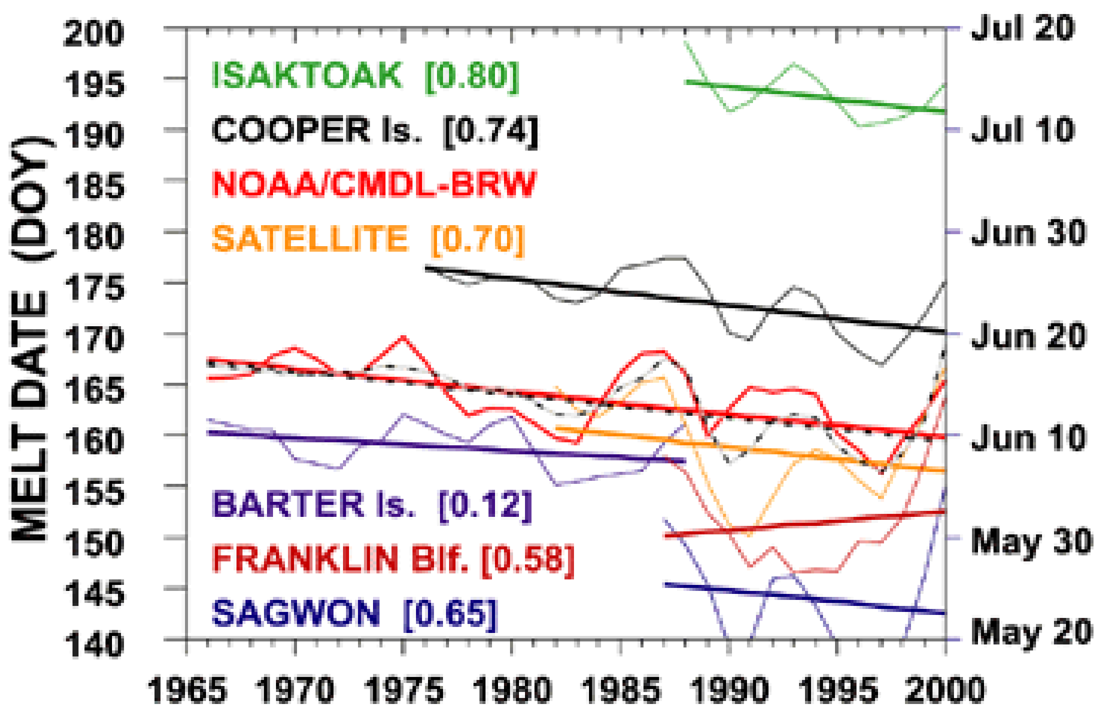

Figure 3. Analyses of six independent time series of melt dates compared with the 1966 to 2000 BRW record (from Figure 2). 5-year-smoothed time series, and linear fits are shown. Each is correlated with the NOAA/CMDL-BRW record with coefficients indicated for each of the sites described in the text. The dashed analysis (unlabeled) is for an ensemble average of the 142-station years, normalized to the BRW time frame.

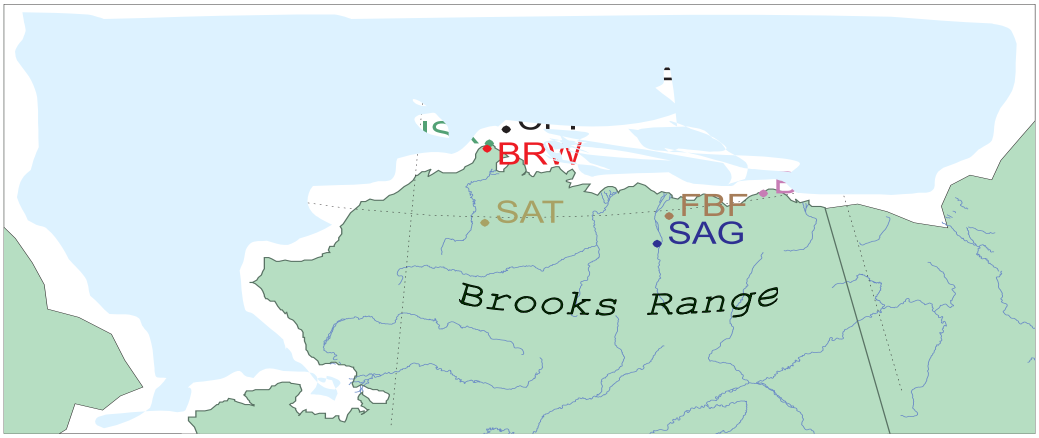

Figure 4. Map view of northern Alaska showing the approximate locations of the seven sites for which time series analyses shown in Figure 3 were made. Each is color-coded for cross-reference.

The upper two curves in Figure 3 are proxy records. Cooper Island (71.7°N, 155.7°W; elev. 3 m) is a time series of dates when a species of Arctic bird, the Black Guillemot, first lays an egg. Each spring Guillemots nest on the island but only after the snow melts do they breed, producing their first clutch about two weeks later (Divoky 1998). Isaktoak is a time series of dates when ice has melted completely off of the Isaktoak Lagoon, which is located in the village of Barrow (C. George, Barrow Wildlife Division, private communication 2000). These proxy records are correlated with each other and with the BRW time series suggesting that snowmelt and ice melt are influenced similarly by variations in climate. The dashed curve in Figure 3 represents an ensemble average of all observations normalized to the timing of the BRW melt. A linear fit of this 142-station-year record shows an advance in the spring melt of 8.0 days over 35 years ±4.0 (CL = 95 percent) suggestive of a regional trend. However, the correlated variations of time series shown in Figure 3 are more indicative of climatic shifts than of a monotonic change. Note also that the melt tends to progress from the more southerly locations of the Kuparuk River Watershed, northward toward the coast (e.g., Barter Is.), and last in the vicinity of Barrow.

Factors that Influence the Date of Snowmelt in Northern Alaska

Two previous investigations provide clues as to why the spring melt is occurring earlier over northern Alaska. Stone (1997) documents a warming trend there, and Curtis et al. (1998) showed that snowfall in the region has decreased. Snowmelt should occur early if snowfall is below average and/or temperatures are above average. It is hypothesized that such conditions have become more common in recent decades, which may explain the observed trend in snowmelt. Figure 5 presents a comparative analysis that supports this hypothesis.

In the vicinity of Barrow, most of the annual snowfall accumulates by the end of February, March tends to be dry and sunny, and by mid-April the snow pack begins a fairly rapid decline. Therefore, to evaluate variations in accumulated snowfall, a time series of water equivalent precipitation (WEPC), integrated for October through February, was constructed (Figure 5b). At BRW a wind-shielded gauge has provided reliable measurements of WEPC since 1977, but the earlier NWS data are from a standard

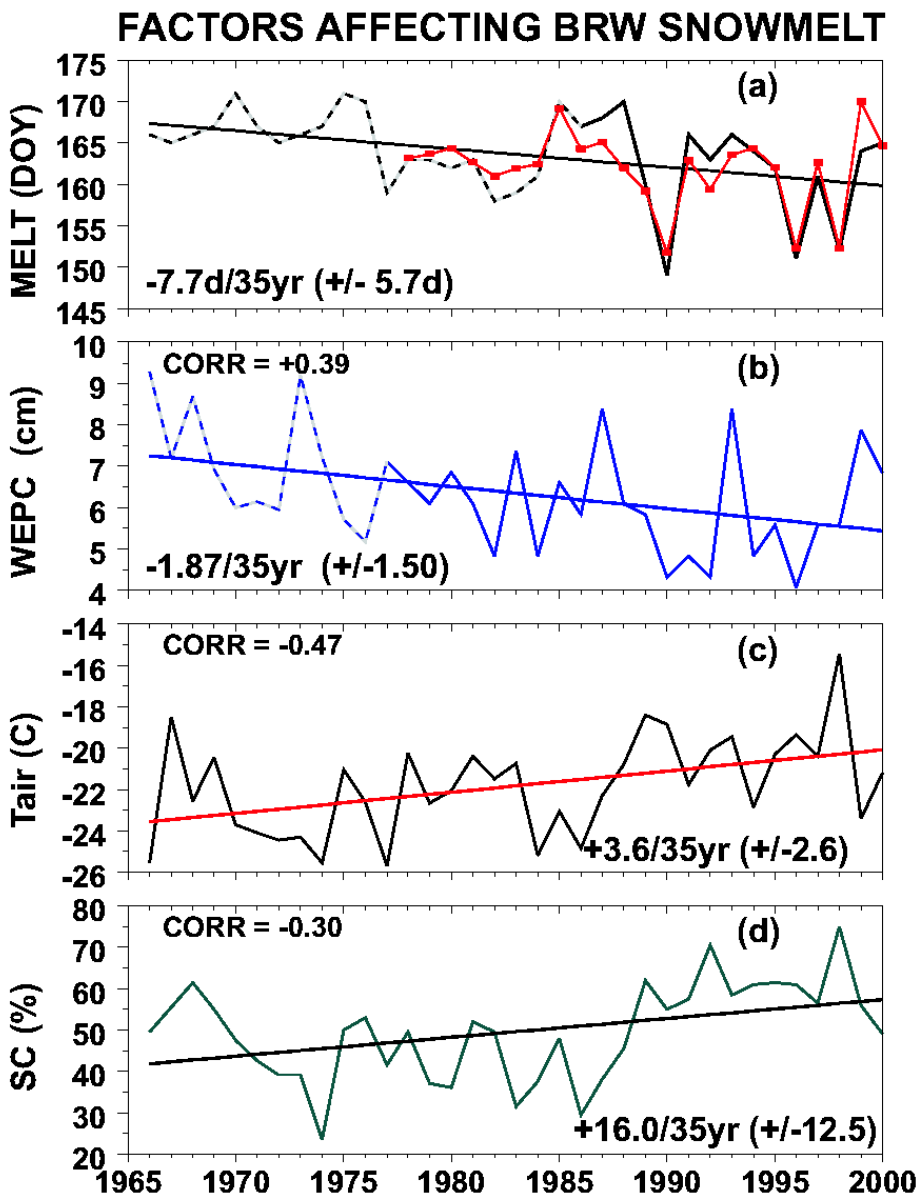

Figure 5. 1966 to 2000 time series of (a) observed, and modeled (filled circles) melt dates at NOAA/CMDL-BRW, (b) October to February water-equivalent precipitation, adjusted prior to 1977 (dashed) to account for "wind-induced undercatch," (c) average March/April 2m air temperature, and (d) average March/April total sky cover. Legends (upper-left) give the correlation of BRW melt dates with respective variables, and the legends at bottom give results of linear fits at a confidence level of 95 percent.

8-inch gauge that is prone to “wind-induced undercatch.” Yang et al. (1998) recommend adjustments be made to standard gauge data on a daily basis to account for varying wind speeds. Lacking the ancillary data needed to do this, a different approach was used. Adjustment factors were determined from monthly mean differences between shielded gauge data from BRW (1976 to 1996) and standard gauge data from NWS-Barrow (1949 to 1996). Using these factors the NWS October to February values of WEPC were scaled, on average, by a factor.

Figures 5c and 5d are time series of average March/April air temperatures (T_{air}) and total sky cover (SC), analyzed to evaluate variations in ambient conditions prior to the spring melt. The record of melt date, Figure 5a, was cross-correlated with each variable and the respective time series were fitted linearly to assess trends. Melt dates are positively correlated with October to February WEPC (snowfall) that has decreased, and anti-correlated with March/April temperatures and sky cover, which show increases. Note also that March/April temperatures are positively correlated with sky cover ($r = 0.73$ for T_{air}:SC) because during spring, clouds in this region enhance thermal emissions more than they attenuate incoming solar radiation (Stone 1997). To further assess the relationship between these factors, a multiple regression model was developed to predict the date of melt Eq. (1). The melt, day-of-year (DOY), is estimated from combining terms of WEPC, T, and SC as follows:

$$DOY \approx 14.0WEPC - 0.95WEPC^{2} - 7.6T - 0.13T^{2} + 0.23SC \qquad (1)$$

The model was evaluated only for the period when shielded gauge data are available. Figure 3a shows that predicted dates (filled circles) are well correlated with the observations: $r = 0.85$ (CL = 95%). This empirical relationship explains >70% of the variance in the date of snowmelt at BRW. If the area affected by the trend is large, as is suggested by previous studies (e.g., Kuang and Yung 2000; Brown and Braaten 1998; Aizen et al. 1997), then these findings are significant in the context of global climate change because of an expected temperature-albedo feedback (e.g., Groisman et al. 1994). It is important to understand what processes underlie the trends indicated in Figure 3 and to determine whether they are natural or can be attributed to anthropogenic effects.

The Influence of Circulation on the Date of Snowmelt in Northern Alaska

Stone (1997) documented how shifts in circulation patterns influence the temperature regime of northern Alaska. Here we evaluate how snowfall is similarly affected by changes in synoptic patterns that are dominated by two pressure systems, the Aleutian Low (AL) and what we refer to as the Beaufort Sea Anticyclone (BSA). Our approach is similar to that of Harris and Kahl (1994; Figure 4) whereby the clustering of back-trajectories is used to quantify the frequency of airflow to BRW from different “source regions.” To evaluate flow associated with the BSA and AL, we define Arctic and North Pacific source regions, respectively. These are indicated in Figure 6. Isentropic back-trajectories and geopotential fields were calculated using gridded data supplied by the European Centre for Medium Range Weather Forecasts. Although individual trajectories are subject to uncertainties arising from the interpolation of sparse meteorological data, we believe that our cluster-average results represent general flow patterns reasonably well.

We analyzed 0000 Universal Time (UT) and 1200 UT 5-day back-trajectories calculated for an arrival altitude of 1500 m in conjunction with 850 hPa geopotential height fields. At BRW this level generally tops the surface inversion layer where the advection of heat and moisture plays an important role in cloud-radiative and dynamical processes. We assume that a source region influences BRW if a back-trajectory passes through some portion of that region within the 5-day period. To evaluate transport that affects winter snowfall, October to February trajectories and geopotential fields were analyzed. A similar analysis was made to assess how synoptic patterns influence March/April temperatures and sky cover. Evaluations are based on the percent frequency of flow from a particular region, by season, and the average time (in days) that it takes an air parcel to reach BRW once it emerges from a particular region.

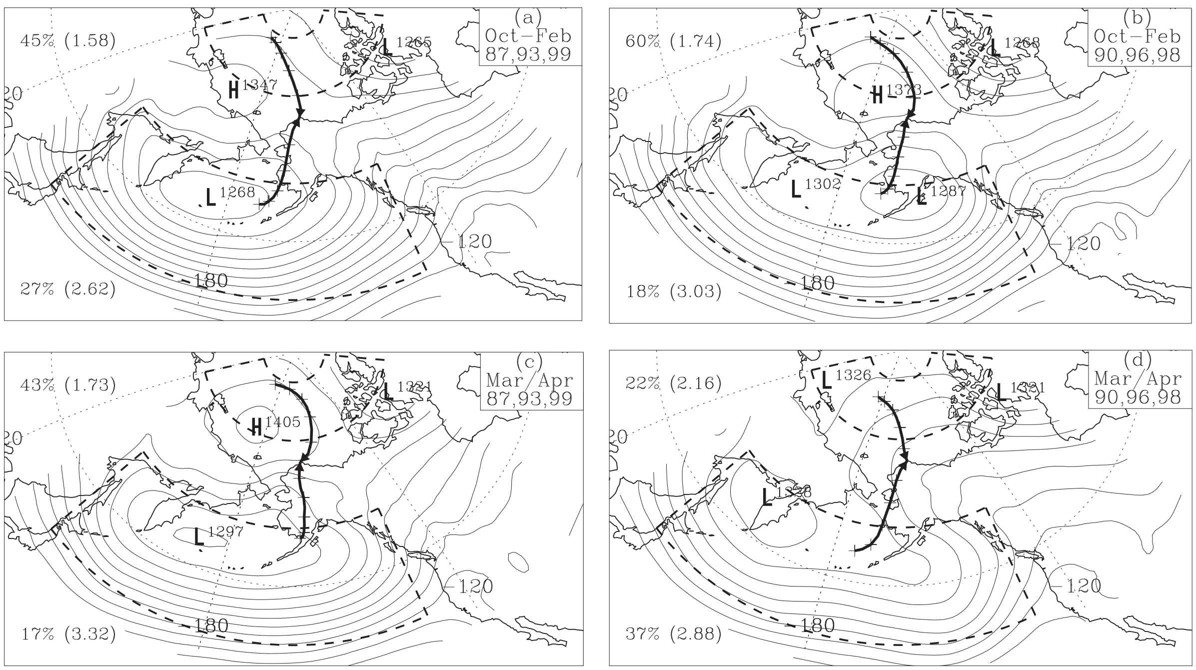

Figure 6. Composite 1500 m back-trajectories and corresponding 850 hPa geopotential height fields for (a) October to February 1987, 1993, and 1999, (b) October to February 1990, 1996, and 1998, (c) March/April 1987, 1993, and 1999, and (d) March/April 1990, 1996, and 1998, showing average 5-day flow from source regions indicated by the dashed boundaries. The frequency (%) and average transit time from each region (in days) are indicated in the legends.

Figure 6 contrasts composite analyses for 3 years of early snowmelt, 1990, 1996, and 1998 (Figures 6b and 6d) with 3 years when the melt occurred much later, 1987, 1993, and 1999 (Figures 6a and 6c). As was indicated in Figure 5, these early (late) melt seasons were associated with below (above) average October to February snowfall and above (below) average March/April temperatures. Figure 6b shows that during October to February 1990, 1996, and 1998, 60 percent of all trajectories reaching BRW emerged from the northern region and only 18% from the south. This pattern inhibits snowfall because northerly winds are very cold and especially dry during winter when extensive sea ice cover limits the supply of moisture. Figure 6d shows that by March/April of these years the pattern had essentially reversed. More vigorous flow from the Bering Sea is dominant, a pattern favoring the advection of heat and moisture to northern Alaska that we know enhances cloudiness and results in warmer conditions there.

Generally, the seasonal patterns for 1987, 1993, and 1999 (Figures 6a and 6c) were the opposite of those noted for 1990, 1996, and 1998. Greater October to February snowfall was associated with more rapid and frequent flow from a deeper AL centered over the Bering Sea. And the cooler March/April conditions were attributed to a twofold increase in northerly flow associated with an intense BSA centered northwest of BRW, effectively blocking warm-air advection from the south.

In summary, years with below (above) average snowfall at BRW are influenced dominantly by flow from the Arctic (Aleutian) source region, while warm (cool) spring conditions occur if flow from the Aleutian (Arctic) region is favored. The juxtaposition and relative intensities of the AL and BSA determine advective patterns that influence the NSA weather seasonally and, in turn, the timing of spring snowmelt. The Aleutian Low, in particular, is a center of action that varies on decadal time scales, affecting modes of the high-latitude circulation (Overland et al. 1998).

Response of the Surface Radiation Budget to Variations in Melt Date

We can estimate the perturbation in the NET surface radiation budget (NSRB) caused by an early melt from continuous irradiance measurements made at NOAA/CMDL-BRW. Table 1 quantifies the average June and seasonal (May-August) total radiative energy received at the surface for 3 years of early snowmelt compared with 3 years when the melt occurred about 2 weeks later. On a seasonal basis the NSRB increases by an average of 8 MJm^{-2} ($\approx$1%) for each day the melt advances. Thus, for an 8-day advance (Figure 3) $\approx$64 MJm^{-2} of additional energy is made available to the climate system, mostly from enhanced solar absorption in early June when the albedo decreases so precipitously. We agree with Maykut and Church (1973); “the most significant factor influencing the magnitude of the yearly net radiation total is the date when snow melt is completed.” Redistribution of the additional energy occurs in complicated ways involving sensible and latent heat exchanges between the surface and atmosphere, compounded by advective processes driven by large-scale dynamics. Although we are unable to quantify these individual components, some degree of atmospheric warming ultimately results. Groisman et al. (1994) suggested that radiative forcing due to a decrease in surface albedo had contributed to the recent warming over NH land areas. Also Aizen et al. (1997) suggest that a feedback involving a long-term decrease in snowfall over the Tien Shan of Russia has contributed to rising June to August temperatures in that region. Our own analysis (Table 1) suggests that June temperatures at BRW rise by a degree, on average, in response to a 2-week advance in melt date, and slightly warmer temperatures may persist through July/August. Our limited samples show large variations, however, prohibiting an accurate assessment of a temperature-albedo feedback, and we do not take into account other factors such as cloud variations, turbulence, or advection. We can conclude only that the radiative perturbation caused by an early melt is very significant locally. Compared with an annual NSRB at

BRW of ≈470 MJm^{-2} (Stone et al. 1996; Figure 9), an 8-day advance in melt results in a 12 to 14 percent increase, or ≈2 Wm^{-2}, of radiative forcing. This is in general agreement with Kuang and Yung (2000) who estimate that a decrease in snow cover from 1979 to 1991 increased shortwave heating by about 2 Wm^{-2} over NH land areas.

Table 1. Comparison of NET surface radiation budget (NSRB) and 2-meter temperatures for early vs. late years of snowmelt at NOAA/CMDL - BRW.

Years Sampled	Late 1992, 1999, 2000	Early 1990, 1996, 1998
Melt date (DOY)[a]	164 (0.8)	150 (0.8)
June NSRB[b] (MJm^{-2})	306 (2)	385 (7)
May-August NSRB (MJm^{-2})	860 (17)	970 (43)
June T_{2m} (C)	0.9 (0.59)	1.8 (0.36)
July/August T_{2m} (C)	3.3 (0.62)	3.6 (0.87)

(a) Day of Year
(b) NET Surface Radiation Budget
Numbers in parentheses give one standard deviation.

Discussion and Concluding Remarks

On average, the spring snowmelt in northern Alaska has advanced by about 8 days since the mid 1960s. The trend is attributed to changes, or shifts, in atmospheric circulation that have diminished winter snowfall and favored warmer conditions in spring. It is possible these shifts are related to the Arctic Oscillation (Thompson and Wallace 1998). However, there may be a higher correlation with the North Pacific (NP) Index (e.g., Trenberth and Hurrel 1994) or the Pacific Decadal Oscillation (PDO) (Bond and Harrison 2000) because these modes of circulation are associated with variations in the Aleutian Low that influence high-latitude climate more directly (Overland et al. 1998).

The radiative impact of an earlier melt in Arctic regions is significant. We estimate that the annual NET radiative forcing associated with a 2-week advance in snowmelt at BRW is ≈2 Wm^{-2}. The most dramatic increase, >150 Wm^{-2} on a daily basis, occurs immediately following snowmelt. Perturbations of this magnitude on a pan-Arctic scale have probably contributed to the recent warming over NH land areas (Kuang and Yung 2000; Aizen et al. 1997; Groisman et al. 1994). Earlier snowmelt may promote an early onset of ice melt as well because the melting of ice is delayed until the snow that insulates it is mostly gone. Thus, decreases in snowfall that have led to an earlier spring snowmelt may have also contributed to a decrease in sea ice cover in recent years (e.g., Maslanik et al. 1996).

Other consequences of an earlier spring melt include a lengthening of the active growing season (Myneni et al. 1997), and an associated increase in the amplitude of the annual cycle of CO_2 (Keeling et al. 1996). There is also evidence that Arctic tundra is becoming a net source of CO_2 (Oechel et al. 1995), and permafrost is thawing (Osterkamp and Romanovsky 1999). Thus, variations in the annual distribution of snow over the high latitudes have far-reaching implications, both in the context of global warming and biogeochemical cycles. While the analysis presented here suggests that natural rather than anthropogenic effects underlie the observed trends (Figure 3), it is possible that the changing circulation patterns (e.g., Figure 6) that underlie the trends are, in turn, a manifestation of greenhouse-forcing involving planetary-scale teleconnections that have yet to be identified. Therefore, it is essential to continue an Arctic-wide monitoring of the causes and effects of variations in snow cover to gain a better understanding of natural versus anthropogenic climate forcing. Moreover, such observations should form a basis for verifying climate models and evaluating feedback mechanisms while improved parameterizations of these physical processes are developed.

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Corresponding Author

R. S. Stone, bstone@cmdl.noaa.gov

References

Aizen, V. B., E. M. Aizen, J. M. Melack, and J. Dozier, 1997: Climate and hydrological changes in the Tien Shan, Central Asia. *J. Climate*, **10**, 218-229.

Bond, N. A., and D. E. Harrison, 2000: The Pacific Decadal Oscillation, air-sea interaction, and central north Pacific winter atmospheric regimes. *Geophys. Res. Lett*., **27**(5), 731-734.

Brown, R.D., and R. O. Braaten, 1998: Spatial and temporal variability of Canadian monthly snow depths, 1946-1995. *Atmos.-Ocean,* **36**, 37-54.

Curtis, J., G. Wendler, R. Stone, and E. Dutton, 1998: Precipitation decrease in the western Arctic, with special emphasis on Barrow and Barter Island, Alaska. *Int. J. Climatol*., **18**, 1687-1707.

Divoky G. J., 1998: Factors affecting the growth of a Black Guillemot colony in northern Alaska, Ph.D. dissertation. University of Alaska, Fairbanks, Alaska.

Dutton, E. G., and D. J. Endres, 1991: Date of snow melt at Barrow, Alaska, USA. *Arctic Alpine Res.,* **23**(1), 115-119.

Foster, J. L., J. W. Winchester, and E. G. Dutton, 1992: The date of snow disappearance on the Arctic tundra as determined from satellite, meteorological station and radiometric in situ observations. *IEEE Transactions on Geoscience and Remote Sensing,* **30**(4), 793-798.

Foster, J. L., 1989: The significance of the date of snow disappearance on the arctic tundra as a possible indicator of climatic change. *Arctic Alpine Res.,* **21**(1), 60-70.

Groisman, P., T. R. Karl, and R. W. Knight, 1994: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. *Science,* **263**, 198-200.

Harris, J. M., and J. D. W. Kahl, 1994: Analysis of 10-day isentropic flow patterns for Barrow, Alaska; 1985-1992. *J. Geophys. Res*., **99**(D12), 25,845-25,855.

Houghton, J. T., L. G. M. Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (Eds.), 1996: *Climate Change 1995: The science of climate change,* p. 572, Cambridge University Press, Cambridge, United Kingdom.

Keeling, C. D., J. F. S. Chin, and T. P. Whorf, 1996: Increased activity in northern vegetation inferred from atmospheric CO_2 measurements. *Nature,* **382**, 146-149.

Kuang, Z., and Y. L. Yung, 2000: Observed albedo decrease related to the spring snow retreat. *Geophys. Res. Lett.,* **27**(9), 1299-1302.

Maslanik J. A., M. C. Serreze, and R. G. Barry, 1996: Recent decreases in Arctic summer ice cover and linkages to atmospheric circulation anomalies. *Geophys. Res. Lett.,* **23**, 1677-1680.

Maykut, G. A. and P. E. Church, 1973: Radiation climate of Barrow, Alaska. *J. Appl. Meteorol.,* **12**, 620-628.

Myneni, R. B., C. D. Keeling, C. J. Tucker, G. Asrar and R. R. Nemani, 1997: Increased plant growth in the northern high latitudes from 1981 to 1991. *Nature,* **386**, 698-702.

Oechel, W. C., G. L. Vourlitis, S. J. Hastings and S. A. Bochkrez, 1995: Effects of Arctic CO_2 flux over two decades: Effects of climate change at Barrow, Alaska. *Ecol. Appl.,* **5**, 846-855.

Osterkamp, T. E. and V. E. Romanovsky, 1999: Evidence for warming and thawing of discontinuous permafrost in Alaska. *Permafrost Periglacial Proc.,* **5**, 137-144.

Overland, J. E., J. M. Adams, and N. A. Bond, 1998: Decadal variability of the Aleutian Low and its relation to high-latitude circulation. *J. Climate,* **12**(5), 1542-1548.

Serreze, M. C., J. E. Walsh, F. S. Chapin III, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W. C. Oechel, J. Morison, T. Zhang, and R. G. Barry, 2000: Observational evidence of recent change in the northern high-latitude environment. *Climatic Change,* **46**, 159-207.

Stone, R. S., E. Dutton, J. Harris, and D. Longenecker, 2001: Earlier spring snowmelt in northern Alaska as an indicator of climate change. *J. Geophys. Res*., in review.

Stone, R. S, 1997: Variations in western arctic temperatures in response to cloud-radiative and synoptic-scale influences. *J. Geophys. Res.,* **102**(D18), 21,769-21,776.

Stone, R., T. Mefford, E. Dutton, D. Longenecker, B. Halter, and D. Endres, 1996: Surface radiation and meteorological measurements: January 1992 to December 1994. *Data Rep. ERL-CMDL-11*, p. 81, NOAA Environ. Res. Labs., Boulder, Colorado.

Thompson, D. W. J. and J. M. Wallace, 1998: The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. *Geophys. Res. Lett.,* **25**(9), 1297-1300.

Trenberth, K. E., and J. W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific. *Clim. Dyn.,* **9**, 303-319.

Yang, D., B. E. Goodison, C. S. Benson, and S. Ishda, 1998: Adjustment of daily precipitation at 10 climate stations in Alaska: Application of the World Meteorological Organization intercomparison results. *Water Resour. Res.,* **34**(2), 241-256, 1998.