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An Intercomparison of Regional Atmospheric Circulation and the Melt Season Loss of Arctic Snow Cover and Sea Ice Extent Across the Land-Ocean Boundary

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An Intercomparison of Regional Atmospheric Circulation and the Melt Season Loss of Arctic Snow Cover and Sea Ice Extent Across the Land-Ocean Boundary

by

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An Intercomparison of Regional Atmospheric Circulation and Melt Season Loss of Arctic Snow Cover and Sea Ice Extent Across the Land-Ocean Boundary

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This study is designed to compare the monthly continental snow cover and sea ice extent loss in the Arctic with regional atmospheric conditions including: mean sea level pressure, 925 hPa air temperature, and mean wind direction among others during the melt season (March-August) over the 29-year study period 1979-2007. Little research has gone into studying the concurrent variations in the annual loss of continental snow cover and sea ice extent across the land-ocean boundary, since these data are largely stored in incompatible formats. However, the analysis of these data, averaged spatially over three autonomous study regions located in Siberia, North America, and Western Russia, reveals a distinct difference in the response of snow and sea ice to the atmospheric forcing. On average, sea ice extent is lost earlier in the year, in May, than snow cover, in June, although Arctic sea ice is located farther north than continental snow in all three study regions. Once the loss of snow and ice extent begins, snow cover is completely removed sooner than sea ice extent, even though ice loss begins earlier in the melt season. Further, the analysis of the atmospheric conditions surrounding loss of snow and ice cover over the independent study regions indicates that conditions of cool

temperatures with strong northeasterly winds in the later melt season months are effective at removing sea ice cover, likely through ice divergence, as are warmer temperatures via southerly winds directly forcing melt. The results of this study set the framework for further analysis of the direct influence of snow cover loss on later melt season sea ice extents and the predictability of snow and sea ice extent responses to modeled future climate conditions.

Acknowledgements

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Chapter 1

Introduction

Concern over the rapid changes in the Arctic cryosphere in recent years has spurred much research into the response of sea ice and snow cover to warming temperatures and the resulting climate feedbacks. However, the vast majority of Arctic climate studies does not assess the response of both continental snow cover and sea ice in concert to the atmospheric conditions present through the data record.

The purpose of this study is to assess the response of both Arctic sea ice and snow cover to the regional scale to melt season atmospheric forcing. By looking at the response of both snow and sea ice cover, one can get a comprehensive look at the cryosphere and determine how snow and sea ice respond to melt forcing through the satellite record. This study focuses on the annual loss of snow and sea ice cover in the Arctic across the land-ocean boundary in three separate study regions located throughout the Arctic region over a 29-year study period (1979-2007). The melt season is defined as the spring and summer months from March through August, before fall freeze-up begins. Anomalous snow and sea ice conditions in three study regions along with the mean atmospheric conditions are analyzed within the hemispheric-scale circulation in three case study years and in the three study regions independently through the 29-year study period during the months of greatest annual variability in the extent of snow and sea ice cover.

The results of the analyses will give insight into how snow cover and sea ice respond to direct atmospheric forcing including: mean sea level pressure, 925 hPa air temperature, and mean wind direction and some of the factors in the early melt season that may influence the loss of snow and ice during the remaining melt season. Looking at melt conditions through the 29-year record, will give an idea of how predictable the response in sea ice and snow cover will be to given atmospheric conditions and also highlight the instances where additional factors may be contributing to the melt response. This systematic assessment of atmospheric circulation patterns is intended to provide a basis for additional research in the hopes of resolving how the Arctic cryosphere will respond to potential changes in future climate.

Chapter 2

Background

2.1 Arctic Sea Ice

2.1.1 Annual Sea Ice Loss and Melt

Arctic sea ice is an important component of the climate system and variations in the age and extent of sea ice cover greatly impact the heat budget of the Arctic by regulating surface air temperatures and changing the surface albedo (Barry et al. 1993, Belchansky et al. 2004, Ogi et al. 2008, Kwok et al. 2009). During the fall, winter, and early spring the presence of sea ice cover acts as an insulator, preventing the exchange of heat from the warmer ocean waters to the cold atmosphere at the surface (Ledley 1993, Serreze & Francis 2006). Conversely, when leads in the ice form and sea ice begins its retreat in the summer, heat and moisture from the open ocean is freely exchanged with the atmosphere. The presence of sea ice cover constrains the summertime air temperatures to near freezing (Ogi & Wallace 2007); however, a daily high temperature only a fraction of a degree above the freezing point is enough to induce melt (Perovich et al. 2007). Once mean daily air temperatures reach -1.2° C, melting in snow cover on the sea ice can occur, leading to reduced surface albedo when leads in the ice open up (Ledley 1993) or melt ponds form several weeks later (Barry et al. 1993).

Satellite observations of the onset of melting on Arctic sea ice are found using the range between passive microwave channels. Melt onset occurs from the presence of liquid water within the snowpack causing a jump in the brightness temperatures for the sea ice surface. The change in brightness temperature is due to the high emissivity of water compared to dry snow and results in a pinpointed date on which melting first occurs (Anderson 1987, Anderson & Drobot 2001, Forster et al. 2001, Belchansky et al. 2004). The annual progression of melt onset generally begins at the lower latitudes and progresses to higher latitudes later in the melt season. However, this northward progression is highly variable, due to synoptic-scale atmospheric activity (Forster et al. 2001) and the individual climate regimes of each location (Anderson & Drobot 2001).

The timing of the annual onset of melting of snow and ice in the Arctic has a strong impact on the total amount of solar radiation absorbed by the ice-ocean system. The date on which melting on sea ice begins in the spring is exceedingly important. This is due to increasing incident solar radiation as the sun rises higher in the Arctic sky in combination with falling albedoes as more open ocean and melt ponds on the sea ice form (Perovich et al. 2007). Early melting in the Arctic lengthens the time period in which ocean and melt pond water can absorb increasing daily amounts of solar radiation before the incident solar radiation declines after the summer solstice. While solar radiation incident in the Arctic peaks in June at the summer solstice, the largest amount of solar radiation absorbed by the Arctic climate system occurs through the months of June and July (Perovich et al. 2007). During these months, the balance of high incident solar radiation with reduced sea ice concentrations, resulting from melting in the ice pack, maximizes the affects of the snow-ice albedo feedback (Curry et al. 1995, Belchansky et al. 2004, Perovich et al. 2007). Since solar radiation in the Arctic gradually tapers off through the summer months, the timing of freeze-up in the fall does not impact the next year’s ice conditions to the same extreme that early melt onset influences the annual low September sea ice extent for the current year (Belchansky et al. 2004, Perovich et al. 2007).

2.1.2 Sea Ice Extent

Since the satellite sea ice record began at the end of 1978, trends in the extent, age, and volume of Arctic sea ice have been closely monitored. Through the record, sea ice cover has been declining steadily except for the most recent decade when this decline has accelerated dramatically. Between 1979 and 1996, the rate of sea ice extent decline was about 2.2% per decade and since 1997, this decline has accelerated to a rate of 10.1% per decade (Comiso et al. 2008) with 2007 being the current record-holding annual low sea ice extent year through 2009 (NSIDC 2010).

Sea ice extent reaches its annual maximum in late February and early March and begins its decline through the spring and summer months reaching its annual low during September. Since the satellite sea ice record began, normal sea ice extent at the beginning of the melt season in March averages 15.19 x 10^6 sq km (Figure 2.1, Table 2.1), slowly decreases through April and May, and begins to reduce more rapidly through June, July, and August, finally reaching the minimum average extent of 6.83 x 10^6 sq km during September.

Through the 29-year climatology, most of the Central Arctic Basin is 100% ice covered in March and April (Figure 2.1). The first major reduction in ice concentration begins in April through the marginal seas and progresses northward through the summer as the amount of solar radiation reaches an intensity great enough to induce melting in the snowpack from sensible heating at progressively northward latitudes (Belchansky et al. 2004), in addition to regional atmospheric forcing. At the end of the melt season, the

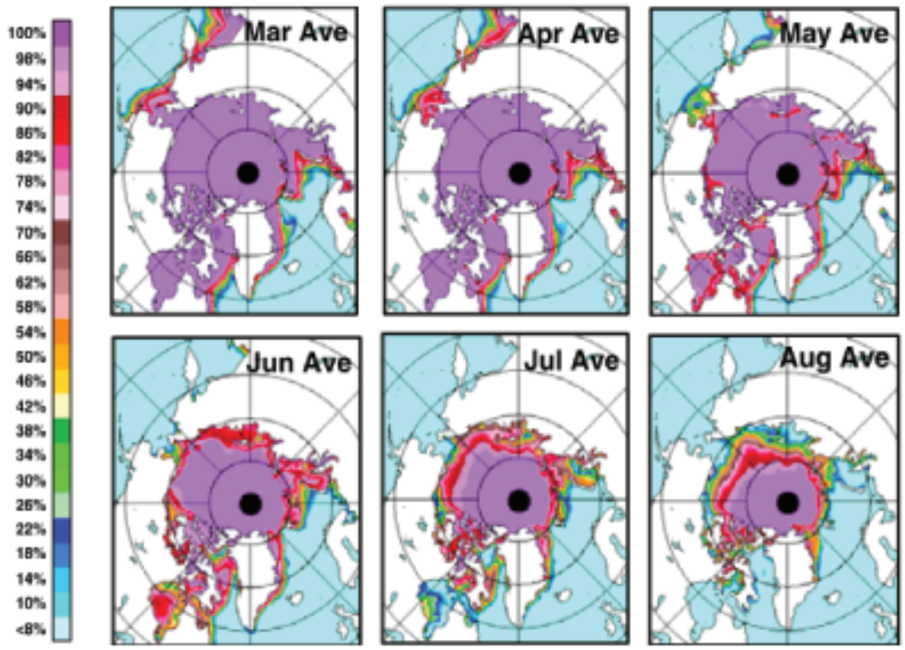

Figure 2.1 Monthly mean sea ice concentrations (1979-2007) [Adapted from Comiso et al. 2008].

Table 2.1 Monthly mean Arctic sea ice extents (10^6 km^2) for the 1979-2007 Climatology [Adapted from Comiso et al. 2008].

	March	April	May	June	July	August	September
Sea Ice Extent	15.19	14.47	13.11	11.78	9.70	7.50	6.83

normal minimum sea ice extent edge leaves portions of the Kara, Laptev, East Siberian, Chukchi, and Beaufort Seas without ice cover (Figure 2.2). In recent record-breaking years over the past decade, the most sea ice extent loss occurs in these marginal seas (i.e. Rigor & Wallace 2004, Stroeve et al. 2006, Maslanik et al. 2007, Comiso et al. 2008, Deser & Teng 2008) (Figure 2.2). Throughout the record, sea ice persists through the summer in the Central Arctic and north of the Canadian Archipelago and Greenland where the largest amount of thick multiyear ice is concentrated (Figures 2.1, 2.3).

2.1.3 Sea Ice Thickness

The sea ice pack that is not held fast to a landmass is almost constantly in motion. Winds are the main driver of sea ice motion with ocean currents also providing some ice transport (Serreze et al. 1995, Lindsay et al. 2009). Two main transport features: the Beaufort Gyre and the Transpolar Drift Stream are responsible for most of the mean sea ice transport. The Beaufort Gyre is a clockwise moving rotation of the ice in the Western Arctic, which causes ice to converge and thicken in the Western Arctic north of Greenland and the Canadian Archipelago. The Transpolar Drift Stream exports sea ice away from the Siberian Coast, across the Arctic Basin, and out through Fram Straight. These two large-scale transport features thicken the sea ice cover via sea ice convergence in the Western Arctic where the ice is more likely to last through the summer melt season and age into multiyear sea ice (Lindsay et al. 2009). Sea ice is advected away from the Siberian coast, thinning remaining ice via sea ice divergence where it is less able to survive a melt season and must reform during the next winter (Vavrus & Harrison 2003).

Multiyear sea ice decline has been inferred from the passive microwave satellite record using the remaining sea ice area and sea ice extent data at the end of the melt

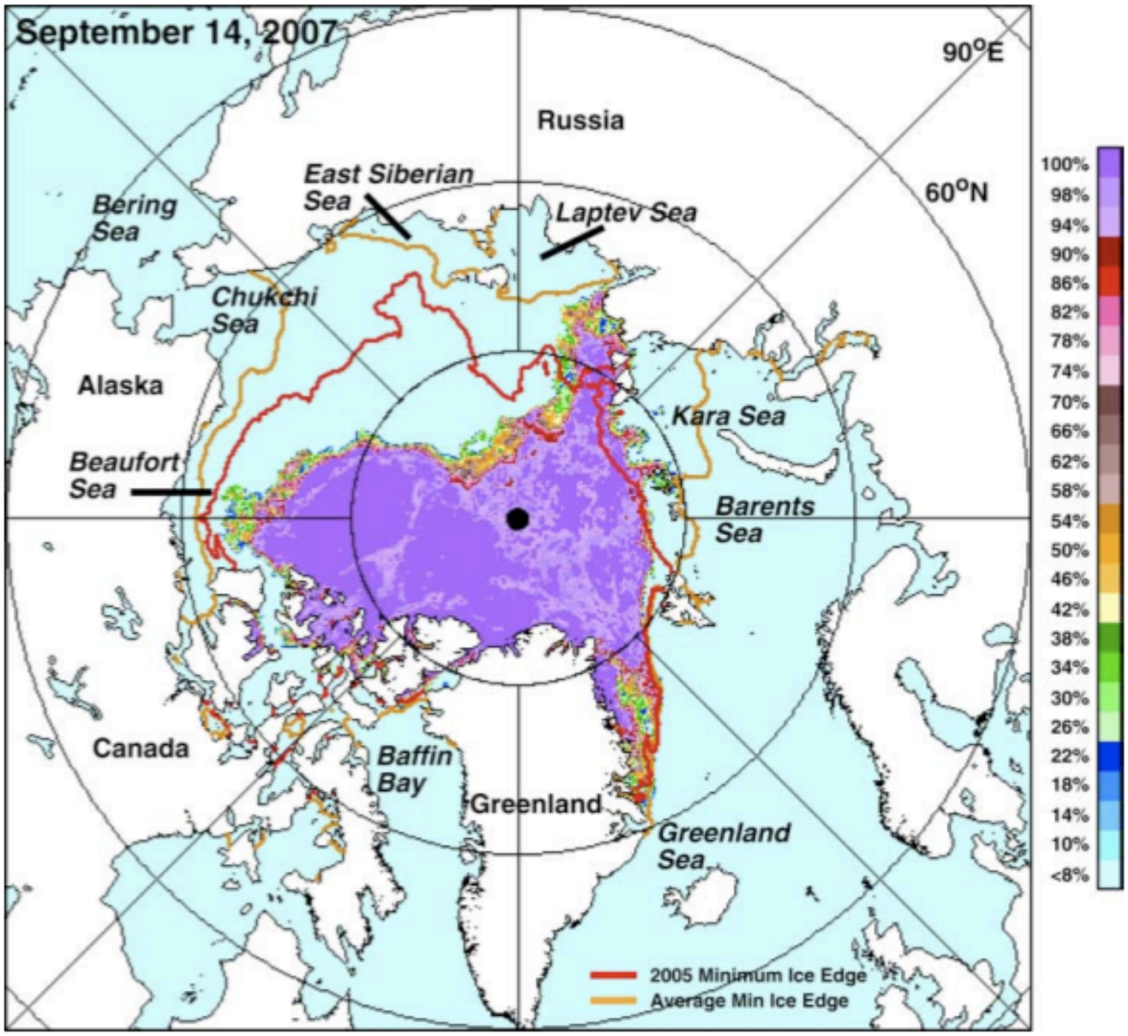

Figure 2.2 Arctic sea ice concentration for 14 September 2007, the record low annual minimum sea ice extent. The yellow line identifies the average minimum September sea ice extent for the period 1979-2006. The red line identifies the second place record for low September minimum sea ice extent in 2005 [From Comiso et al. 2008].

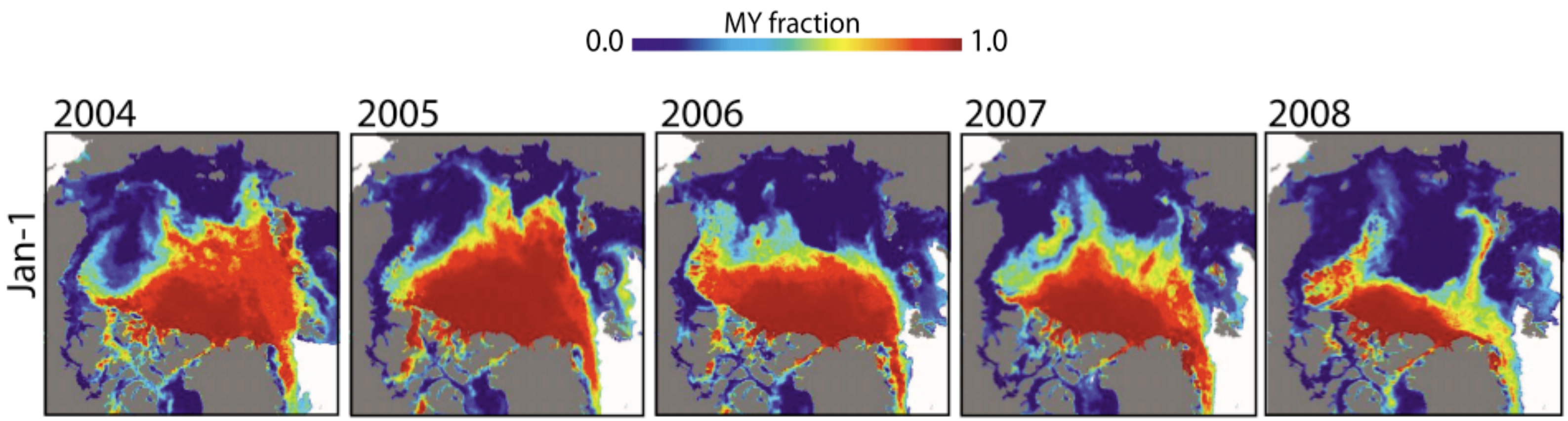

Figure 2.3 Multiyear ice fraction on 1 January 2004-2008 [Adapted from Kwok et al. 2009].

season. It is assumed that by the end of the melt season, any thin, first-year sea ice that has survived melting, combined with the thick, multiyear ice from previous years make up the next year's multiyear extent. Most multiyear ice is found in the Central Arctic or in the Western Arctic north of Greenland and the Canadian Archipelago (Figure 2.3). A 9% per decade decline in multiyear sea ice was reported between 1978 and 2000 (Comiso et al. 2002). A more recent study of the thickness and volume of sea ice cover from 2003 through 2008 using ICESat lidar data has indicated that total multiyear sea ice volume in the winter has lost 6,300 cu km, more than 40% ice volume since 2005 (Kwok et al. 2009). Most of the loss of multiyear ice in the last half of the decade has been from the Central Chukchi Sea, Beaufort Sea, Laptev Sea, and extending into the Central Arctic Basin (Figure 2.3). The remaining multiyear ice is still concentrated in the Western Arctic, north of the Canadian Archipelago and Greenland, a result of the Beaufort Gyre.

2.1.4 Atmospheric Forcing

At the regional scale, it has been shown that low annual September sea ice extents are influenced by preconditioning factors which force a thinner sea ice pack at the beginning of the melt season and atmospheric forcing through the spring and summer which increase melt and transport of sea ice through the melt season (Rigor & Wallace 2004, Deser & Teng 2008, Ogi et al. 2008). These preconditioning factors can include the extensive loss of multiyear sea ice in previous years (Ngheim et al. 2007), overall thinning of the multiyear ice cover (Kwok et al. 2009), and warm winter months hindering sea ice growth in extent and thickness (Comiso et al. 2008). Some summer circulation conditions that can compound the effects of preconditioning include: warm air advection via southerly surface winds, the wind-driven transport of ice northward away from the coastlines, and the export of sea ice out of the Arctic completely (Zhang et al. 2000, Comiso et al. 2008, Ogi et al. 2008, Lindsay et al. 2009). In fact, slight displacements in the relative location of low or high pressure systems can greatly change the local ice transport and influence local sea ice extent on a day-to-day basis (Maslanik et al. 2007).

Through 2009, 14 September 2007 marked the record lowest sea ice extent at 4.1 x 10^6 sq km, 37% below normal (Comiso et al. 2008). Most of the reduction in sea ice extent was focused in the marginal seas of the Arctic Basin including: the Beaufort, Chukchi, East Siberian, Laptev, and Kara Seas (Figure 2.2). This anomalously low September sea ice extent is a perfect example of the combination of preconditioning factors and anomalous summer conditions. The ongoing loss of multiyear ice and replacement with first-year ice (Ngheim et al. 2007), warmer wintertime air temperatures inhibiting the extent and thickness of first-year sea ice growth, anomalously high air temperatures dominating the spring and summer months, and anomalous southerly winds in the Chukchi and Beaufort Seas aided in the northward push of the sea ice extent boundary combined to create the record-breaking sea ice conditions of 2007 (Comiso et al. 2008). These factors caused a precipitous decline in extent from mid-June to mid-September from an otherwise normal early start to the melt season (Comiso et al. 2008).

2.2 Hemispheric Snow Cover Extent

Annual Northern Hemispheric snow cover extent is also highly variable. The snow cover reaches a maximum during the months of January and February after rapidly accumulating through the fall season beginning in September. Spring and summer ablation, however, occurs more slowly until reaching the annual minimum extent in August. Through the spring and summer months the southernmost snow cover extents retreat northward until August when only the Greenland ice sheet and a few mountainous ice caps remain snow covered (Robinson & Frei 2000).

Annual snow cover extent varies based on a number of atmospheric controls including temperature and the availability of moisture for precipitation. In Europe and southwestern Asia, temperatures are the main control of inter-annual snow cover variability. Whereas in Eastern Asia and Siberia, where winter temperatures are colder, variation in snow extent is more controlled by the availability of moisture (Clark et al. 1999). These relationships between temperature, moisture, and the resultant snow cover also occur in Canada. At the coldest Canadian land-locked weather stations an increase in mid-winter temperatures increases snowfall amounts due to an increase in potential moisture content of the air (Davis et al. 1999). Conversely, stations located in areas with higher mean winter temperatures, nearer to the coasts, see a decrease in the amount of snowfall as temperatures rise due to a lack of sufficiently deep cold air at the surface. However, despite these general relationships, snow cover extent is highly variable both inter- and intra-annually.

Below freezing temperatures are needed to maintain snow-covered ground, thus snow cover extent is inversely related to air temperature (Robinson & Dewey 1990). However, the presence of snow-covered ground, like sea ice cover, also has the ability to influence surface air temperatures. It has also been suggested that through a number of climate feedbacks that are not yet thoroughly understood, snow cover extent influences hemispheric scale circulation patterns at 500 hPa heights and sea level pressures (Frei &

Robinson 1999, Cohen & Entekhabi 2001). Since research has shown that conditions in the Arctic cryosphere both respond to and influence atmospheric forcing, it is important to look at the simultaneous snow cover and sea ice conditions through the record .

Chapter 3

Data and Methods

3.1 Data

The focus of this study is to compare monthly atmospheric conditions and the corresponding impacts on the snow and sea ice cover across the land-ocean boundary. To perform this study, four types of data are used. These include: monthly hemispheric satellite snow cover extent on land, passive microwave derived monthly Bootstrap sea ice concentrations and snow melt onset dates over sea ice, and monthly model assimilated atmospheric data.

The monthly Northern Hemispheric snow cover extent over land are available from Rutgers University Global Snow Lab [available online at http://climate.rutgers.edu/snowcover/]. These data are produced using visible satellite imagery from the Very High Resolution Radiometer launched in 1972 and Advanced Very High Resolution Radiometers since 1978 (Robinson et al. 1993, Robinson & Frei 2000). Monthly data are produced by weighting NOAA weekly snow cover maps based on the number of days of the week that fall within the month, resulting in the average monthly extent of snow cover. The weekly snow cover extent grids present a binary value (snow-covered or snow-free) for the snow condition at each grid point for the last cloud-free day of the week, using a 50% snow-covered threshold. The grid for these data is an 89 x 89 cell Cartesian grid over a polar stereographic projection of the Northern Hemisphere. The resolution of this grid is very coarse, which results in a ground cover resolution ranging from 16,000 to 42,000 sq km per pixel across the hemisphere. Although coarse, these data are the longest consistent record of snow cover at the hemispheric scale. Hemispheric snow cover data are now available at a finer resolution; however, these data do not extend far enough back in time (since 1998) to be appropriate for use in this study.

Passive microwave derived monthly Bootstrap algorithm sea ice concentrations were chosen for this study (Comiso 2008). These data extend back to October 1978 when the Scanning Multichannel Microwave Radiometer (SMMR) sensor was launched and was later replaced by a series of several Special Sensor Microwave/Imagers (SSM/I). Like many sea ice concentration algorithms, the Bootstrap ice concentration for a given location can be expressed as

$$C_I = \frac{T_B - T_O}{T_I - T_O}$$

where T_B is the sensor-measured brightness temperature, T_O is the brightness temperature of open ocean water, and T_I is the brightness temperature of sea ice (Comiso 2007). To determine the unknowns (T_I and T_O) under given atmospheric and ocean surface conditions, the range between two microwave channels at the horizontal or vertical polarizations is selected to maximize the differences in emissivity between open ocean and the sea ice surface (Comiso 2007). The resulting sea ice concentrations are presented as a 304 x 448 pixel grid centered over the North Pole with a 625 sq km (25 x 25 km) resolution.

The snowmelt onset dates over sea ice used in this study are derived from the SMMR and SSM/I passive microwave brightness temperatures and provide the date on which melting begins within the snowpack on sea ice cover (Drobot & Anderson 2001). The melt onset algorithm utilizes the difference between the horizontally polarized 19 GHz (18 GHz from the SMMR record) and 37 GHz daily brightness temperatures (Anderson & Drobot 2001). When this difference nears zero or less than zero, the emissivity in the snowpack reaches that of water and it can be assumed that melting is taking place in the snow cover. The date on which liquid water first becomes present in the snowpack is assigned to each pixel point location. This data set is available with the same 304 x 448, 625 sq km resolution grid as the Bootstrap sea ice concentrations, excluding a 2-pixel no-data buffer to prevent land contamination.

The atmospheric data used in this study are from the NCEP DOE AMIP-II Reanalysis Project (hereafter Reanalysis 2) (NOAA 2010). Reanalysis 2 is a globally gridded data set of multiple atmospheric variables that extends from 1979 to present. The global data are model assimilated from multiple types of quality controlled atmospheric observations over the data record using one state-of-the-art modeling system consistently through the entire project analysis record (Kanamitsu et al. 2002). Essentially, a global circulation model is employed to propagate observations from data rich locations, to areas globally where the observational record is poor while continuously reinitializing the boundary conditions based on the observational data.

Several atmospheric variables that are known to be related to melting in snow and ice cover were chosen from the Reanalysis 2 set of data for this study including: mean sea level pressures, percent cloud cover through the entire atmospheric column, 500 hPa geopotential heights, 925 hPa air temperatures, and U and V vector wind components. The geopotential height, sea level pressure, and temperature data are 2.5° longitude by

2.5° latitude global gridded values while the cloud cover and U and V wind vector data are available in the T62 Gaussian global grid (Kanamitsu et al. 2002). Hereafter, temperature refers only to 925 hPa air temperature and pressure refers only to mean sea level pressure (MSLP), since these are the only temperature and pressure data used in this study.

3.2 Methods

This study is focused on a 29-year temporal scale from 1979 through 2007. The spring and summer melt season months including: March, April, May, June, July, and August are the main period of interest for each year. To complete the study, three domains were chosen; Eastern Russia (Siberia), Western Russia (Russia), and North America (Figure 3.1). Each domain contains a land-ocean boundary that is roughly parallel to latitude and extends from over land northward into an Arctic marginal sea that is subject to considerable inter-annual variability in the extent and retreat of both snow and sea ice during the warm season. Each domain area was also selected to include a minimal extent of mountainous areas where persistent snow cover throughout the year could misrepresent the seasonal northward progression of snow cover lost, relative to other land domains in the study.

Each study region is 20° in longitude by 10° in latitude (Figure 3.1). The first of these regions is the Siberian Region that ranges from 150 E to 170 E and 65 N to 75 N. The ocean portion of this domain extends into the East Siberian Sea. The second region is the North American Region, which ranges from 140 W to 120 W and 65 N to 75 N with the ocean portion of this region extending north into the Beaufort Sea. The third region is

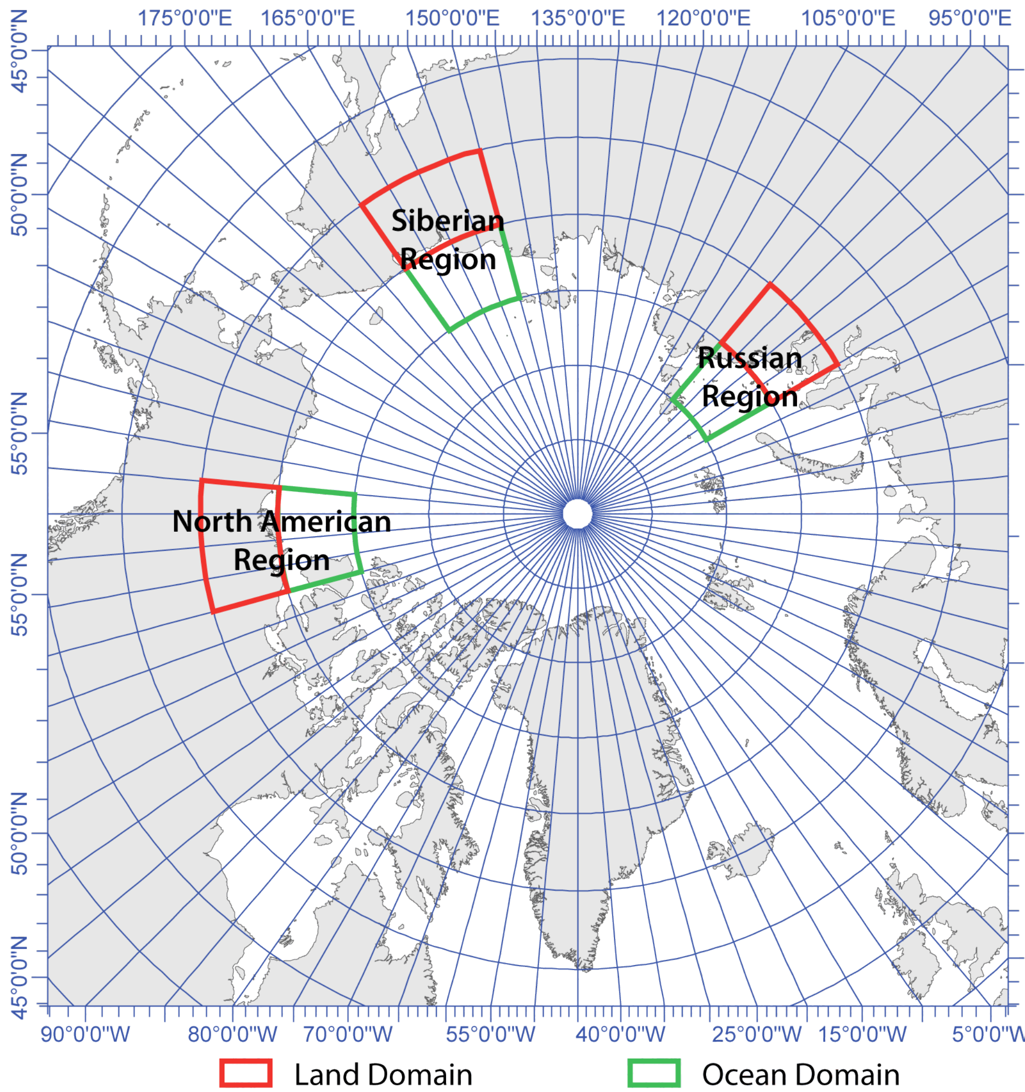

Figure 3.1 Locations of Siberian, North American, and Russian study regions. Land and ocean sub-regions are also identified.

the Russian Region (located west of the Siberian Region) that is defined from 75 E to 95 E and 70 N to 80 N. The ocean portion of this domain is located in the Kara Sea. For the analysis of sea ice concentration, snowmelt onset dates, and hemispheric snow cover, these data are restricted to the 20° in longitude by 5° in latitude ocean or land half of each complete study region (Figure 3.1).

For the three regions in this study, a ‘drop in the bucket’ method was used to calculate a spatial mean for each month for each of the atmospheric and cryospheric parameters. From the spatial means, the monthly anomalies for the snow, sea ice, and atmospheric data (excluding U and V vector wind components) were normalized to allow for meaningful comparisons. See Figure 3.2 for a key to interpret the atmospheric anomalies and the wind direction based on U and V vector components used in this study. The calculation of spatial means and normalized anomalies is necessary for this study because the data used have widely variable grid resolutions and map projections. Using a normalized anomalous value calculated from the spatial mean for each parameter for each study month also removes seasonal effects of the annual atmospheric cycle. However, the progressions of snow and sea ice melt are not independent of the affects of melting in previous months. For example, anomalously extensive sea ice cover present during July under warm conditions can be a result of cooler conditions and anomalously less melt during June, and an anomalous loss of sea ice extent during June reduces the amount of remaining ice cover at the beginning of July, that is, the amount of sea ice available to melt during July.

For the monthly hemispheric snow cover extent data, spatial areas of snow cover lost by month are calculated from qualitative snow-covered or snow-free data points.

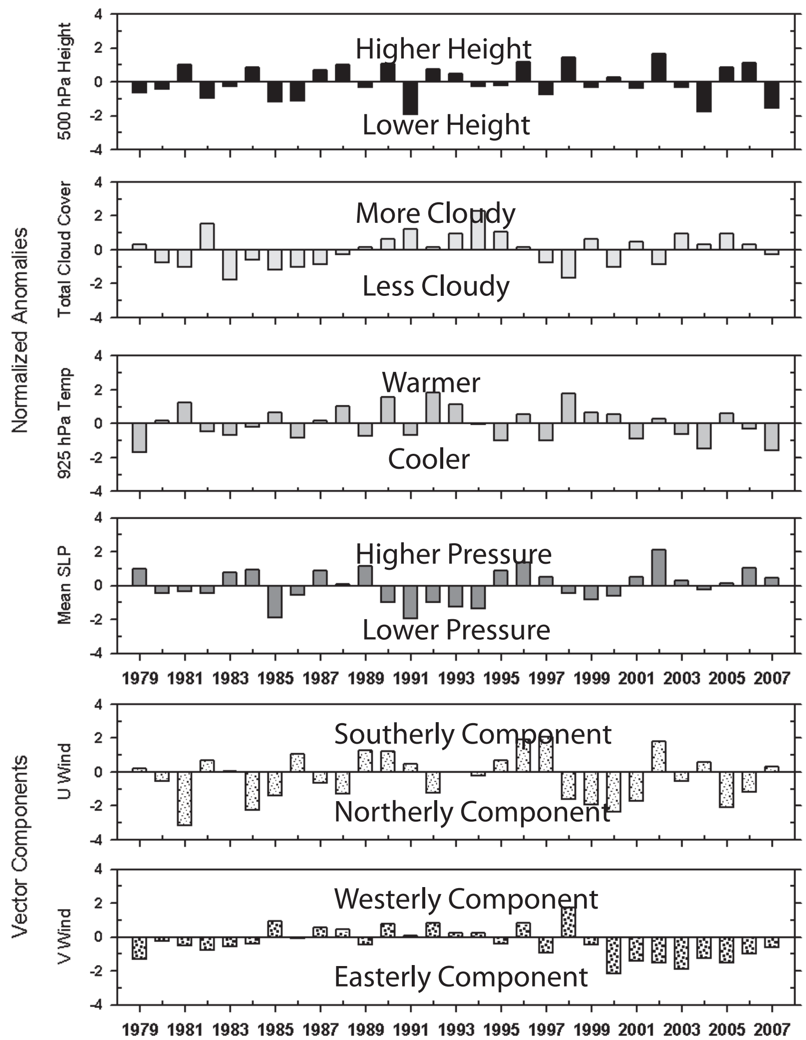

Figure 3.2 Key for interpreting monthly atmospheric anomalies and mean U and V vector wind components for study regions.

Grid points are considered snow-covered if they are at least 50% snow-covered at any time during the month within each land portion of the study domains. The qualitative snow-covered or snow-free categories are then quantified by summing the relative ground cover area for each snow-covered grid point for every month in each study region.

This study focuses on the relative changes in the extent of sea ice qualitatively meeting one threshold concentration rather than on the entire sea ice concentration range, since these data contain larger errors during the summer months (Maslanik et al. 1996). To make the snow and sea ice data as uniform as possible, a 50% sea ice concentration threshold is used to define areas that are sea ice-covered. This mirrors the threshold of the snow-covered land area data, allowing the sea ice data points to be qualitatively categorized as either sea ice-covered or sea ice-free in the same way that the snow cover extent data have been handled. Doing so allows for the calculation of the quantitative area of sea ice cover for the study months in each ocean domain. During the spring and summer months, melting on sea ice and the formation of melt ponds can result in an underestimation of the ice concentration by as much as 10-20% (Maslanik et al. 1996), thus using a concentration threshold de-emphasizes these errors.

A mean snowmelt onset date is calculated for all three ocean domains as well as the percentage of melted sea ice area in each domain by month. The percentage of melted sea ice area simply identifies the percentage of each domain area melted per study month annually. The calculation of a mean snowmelt onset date helps identify the cause of sea ice cover loss, distinguishing between melt or loss due to ice transport either out of the region or from ice convergence within the region caused by a shift in the mean wind direction.

The monthly atmospheric variables are spatially averaged and normalized over the full extent of each land-ocean domain. These atmospheric anomalies, combined with the individual continental snow cover and sea ice extents and snowmelt onset dates allow for an analysis across the land-ocean boundary. The use of adjacent land and ocean domains with atmospheric data averaged across both of these domains is an effort to merge the snow cover and sea ice condition data together with common variables.

Anomalous snow-covered land area and sea ice extent area are compared to the atmospheric parameters during the melting season throughout the 29-year period. Based on an analysis of the snow cover and sea ice extent anomalies, three snow and sea ice anomaly patterns are defined and most years in the study period are classified. Three case years, each representing a defined snow and sea ice anomaly pattern, are selected for further analysis to characterize and verify the regional atmospheric anomaly patterns in each melt season against the actual monthly Arctic-wide atmospheric patterns. Further, monthly snow cover and sea ice extent anomalies through the entire 29-year study period are characterized by atmospheric conditions present in each region. Analyzing the atmospheric conditions and resultant snow and sea ice responses, for each study region independently tests the influence that selected atmospheric parameters have on the variability of melt forcing in the snow and sea ice cover concurrently. The methods outlined above are utilized to perform an analysis across land-ocean boundaries in the Arctic with data that are typically not compatible because of the inconsistent gridding between data sets.

Chapter 4

Results I: Monthly Sea Ice and Snow Cover Extent Anomaly Observations

4.1 Annual Timing of Sea Ice and Snow Cover Extent Loss

Normalized anomalies of sea ice and snow cover extent have been calculated for the months of May, June, July, and August for the three study regions through the 29-year study period (Figures 4.1-4.8). The earliest sea ice extent losses, corresponding to negative sea ice extent anomalies, occur during May for all three domains (Table 4.1, Figure 4.1). Greatest sea ice extent variability occurs during the months of July in the North American Region and August in the Siberian and Russian Regions as the sea ice cover retreats towards the annual minimum in September (Tables 4.1, 2.1). The July peak in sea ice variability in the North American Region is likely due to the higher multiyear ice fraction present in the Beaufort Sea (Figure 2.3). During August when first-year ice continues to be removed in the Siberian and Russian Regions, multiyear ice cover is still present in the North American Region. The North American Region loses only 12.2% of area extent between July and August, much lower than the 40.5% and 31.3% lost in the Siberian and Russian Regions respectively (Table 4.1). The annual melt season total accumulated percentage of sea ice extent lost by August is only 46.1% for the North American Region as compared to 59.1% for the Siberian and 54.6% for the Russian Region (Table 4.1).

The annual loss of snow cover extent typically begins in the month of June for the North American and Siberian study regions, later than sea ice extent losses

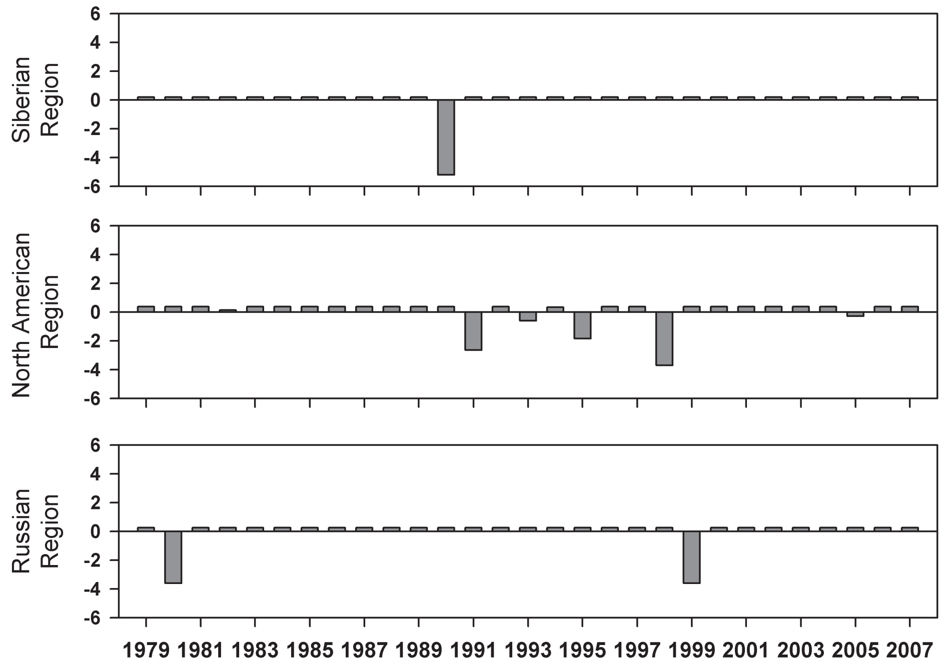

Figure 4.1 May normalized sea ice extent anomalies for the Siberian, North American, and Russian study regions.

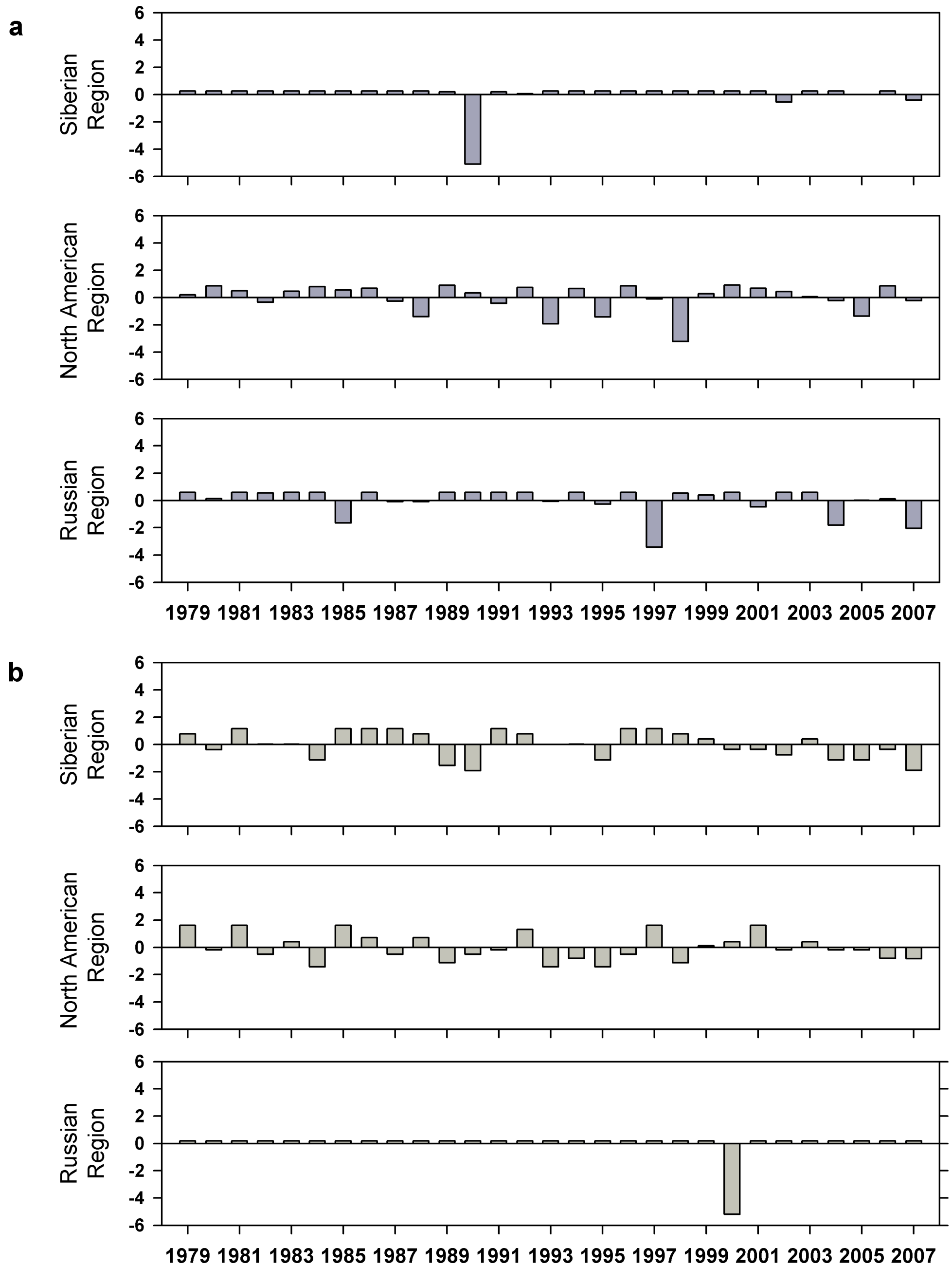

Figure 4.2 June normalized (a) sea ice extent and (b) snow cover extent anomalies for the Siberian, North American, and Russian study regions.

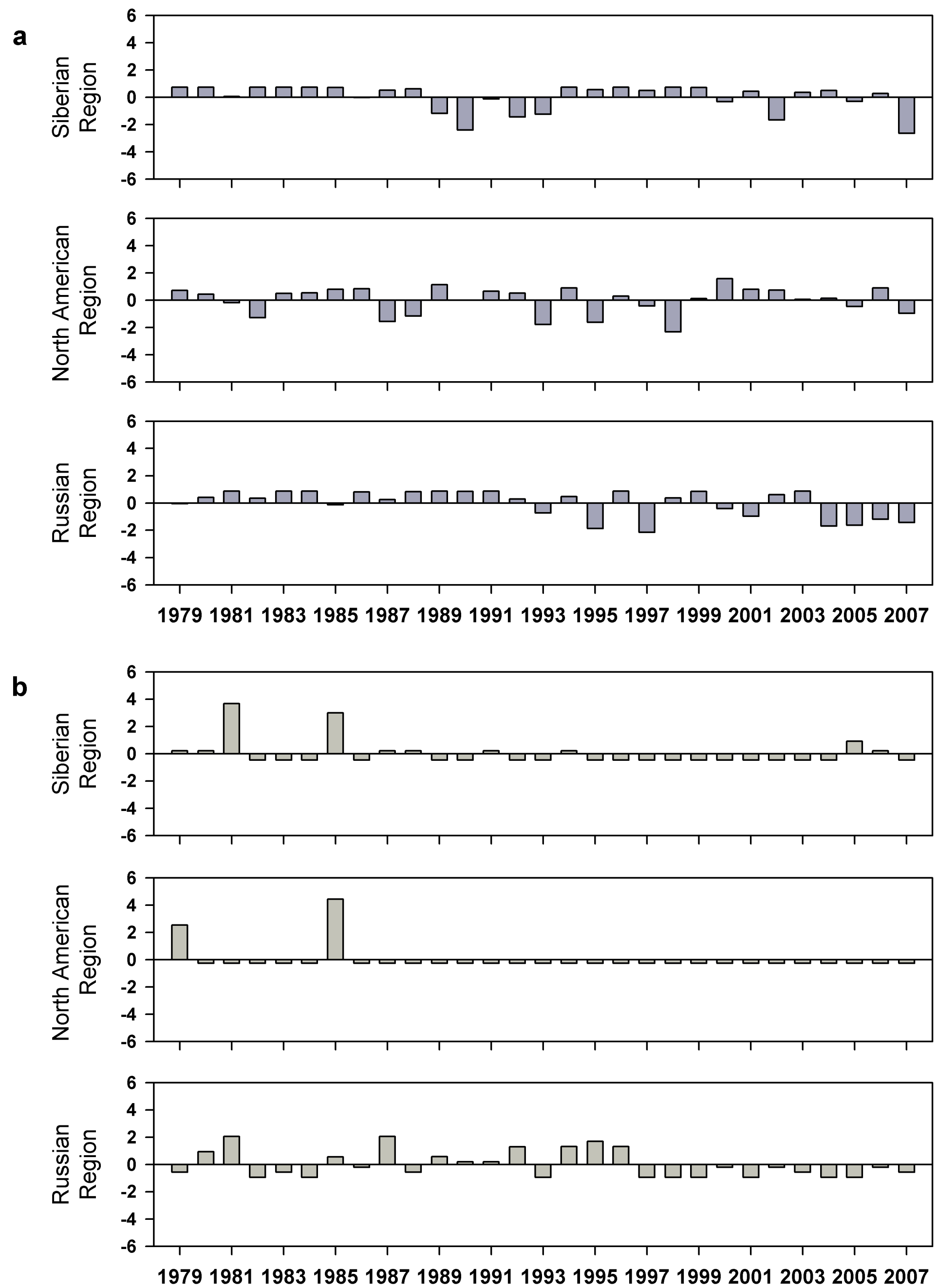

Figure 4.3 July normalized (a) sea ice extent and (b) snow cover extent anomalies for the Siberian, North American, and Russian study regions.

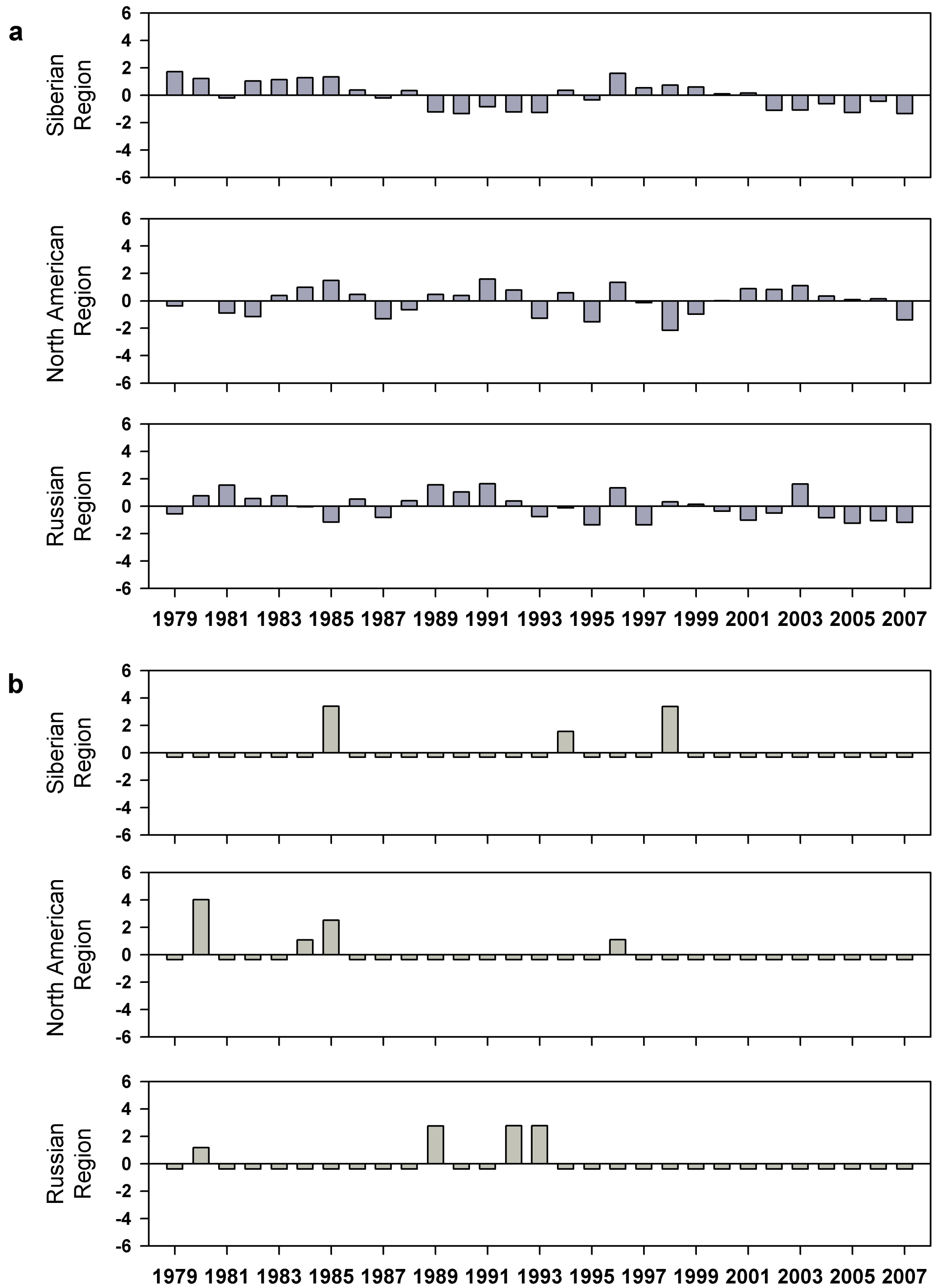

Figure 4.4 August normalized (a) sea ice extent and (b) snow cover extent anomalies for the Siberian, North American, and Russian study regions.

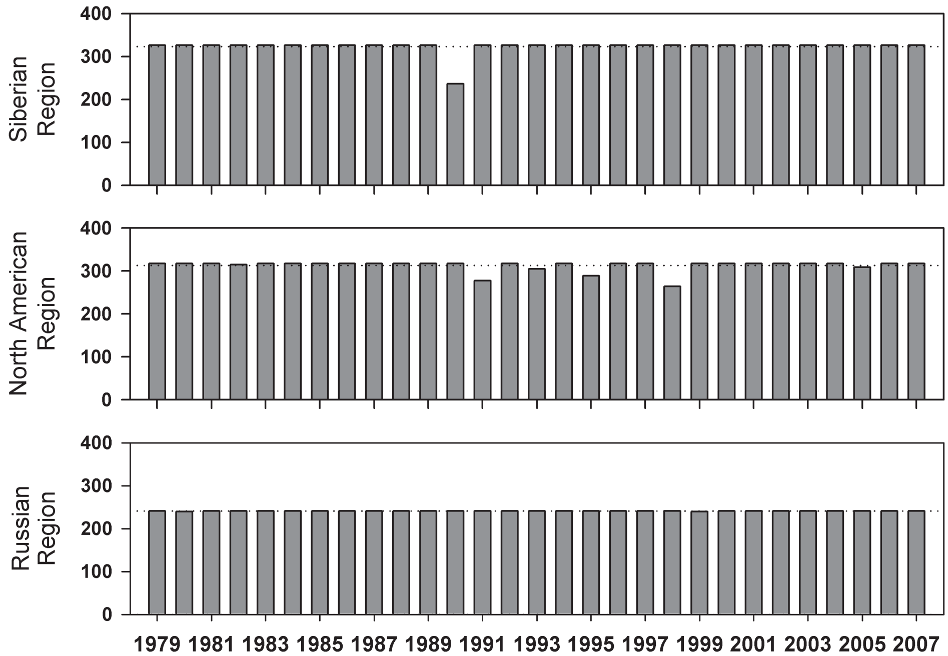

Figure 4.5 May sea ice extent area in 10^3 km^2 and mean extent (dotted line) for the Siberian, North American, and Russian study regions.

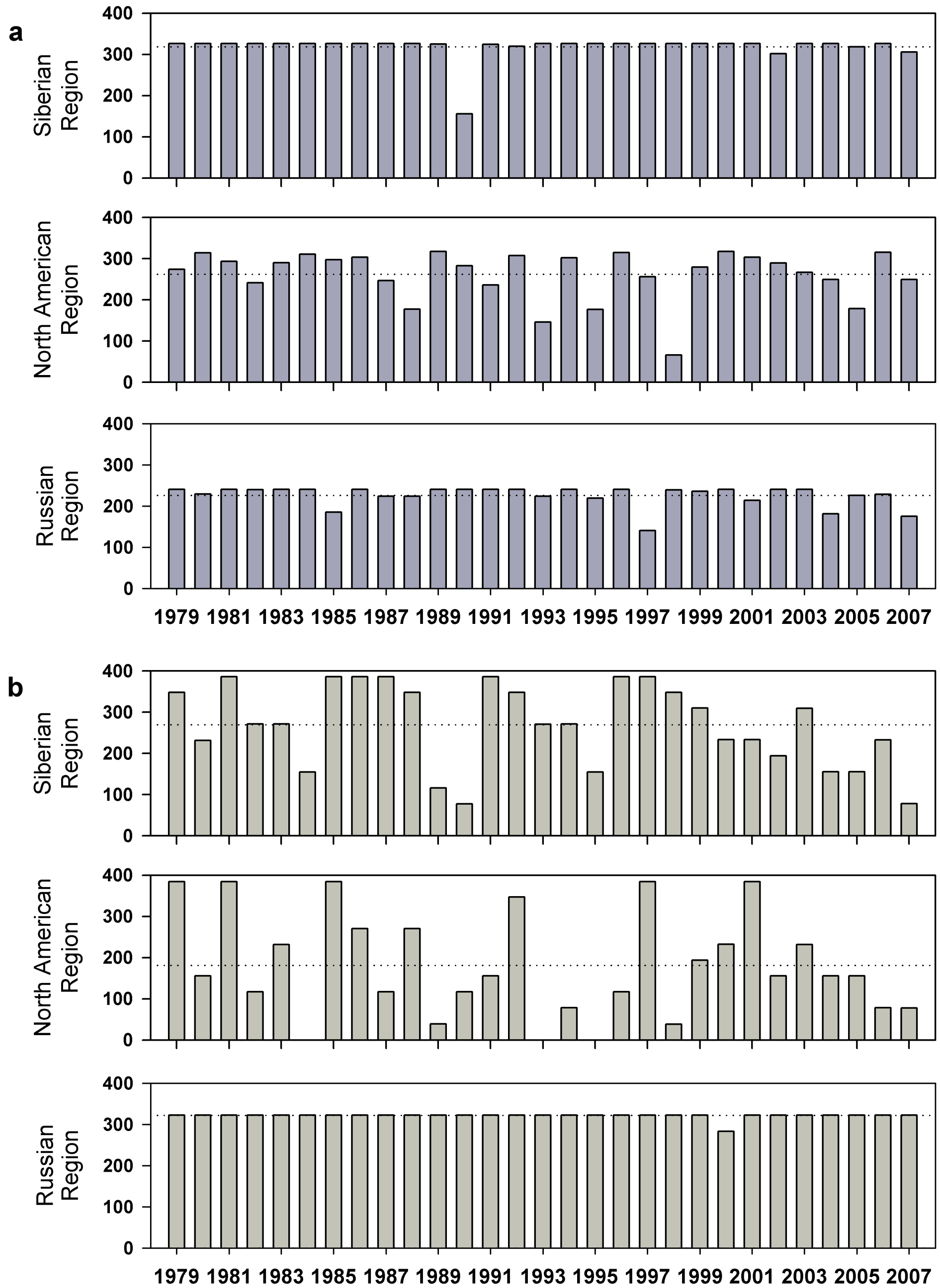

Figure 4.6 June (a) sea ice extent area and (b) snow cover extent area in 10^3 km^2 and mean extent (dotted line) for the Siberian, North American, and Russian study regions.

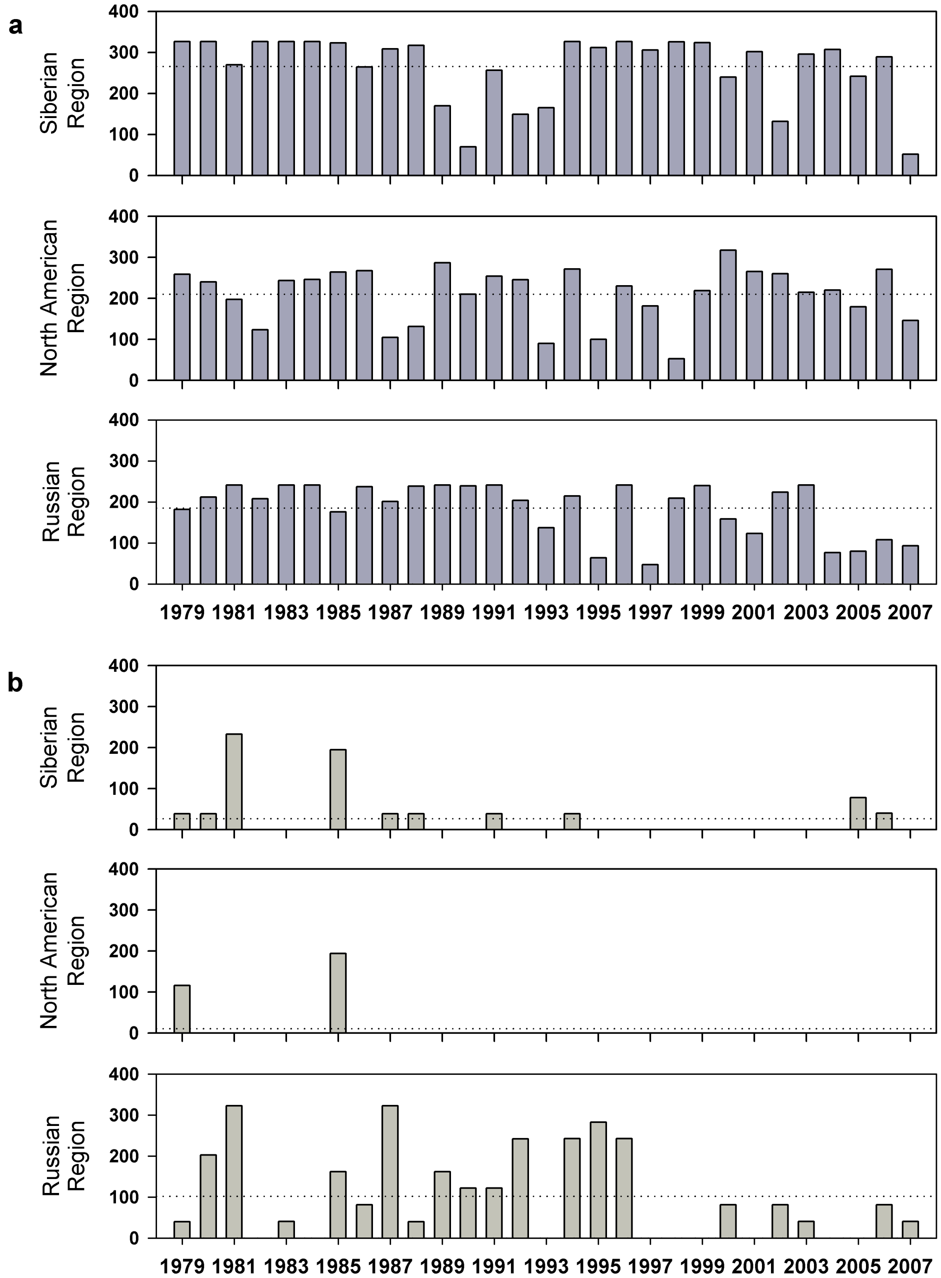

Figure 4.7 July (a) sea ice extent area and (b) snow cover extent area in 10^3 km^2 and mean extent (dotted line) for the Siberian, North American, and Russian study regions.

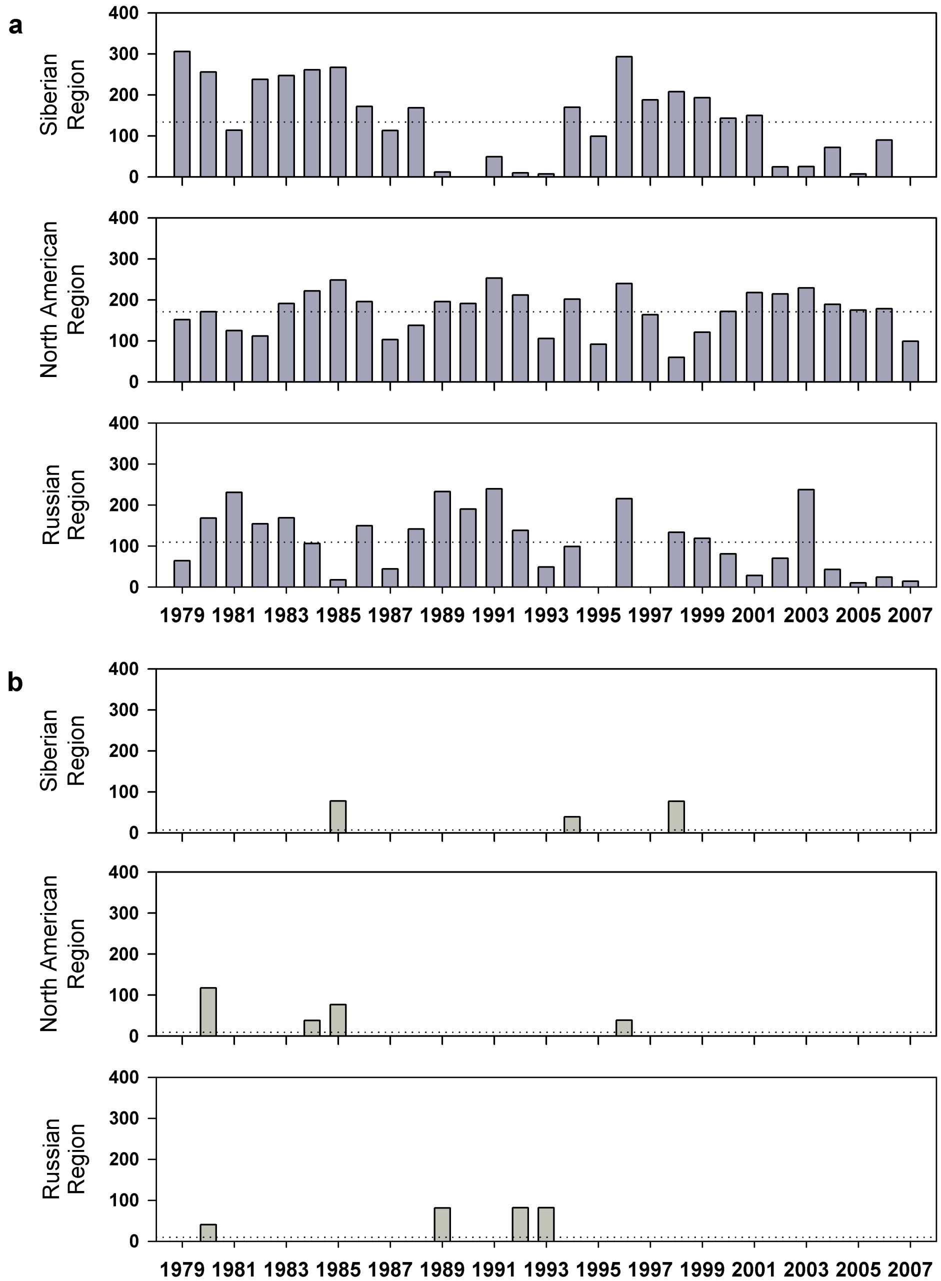

Figure 4.8 August (a) sea ice extent area and (b) snow cover extent area in 10^3 km^2 and mean extent (dotted line) for the Siberian, North American, and Russian study regions.

Table 4.1 Monthly means (10^3 km^2), standard deviations (10^3 km^2), and cumulative area lost percentage of sea ice extent for the Siberian, North American, and Russian study regions during the melt season (1979-2007).

	Siberian Region			North American Region			Russian Region		
	Mean	Std. Dev.	% Lost	Mean	Std. Dev.	% Lost	Mean	Std. Dev	% Lost
March	326.3	0.0	0.0	317.5	0.0	0.0	240.6	0.0	0.0
April	326.3	0.0	0.0	317.5	0.0	0.0	240.6	0.0	0.0
May	323.2	16.7	1.0	312.4	13.2	1.6	240.5	0.3	0.0
June	318.2	31.8	2.5	261.9	60.8	17.5	226.1	24.8	6.0
July	265.5	81.3	18.6	209.8	67.6	33.9	184.5	64.3	23.3
August	133.6	100.0	59.1	171.1	51.7	46.1	109.2	79.2	54.6

(Table 4.2, Figures 4.1-4.2). In the Russian Region, the annual loss of snow cover extent usually begins one month later, during July (Figure 4.3b). The exception was in 2000 when snow cover loss began anomalously early during June (Figure 4.2b). A greater amount (52.6%) of snow cover is lost in the North American Region during June than in the Siberian Region (30.2%) (Table 4.2). Although these two regions are at the same latitude (Figure 2.4), local geography allows for faster melt in the North American Region, because mountains to the south of the Siberian Region are likely able to dam colder temperatures from the north in the region, reducing the amount of snow cover lost as compared to the North American Region. The month of greatest variability in snow cover extent from year-to-year, or the month with the largest standard deviation, is June for the North American and Siberian Regions and July for the Russian Region (Table 4.2). By July, the majority of snow cover in the Siberian and North American Regions has been lost, 93% and 97.2% of the geographic area for each region respectively (Table 4.2). The snow cover extent anomalies also indicate that most snow cover in the North American and Siberian Regions has melted by July, due to the lack of early loss anomaly outliers (Figure 4.3b, 4.7b). Anomalous July snow conditions (positive anomalies) indicate an abnormal amount of snow cover remaining (Figures 4.3b, 4.7b). The Russian Region has the most precipitous decline in percentage of snow cover extent lost observed between the months of June and July (Table 4.2). July is also the month of greatest inter-annual variability in snow cover extent for the Russian Region (Table 4.2). In August, all study regions reach the annual minimum snow cover extent (Table 4.2).

Table 4.2 Monthly means (10^3 km^2), standard deviations (10^3 km^2), and cumulative area lost percentage of snow cover extent for the Siberian, North American, and Russian study regions during the melt season (1979-2007).

	Siberian Region			North American Region			Russian Region		
	Mean	Std. Dev.	% Lost	Mean	Std. Dev.	% Lost	Mean	Std. Dev	% Lost
March	386.3	0.0	0.0	384.4	0.0	0.0	322.8	0.0	0.0
April	386.3	0.0	0.0	384.4	0.0	0.0	322.8	0.0	0.0
May	386.3	0.0	0.0	384.4	0.0	0.0	322.8	0.0	0.0
June	269.5	100.8	30.2	181.1	126.6	52.9	321.4	7.4	0.4
July	26.9	56.1	93.0	10.7	41.2	97.2	101.9	107.2	68.4
August	6.7	20.9	98.3	9.3	26.7	97.6	9.8	25.8	97.0

Snow cover loss in the Russian Region generally lags one month behind the other two regions (Figures 4.2b, 4.3b; Table 4.2), both in the onset of snow cover extent loss and the month of highest inter-annual variability (largest standard deviation) in covered area (Table 4.2). The Russian Region should lag behind the other two domains due to the geographic differences between the study domains. Although all three regions are of the same latitude and longitude dimensions, the Russian Region sits five degrees farther north than the other two domains (Figure 3.1), thus it receives different solar radiation than the regions at lower latitudes. Besides radiation, many other important factors can also influence the annual timing of snow cover loss including the advection of warmer (colder) air, which can cause the removal (persistence) of snow cover.

Although variations in sea ice extent through the study period begin earlier in the year than variations in snow cover extent (Figures 4.1-4.8), snow cover is completely removed in a shorter amount of time. The greatest variability of snow cover extents occurs as soon as melt begins in June for the North American and Siberian Regions (Figure 4.2b, Table 4.2) with a one month lag, July, for the Russian Region (Figure 4.3b, Table 4.2). Sea ice extent loss reaches its greatest year-to-year variability (largest standard deviation) one month later in the melt season than the month of greatest snow cover variability for all three study regions (Tables 4.1, 4.2). Snow cover loss occurs at a more precipitous rate than the loss of sea ice extent, reaching almost completely snow-free land conditions in the three study regions in August (Table 4.2). For the same time period, sea ice extent has only lost 46.1-59.1% of the area for each study region (Table 4.1) with minimum sea ice cover usually occurring in September.

4.2 Anomalous Sea Ice and Snow Cover Loss

Years with early (negative) May sea ice extent anomalies reflect the change in sea ice extent from complete coverage of the study area in the early melt season to small losses in sea ice extent during May, which appear as large anomalies (Figure 4.1). An early loss of sea ice extent is observed in the North American Region during five years, whereas in only one year in the Siberian and two years in the Russian Region do early May sea ice losses occur (Figure 4.1). When looking at the calculated standard deviations for each region, the Siberian Region appears to have the most inter-annual variability during May (Table 4.1), although there is only one May with early loss over the record. This early loss of sea ice extent during May 1990 is large enough to skew the May standard deviation of Siberian sea ice loss, highlighting that standard deviation is not necessarily a robust nor outlier-resistant statistical measure. Thus variability as measured by standard deviation in the Siberian Region appears larger than that of the North American Region and slightly larger than that of the Russian Region (Table 4.1), although the North American and Siberian Regions have more cases of early sea ice loss (Figure 4.1).

During the month of June, the North American and Russian Regions have more variability (more positive and negative anomalies) in the extent of sea ice cover (Figure 4.2). However, in the Siberian Region, all anomalous cases indicate early melting (negative anomalies) in June (Figure 4.2a) and do not show any year-to-year variability of early and late melting conditions (negative or positive anomalies) until July and August (Figures 4.3a, 4.4a). The inter-annual variability in early and late melt conditions does not appear until July and August because these months are late enough in the melt season that melting of sea ice extent in the Siberian Region has already begun; that is, the normal sea ice condition this late in the melt season is not 100% sea ice-covered. The highly anomalous early sea ice extent loss in the Siberian Region in May 1990, when sea ice cover is typically 100% (Figures 4.1, 4.5), carries over into the months of June and July (Figures 4.2a, 4.3a). This huge anomaly also skews the representative size of Siberian anomalies for all Junes in the record. Thus the sea ice extent anomalies in the Siberian Region, excluding June 1990, appear more normal or less extreme than the anomalies in the other two regions.

Snow cover extent loss begins in June for the Siberian and North American Regions (Figure 4.2b) and in July for the Russian Region (Figure 4.3b). However, what appears to be highly anomalous early snow cover loss begins early for the Russian Region, during June in the year 2000 (Figure 4.2b). Although anomalous in the snow cover extent record, there is not, realistically, a large loss of snow cover in the Russian Region during June 2000 (Figure 4.6b). Due to the large grid spacing of the hemispheric snow cover extent data and the low number of grid points in each domain (10 grid points for both the North American and Siberian Regions and 8 in the Russian Region), the area of snow cover lost during the anomalously early loss of snow in June 2000 is equivalent to the early loss of snow cover in just one grid point pixel in the Russian domain. The actual area of snow cover lost in June 2000 for this region is roughly equivalent to 4×10^4 sq km or 12.3% of the total land area of the region (Figure 4.6b). The small number of data points in the domain results in a very low normalized anomaly for the Russian Region when the annual loss of snow cover begins in June (Figure 4.2b). Caution must be used when interpreting anomalous snow cover extent in the earliest part of the melt season without first understanding normal snow cover conditions for each study region, due to poor data resolution.

Based on the anomaly analysis of the sea ice and snow cover extent loss, snow cover, which is less dense than sea ice, has a faster response time to melt-forcing conditions than the sea ice. Although anomalous loss of sea ice extents first appear in May (Figure 4.1), earlier than anomalous loss of snow cover extent which first appears in June, the sea ice extent is less variable from month-to-month than the continental snow cover (Tables 4.1, 4.2). Each study region is completely snow and sea ice covered at the beginning of the melt season and reaches minimum snow cover in August and minimum sea ice extent during September. Over the three month time period June through August, the snow cover disappears, while both positive and negative sea ice cover anomalies continue to occur in the remaining August sea ice cover, indicating the ice has not yet reached annual minimum extent. Although small changes in wind direction or temperature can cause the transport or melt of sea ice cover over a short timescale on the order of days, leading to noticeable changes in sea ice extent observations, sea ice cover persists in the study regions over a longer time period than the snow cover extent. Thus the snow cover responds more quickly to the same regional scale melt season atmospheric forcing than the sea ice cover.

4.3 Mixed Phase and In-phase Regional Anomaly Patterns

The location of the North American, Siberian, and Russian study regions across the Arctic and the position of atmospheric Rossby wave patterns can influence the sea ice and snow cover conditions observed during the melt season among the study regions.

Variation in the total number of Rossby waves and shifting locations of ridges and troughs within the wave pattern change the large-scale atmospheric pattern, which can create similar circulation influences on pairs of study regions. Based on the analysis of snow cover and sea ice extent anomalies, three types of anomaly patterns commonly appear between the study regions at the end of the melt season. These patterns include: an early or late in-phase regional anomaly or a mixed-phase regional anomaly.

In mixed-phase years, the melt season sea ice and snow cover extent anomalies of two study regions are in the same direction, either positive or negative indicating areas of anomalously late or early melt respectively, while the third study region has sea ice and snow cover extent anomalies opposite to that of the other two regions. A mixed-phase pattern is observed in 12 years out of the 29-year study period (Table 4.3). In six other years, the sea ice and snow cover extent anomaly direction is in-phase across all three study regions (Table 4.3). For in-phase years the atmospheric pattern results in either the same late (positive) or early (negative) sea ice and snow cover loss anomaly conditions. In some cases (1993, 1995, and 2007), the melt season anomalies are in-phase and early (negative) across all regions and in others (1983, 1986, and 1996) the anomalies are in-phase and late (positive) for all regions (Table 4.3).

For the remaining 11 melt seasons, sea ice extent anomalies are very close to normal for one or more study regions (Table 4.3) and could not be grouped into one of the above categories. Using only a comparison of anomaly patterns is not sufficient to classify these remaining melt seasons into one of the three sea ice and snow cover condition patterns described above. Although it is presumed that many of these

Table 4.3 August sea ice extent region anomalies by melt phase. Mixed-phase years are those in which the sign of sea ice extent anomalies of two study regions are opposite to the anomaly sign of the third region. In-phase years are those in which the sign of melt season sea ice extent anomalies are the same in all three regions. Years in which one or more regions have a normal sea ice extent anomaly value at the ±0.2 threshold are not classified. Instances of normal sea ice extent are identified by the * symbol.

	Siberian Region	North American Region	Russian Region	Phase
1979	+	-	-	MIXED
1980	+	*	+	
1981	*	-	+	
1982	+	-	-	MIXED
1983	+	+	+	IN
1984	+	+	*	
1985	+	+	-	MIXED
1986	+	+	+	IN
1987	*	-	-	
1988	+	-	+	MIXED
1989	-	+	+	MIXED
1990	-	+	+	MIXED
1991	-	+	+	MIXED
1992	-	+	+	MIXED
1993	-	-	-	IN
1994	+	+	*	
1995	-	-	-	IN
1996	+	+	+	IN
1997	+	*	-	
1998	+	-	+	MIXED
1999	+	-	*	
2000	*	*	-	
2001	*	+	-	
2002	-	+	-	MIXED
2003	-	+	+	MIXED
2004	-	+	-	MIXED
2005	-	*	-	
2006	-	*	-	
2007	-	-	-	IN

unclassified years will have similar atmospheric patterns to either mixed- or in-phase melt seasons, years with regions of normal sea ice or snow cover will not be classified.

4.4 Sea Ice and Snow Cover Observations and Anomalies Summary

Based on the analysis of snow cover and sea ice extent loss in the three study regions during the study period, several characteristics of melt timing stand out. Although the ocean area is located farther north than the adjacent land portion of each study region, sea ice extent is lost earlier in the year (during May) than continental snow cover (during June) in all regions throughout the study period (Tables 4.1, 4.2). This is the case even though the response of snow cover to atmospheric forcing appears to be much faster than the sea ice response (i.e. a much higher percentage of snow cover extent lost by month than percentage of sea ice cover lost). In addition, the timing of annual snow cover loss shows a dependence on latitude, since snow cover loss in the Russian Region typically lags behind the other two regions (Figures 4.2b, 4.6b; Table 4.2). The North American Region contains the largest multiyear ice fraction of the three study regions and as a result, does not lose as much sea ice cover as other regions during August, demonstrating the dependence of annual sea ice loss on ice type and overall thickness (Figure 2.3, Table 4.1). To better understand how the atmospheric conditions influence the annual melt response, atmospheric parameters must be analyzed across the three study regions and in each region independently.

Chapter 5

Results II: Intercomparison of Hemispheric Snow, Sea Ice, and Atmospheric Conditions in Case Study Years

The atmospheric pattern in three case years 1985, 1996, and 2007, representing each type of melt phase pattern, have been analyzed to understand the atmospheric setting surrounding annual melt of sea ice and snow cover for the Siberian, North American, and Russian study regions. The atmospheric parameters used in the analysis for each individual study region include: 500 hPa geopotential heights, total percentage of cloud cover, 925 hPa air temperature, MSLP, and U and V vector wind components (Figures 5.1-5.6).

5.1 Mixed-phase Sea Ice and Snow Cover Anomaly Case Year: 1985

Considering the locations of the study regions across the Arctic and variations in the atmospheric Rossby wave pattern, it is expected that one or more of the study regions could have similar atmospheric conditions given the placement and number of waves in relation to all three study areas. A wave pattern similarly mirrored over two regions can be out of phase with the third region, resulting in a mixed-phase anomaly pattern. In 1985, the North American and Siberian Regions are in-phase, meaning both regions have late loss of snow cover (positive anomalies) during the June to August snow melt season and late loss of sea ice extent (positive anomalies) beginning in June in the North American Region and through July and August for both the North American and Siberian

a

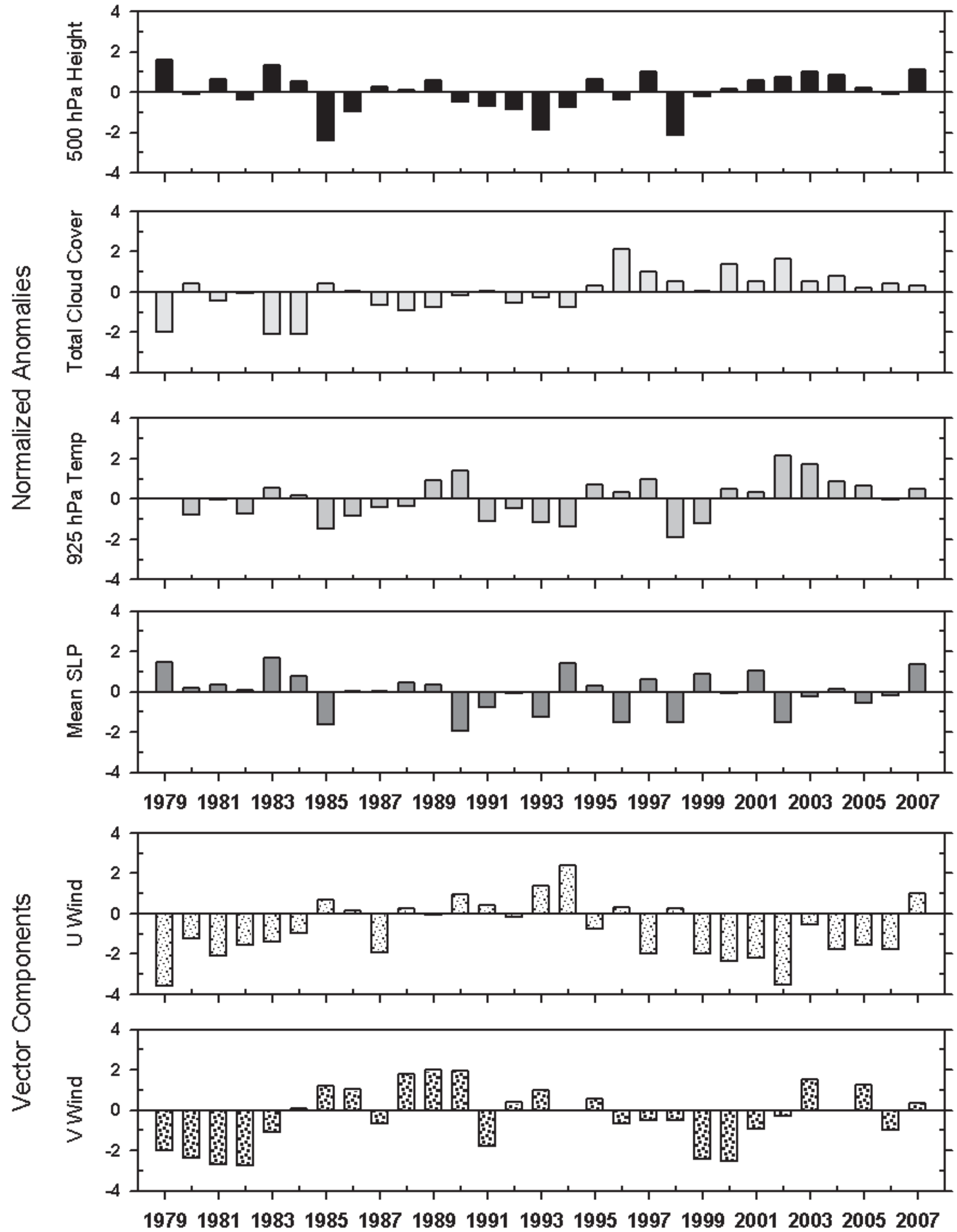

Figure 5.1 Siberian Region normalized anomalies for (a) March, (b) April, (c) May, (d) June, (e) July, and (f) August 500 hPa geopotential heights, total cloud cover, 925 hPa air temperature, and MSLP and mean vector U and V wind components.

b

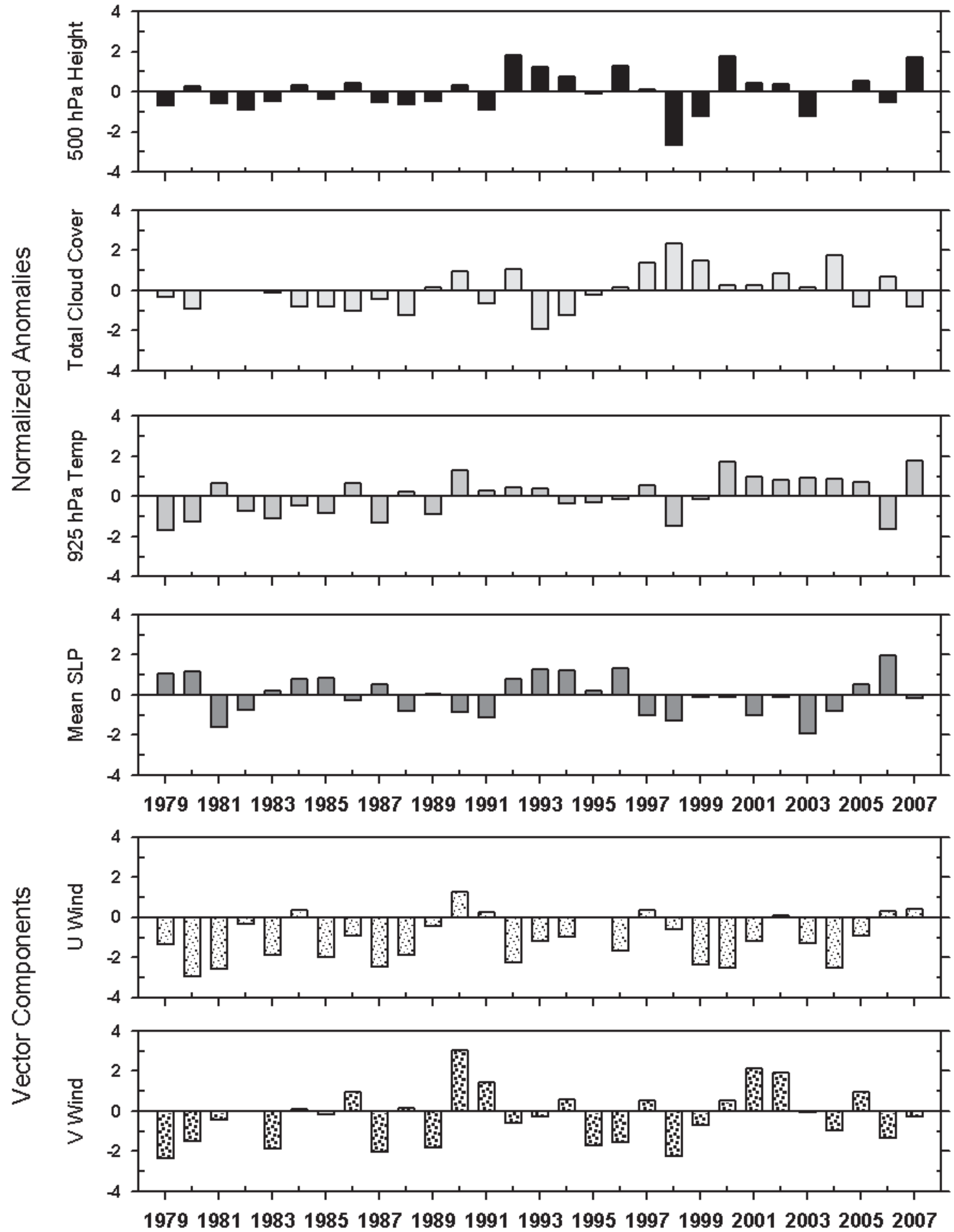

Figure 5.1 (b) April **(**continued).

c

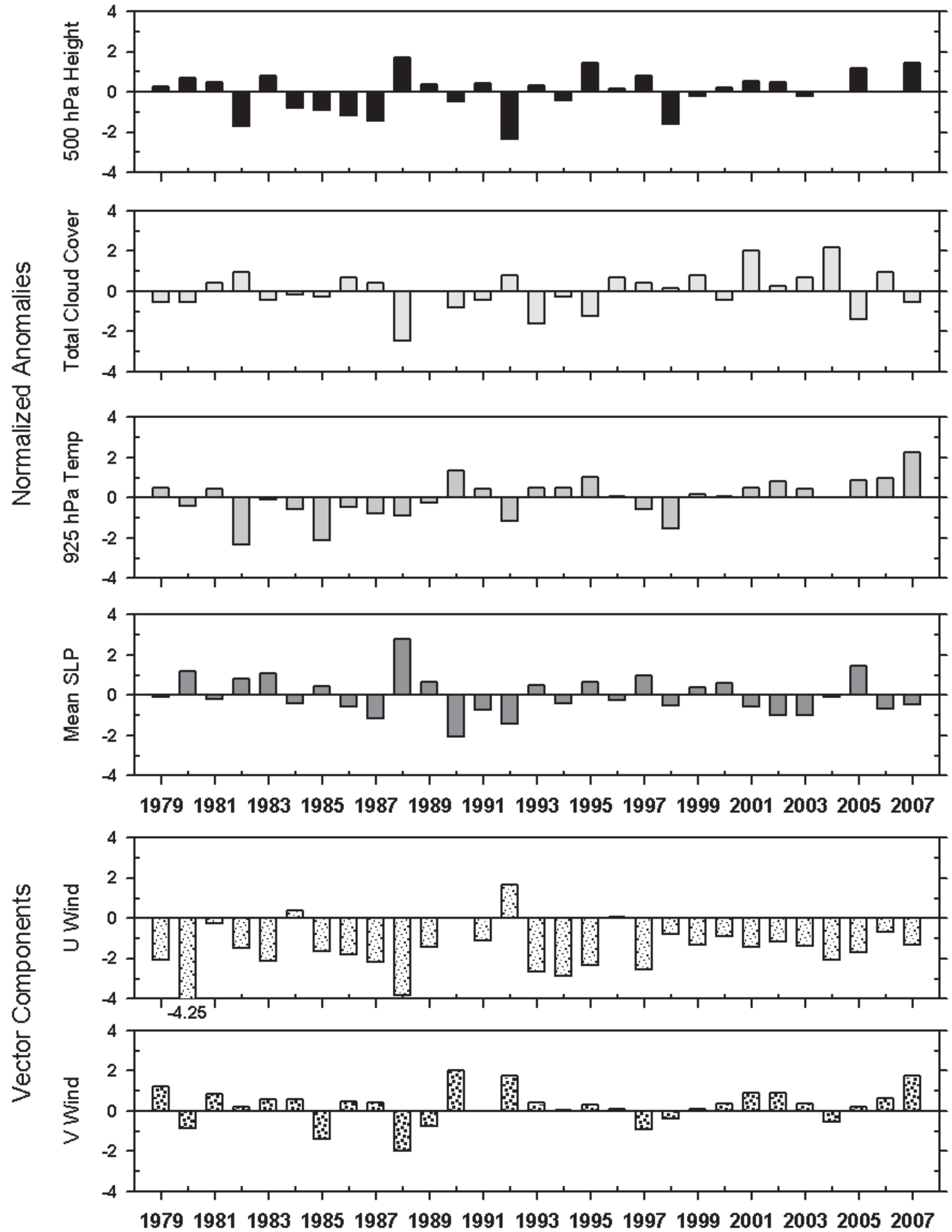

Figure 5.1 (c) May (continued).

d

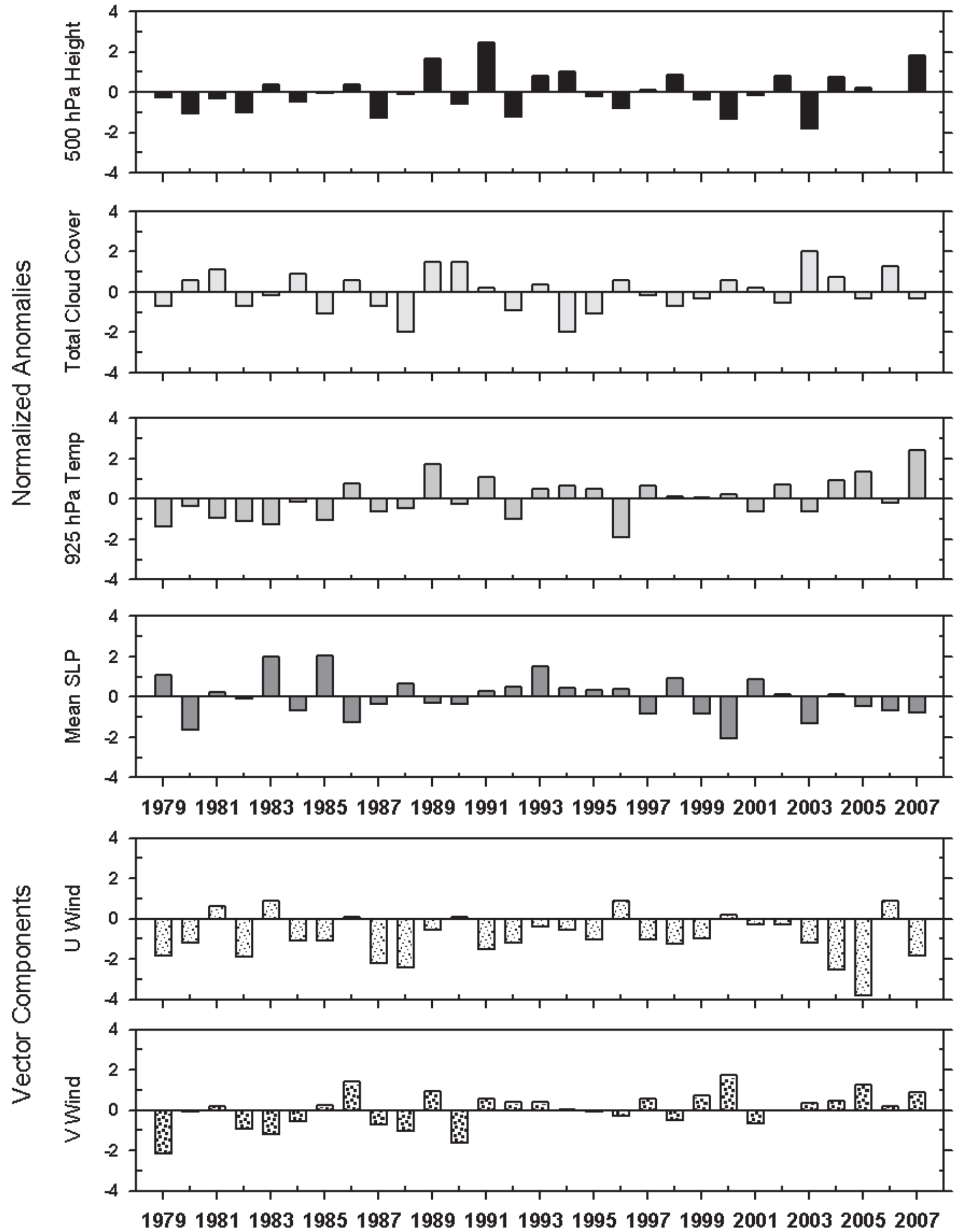

Figure 5.1 (d) June (continued).

e

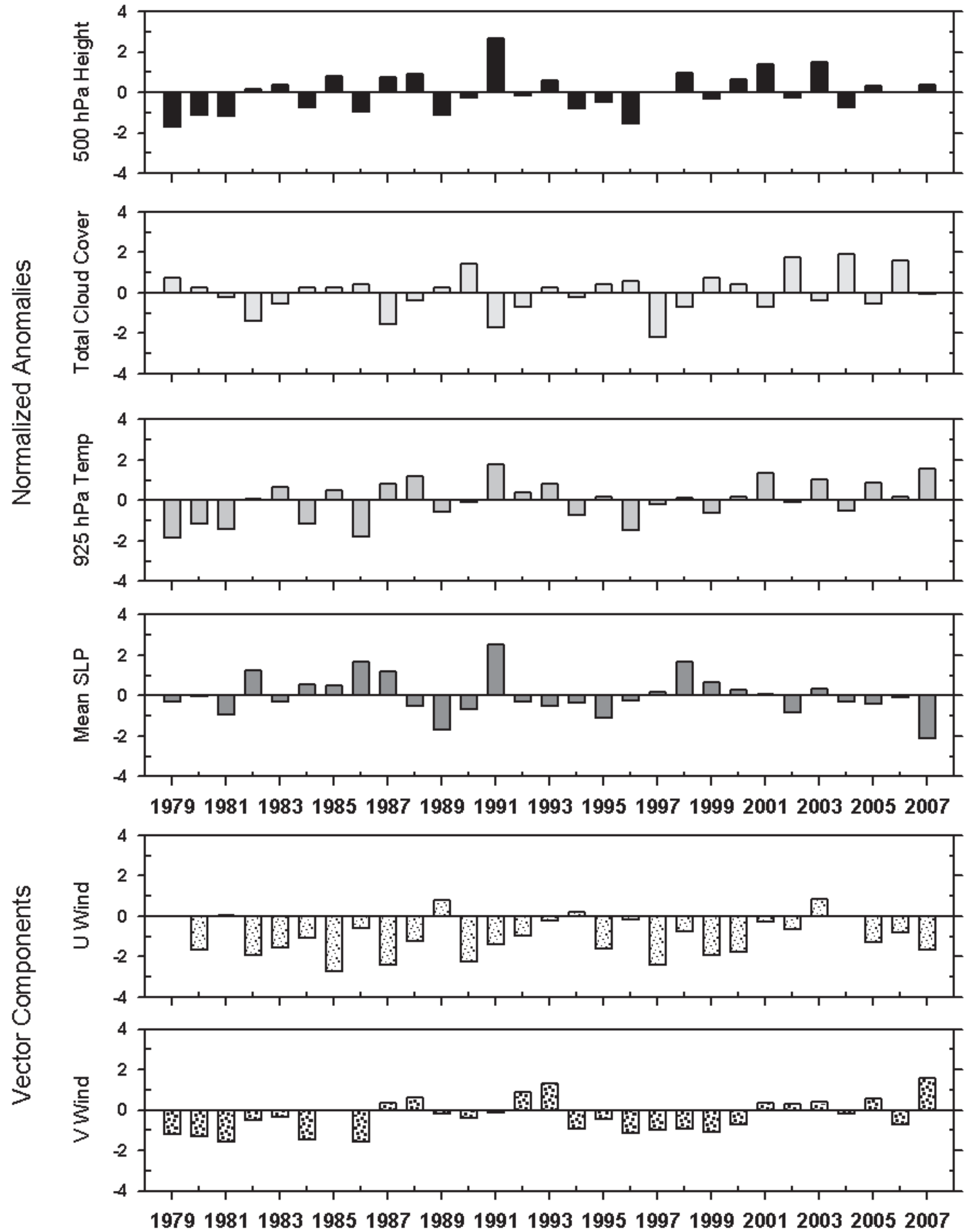

Figure 5.1 (e) July (continued).

f

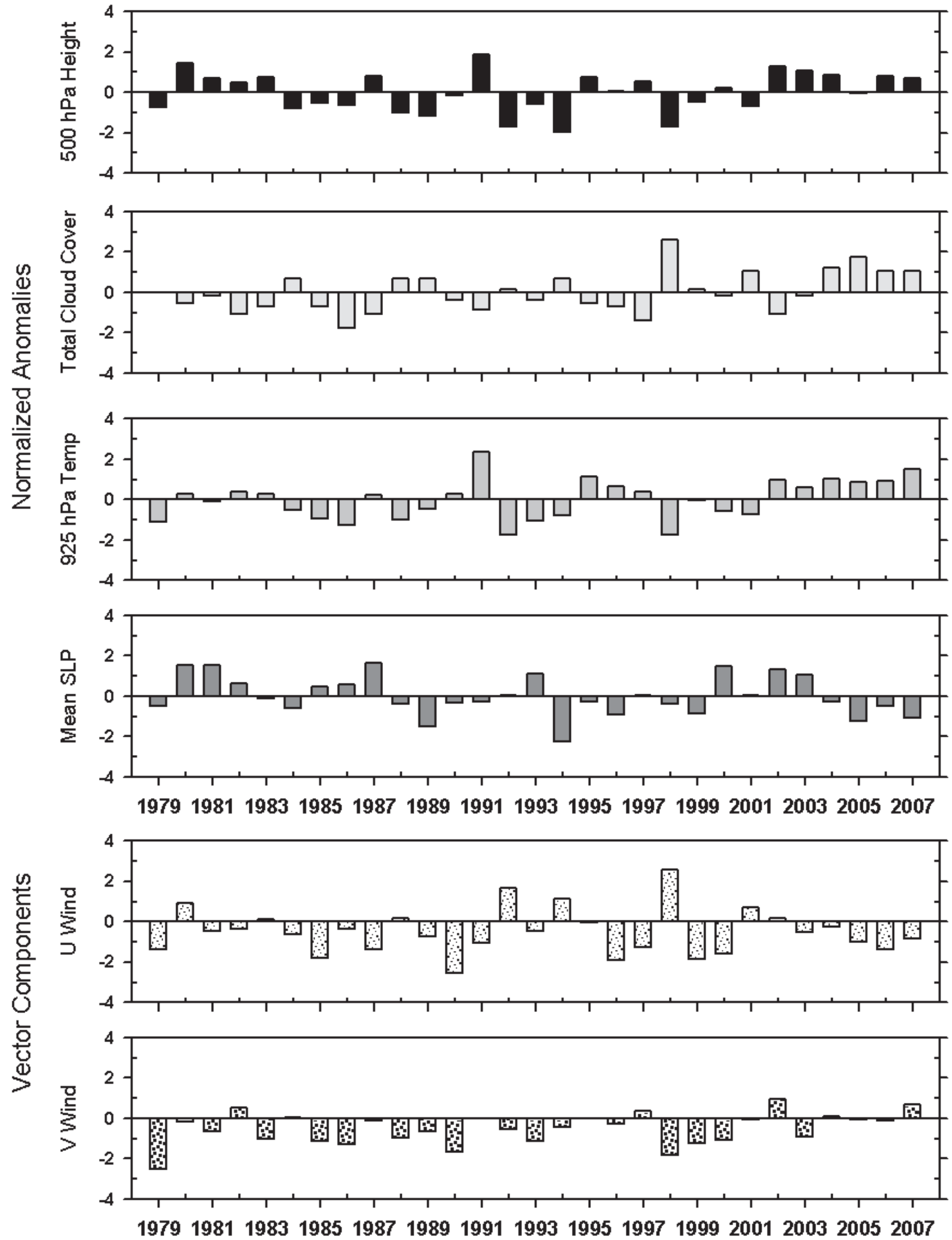

Figure 5.1 (f) August (continued).

a

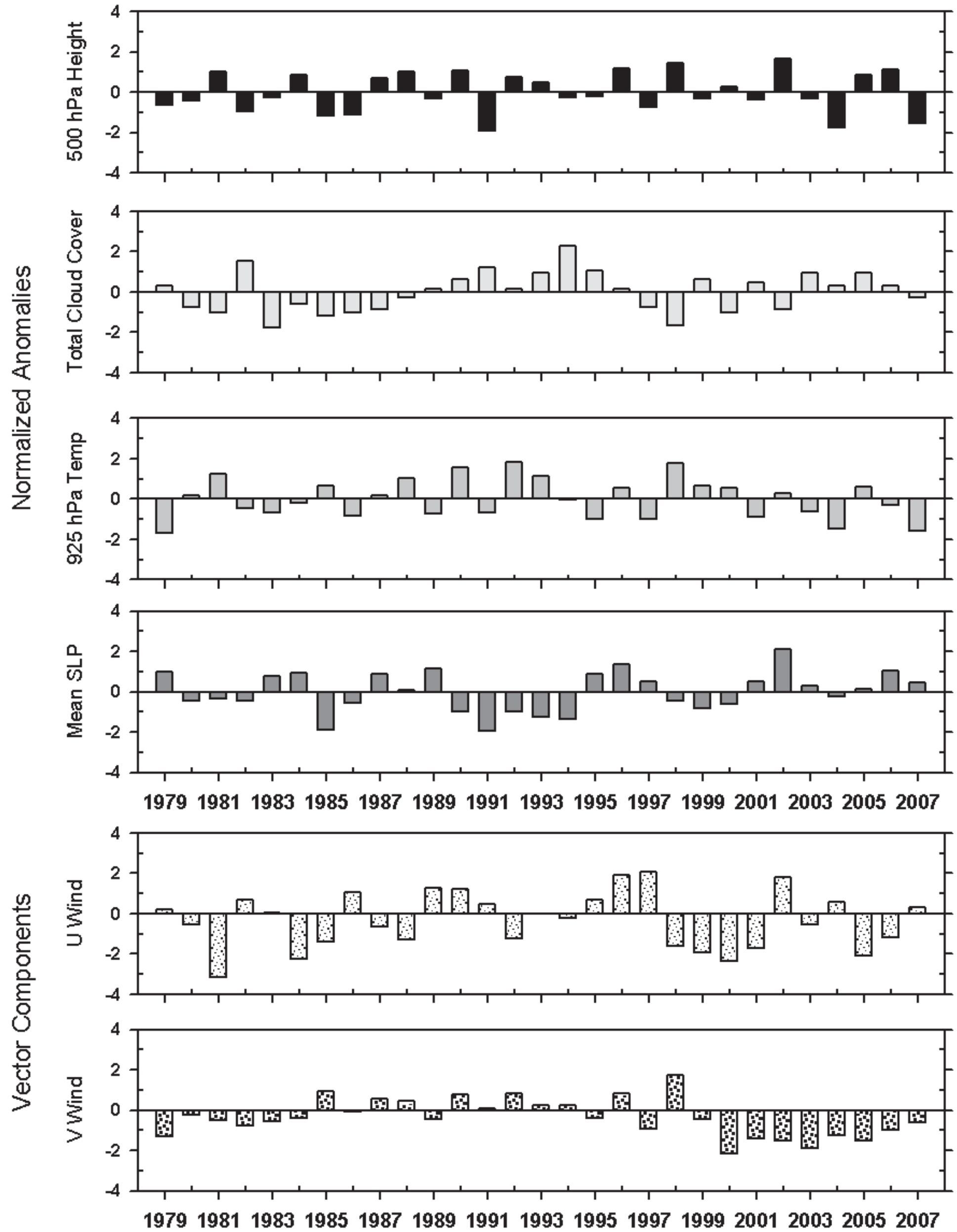

Figure 5.2 North American Region normalized anomalies for (a) March, (b) April, (c) May, (d) June, (e) July, and (f) August 500 hPa geopotential heights, total cloud cover, 925 hPa air temperature, and MSLP and mean vector U and V wind components.

b

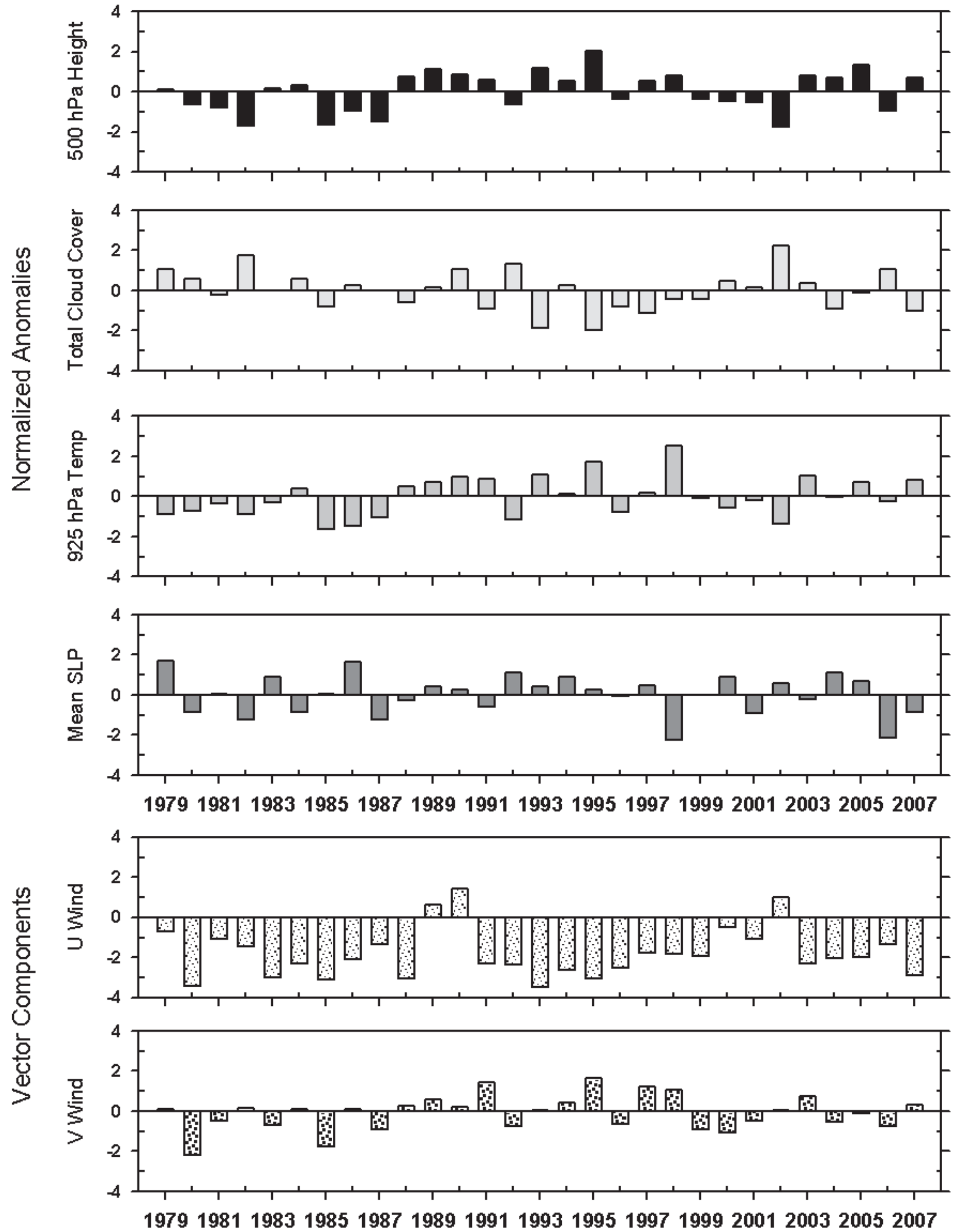

Figure 5.2 (b) April (continued).

c

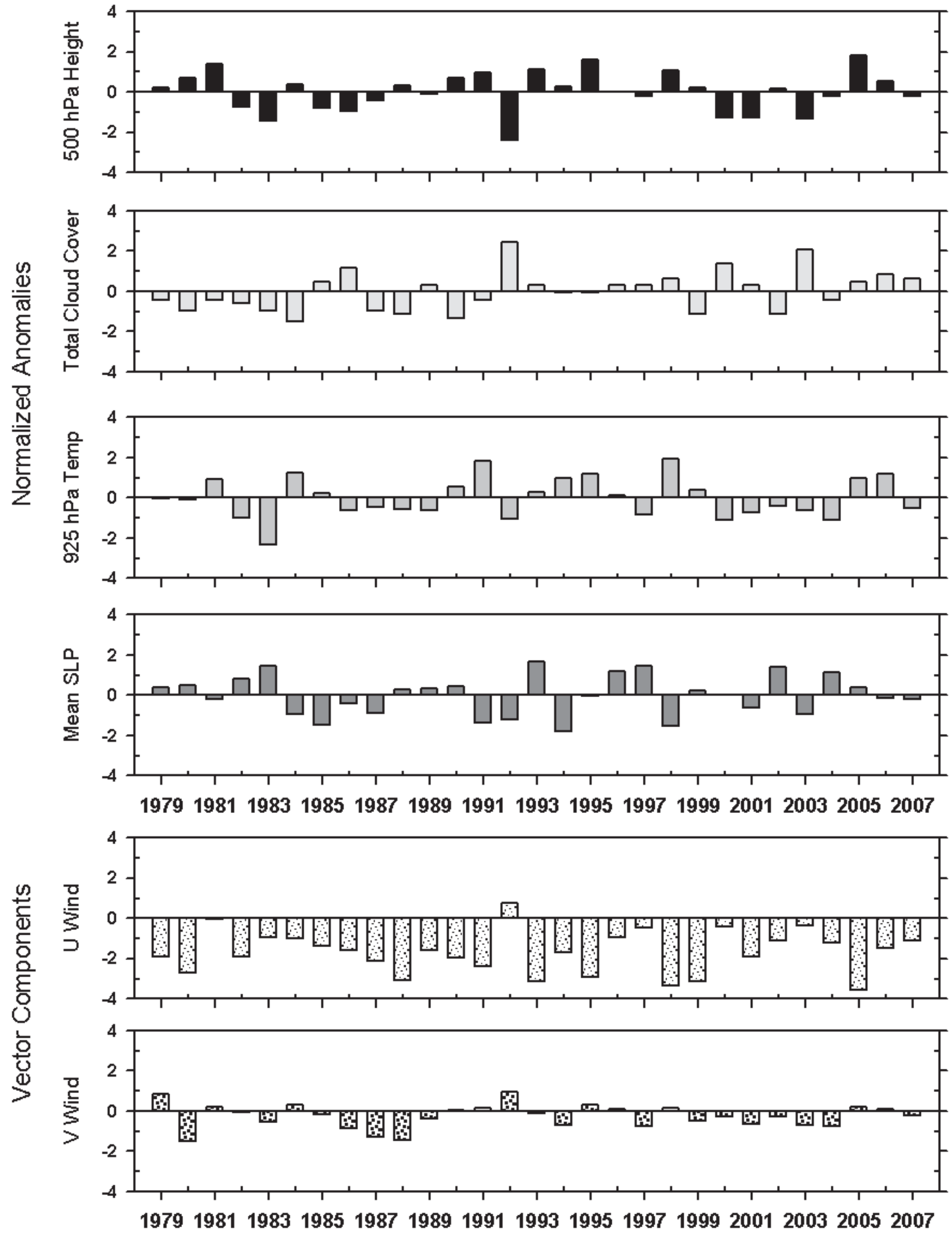

Figure 5.2 (c) May (continued).

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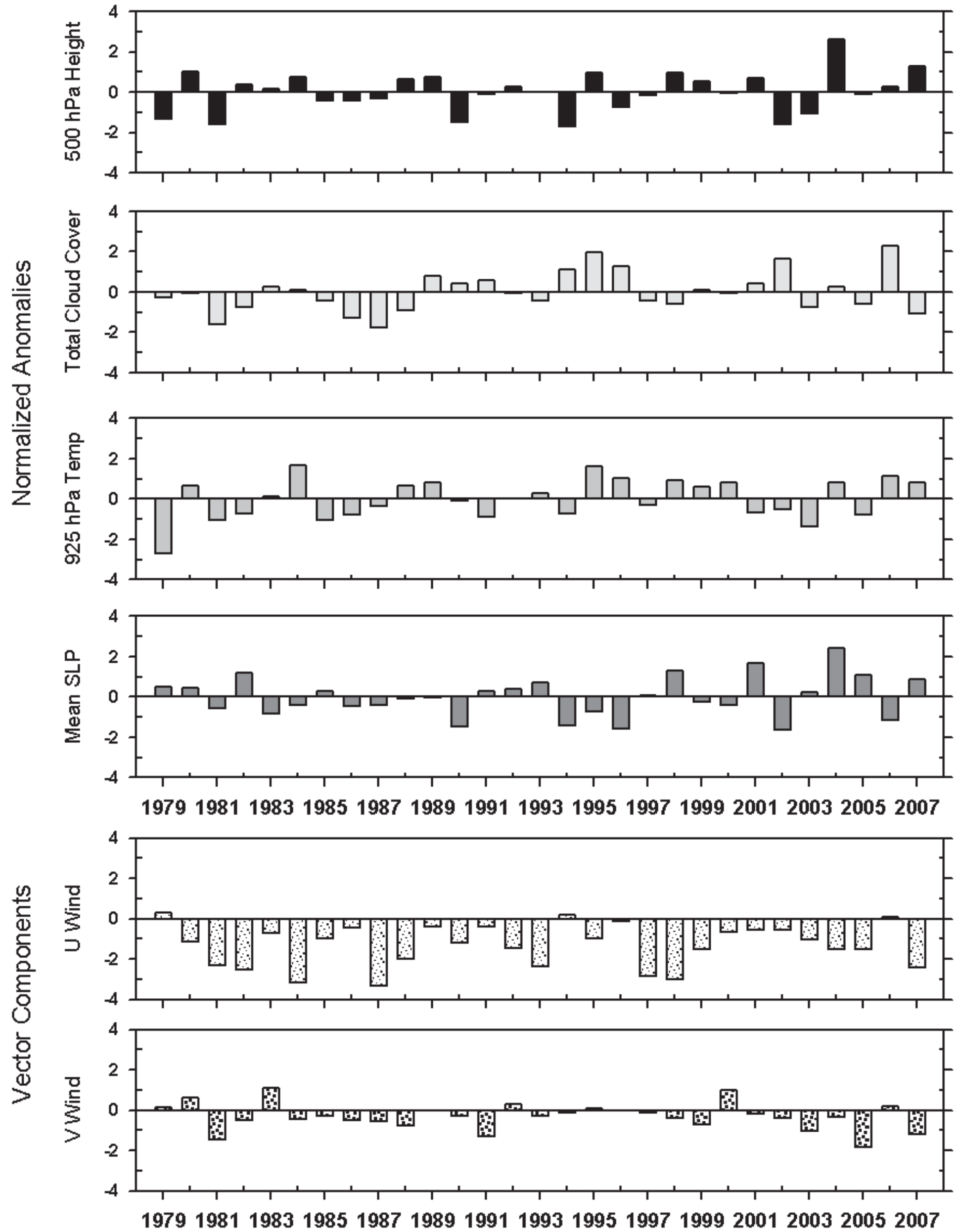

Figure 5.2 (d) June (continued).

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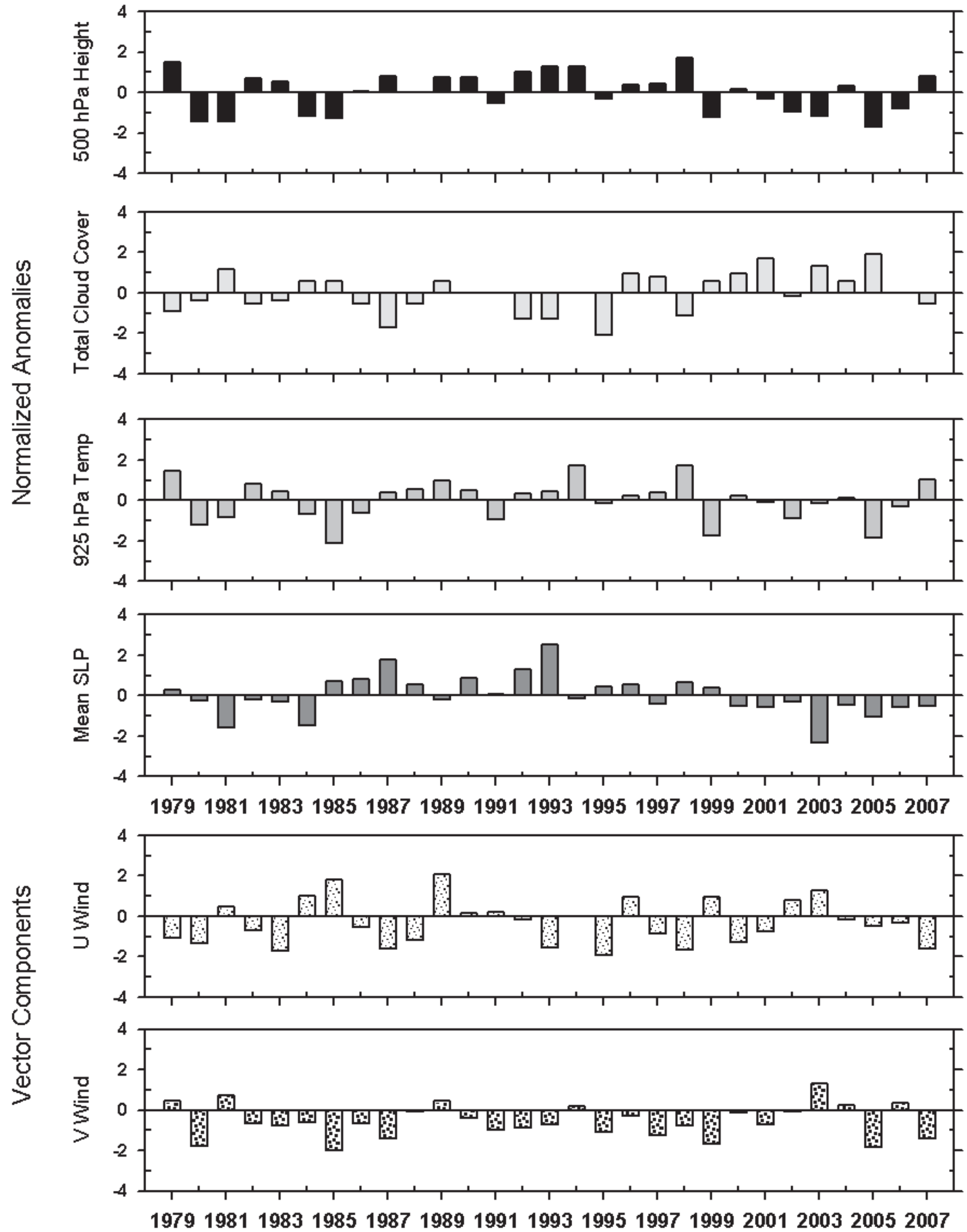


Figure 5.2 (e) July **(**continued).

f

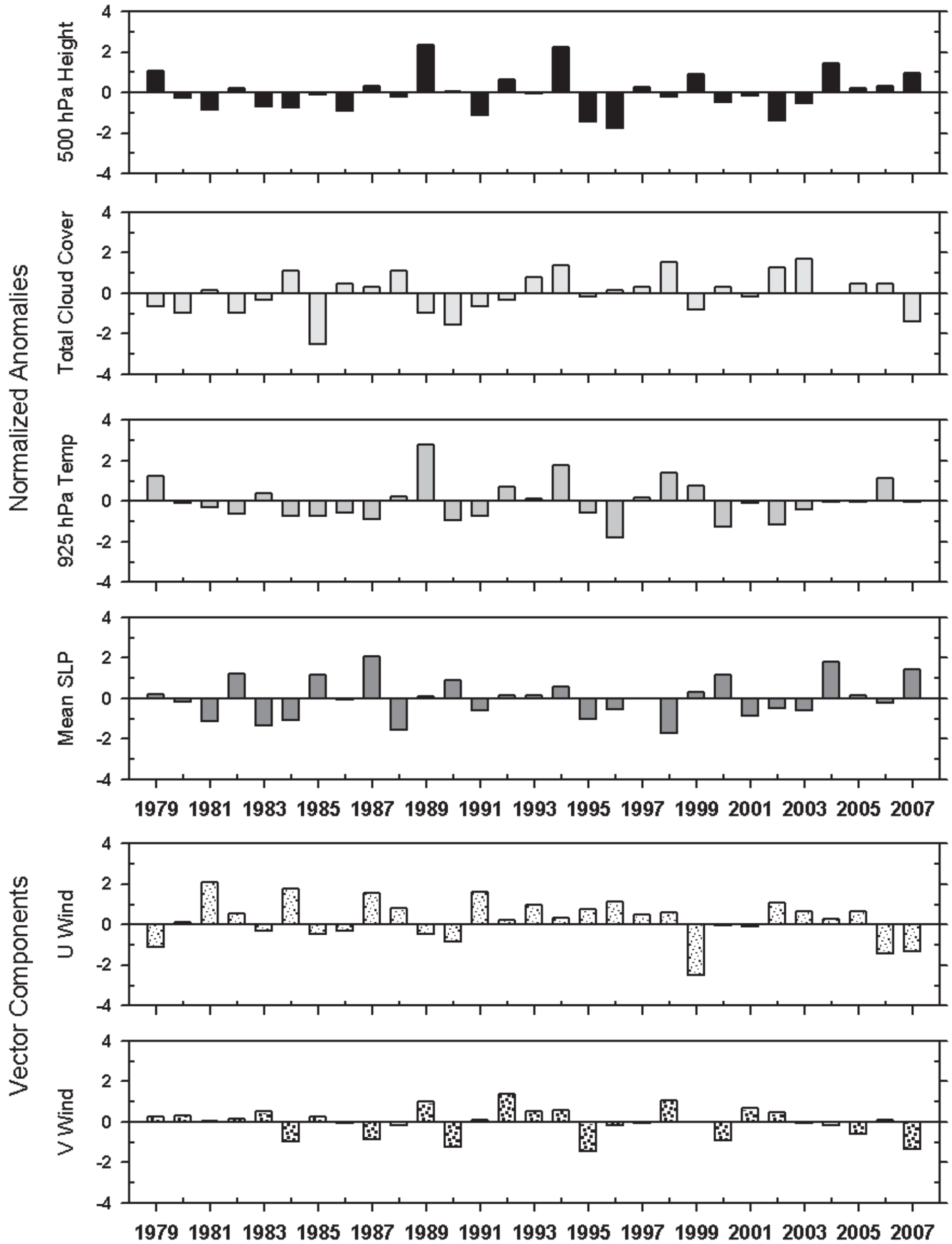


Figure 5.2 (f) August (continued).

a

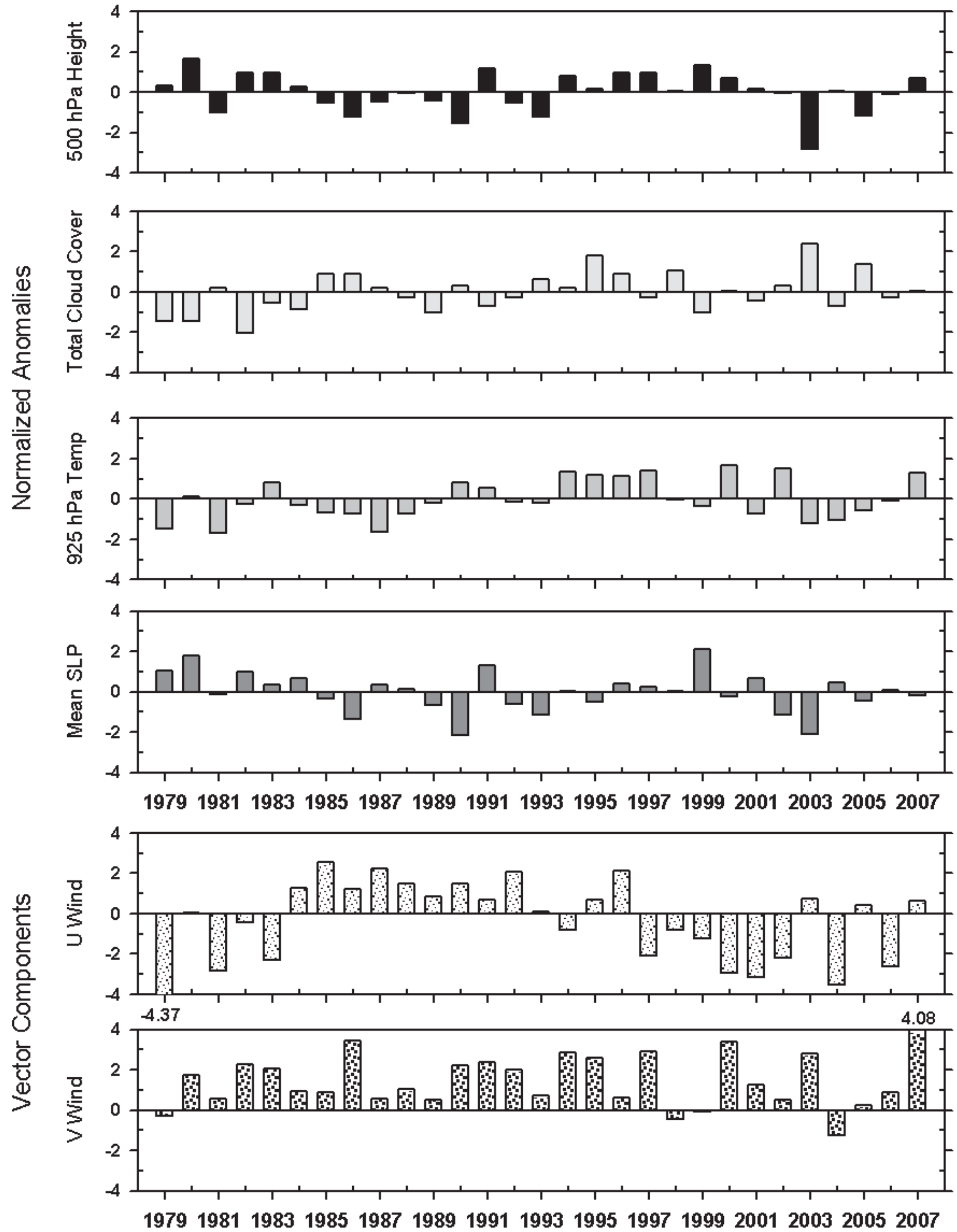


Figure 5.3 Russian Region normalized anomalies for (a) March, (b) April, (c) May, (d) June, (e) July, and (f) August 500 hPa geopotential heights, total cloud cover, 925 hPa air temperature, and MSLP and mean vector U and V wind components.

b

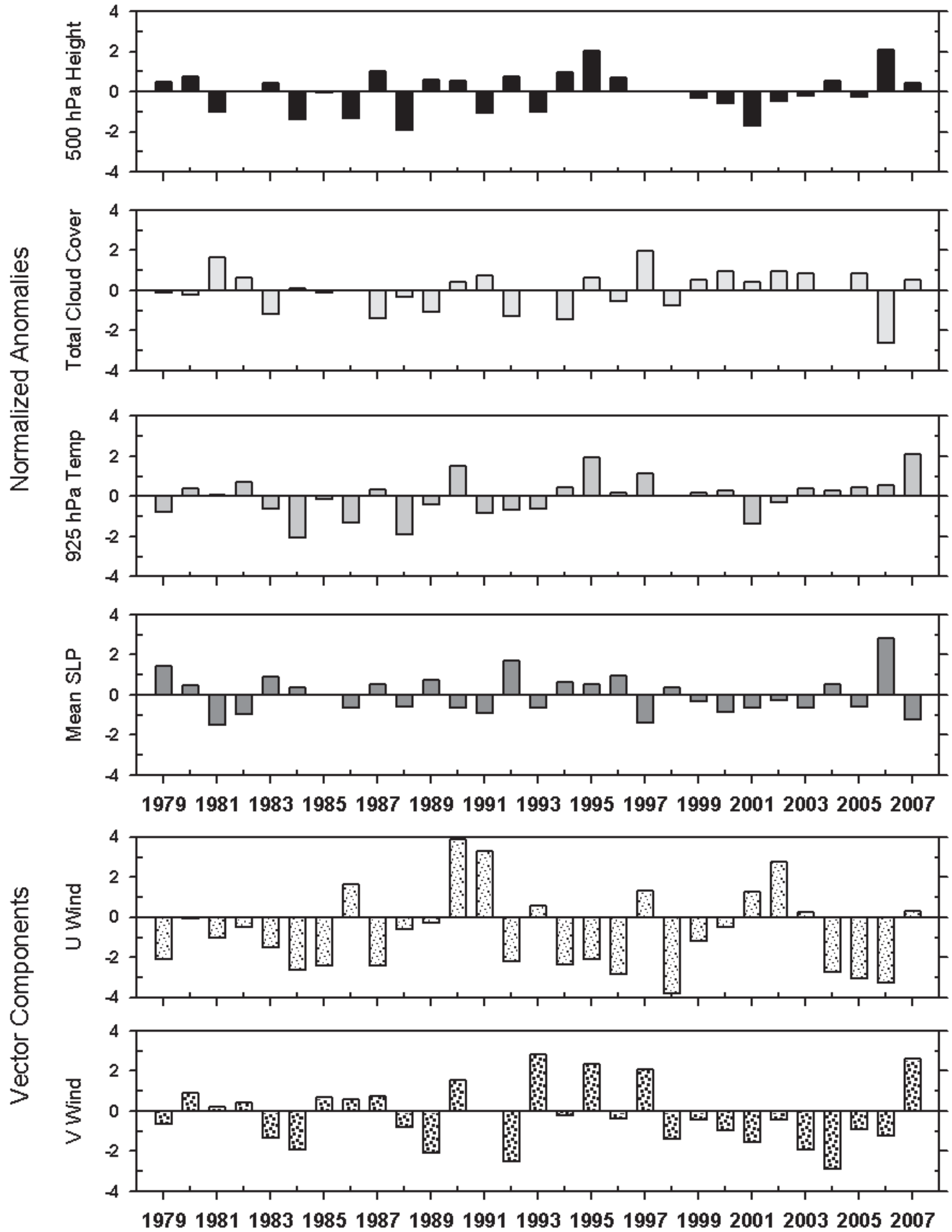


Figure 5.3 (b) April (continued).

c

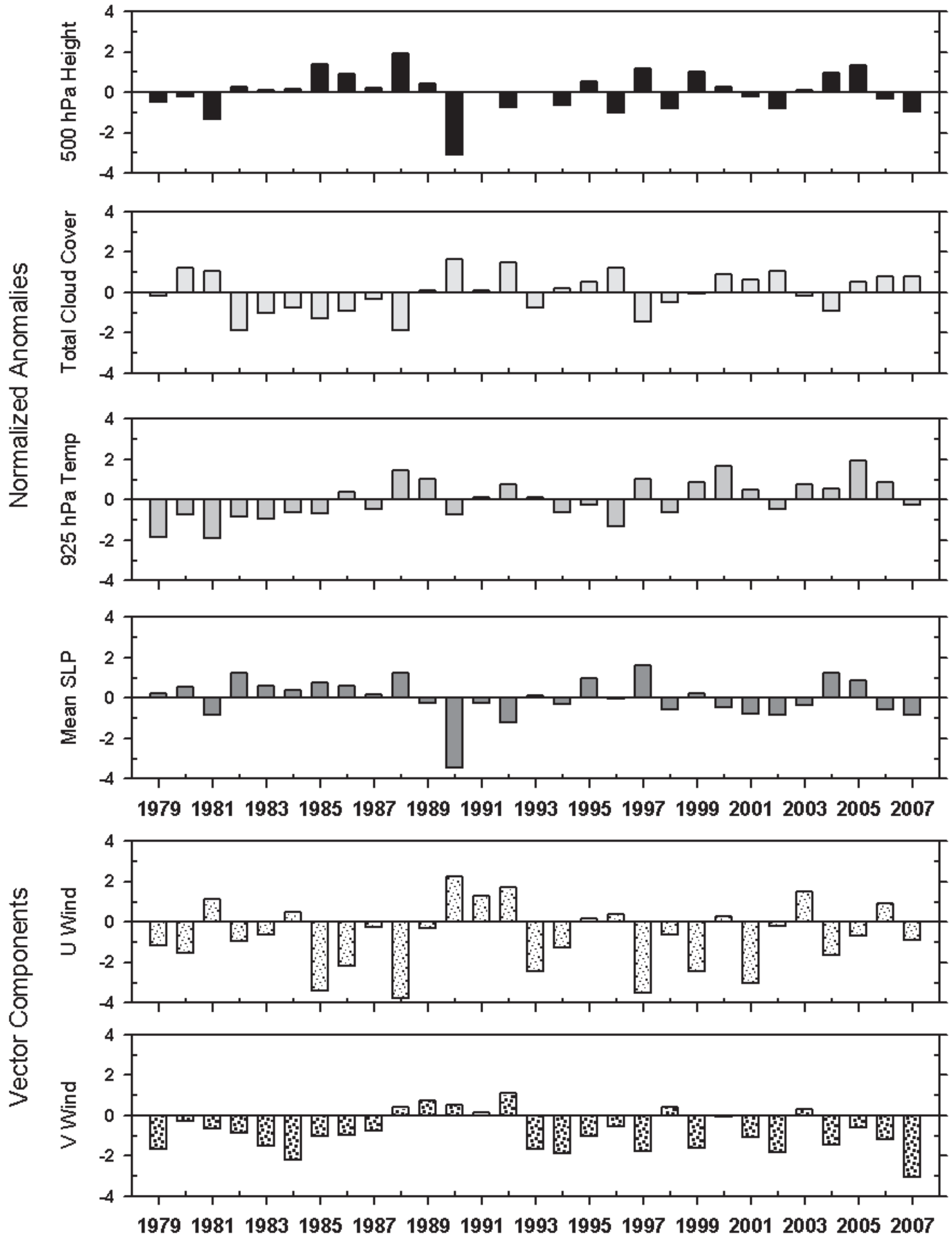


Figure 5.3 (c) May (continued).

d

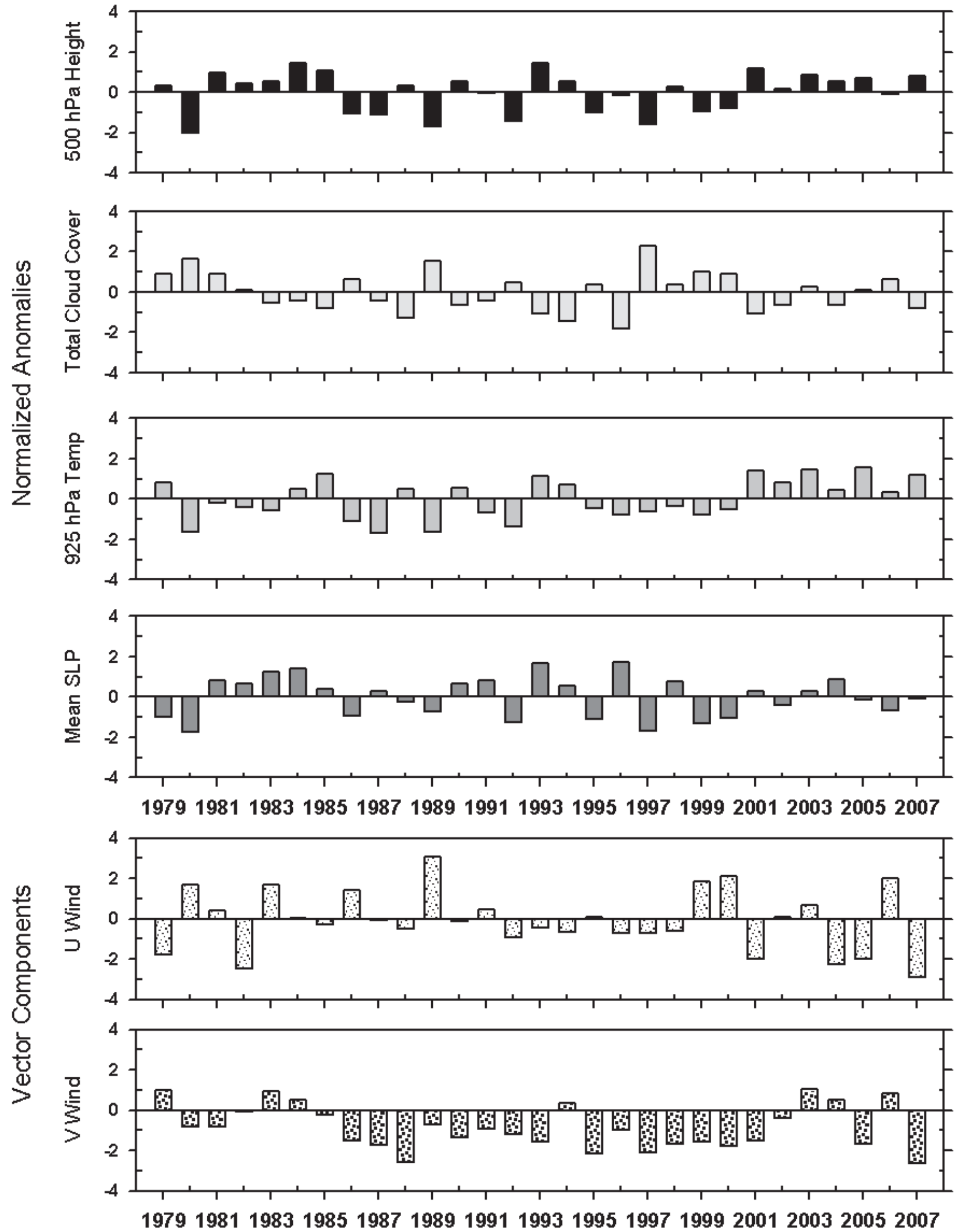


Figure 5.3 (d) June (continued).

e

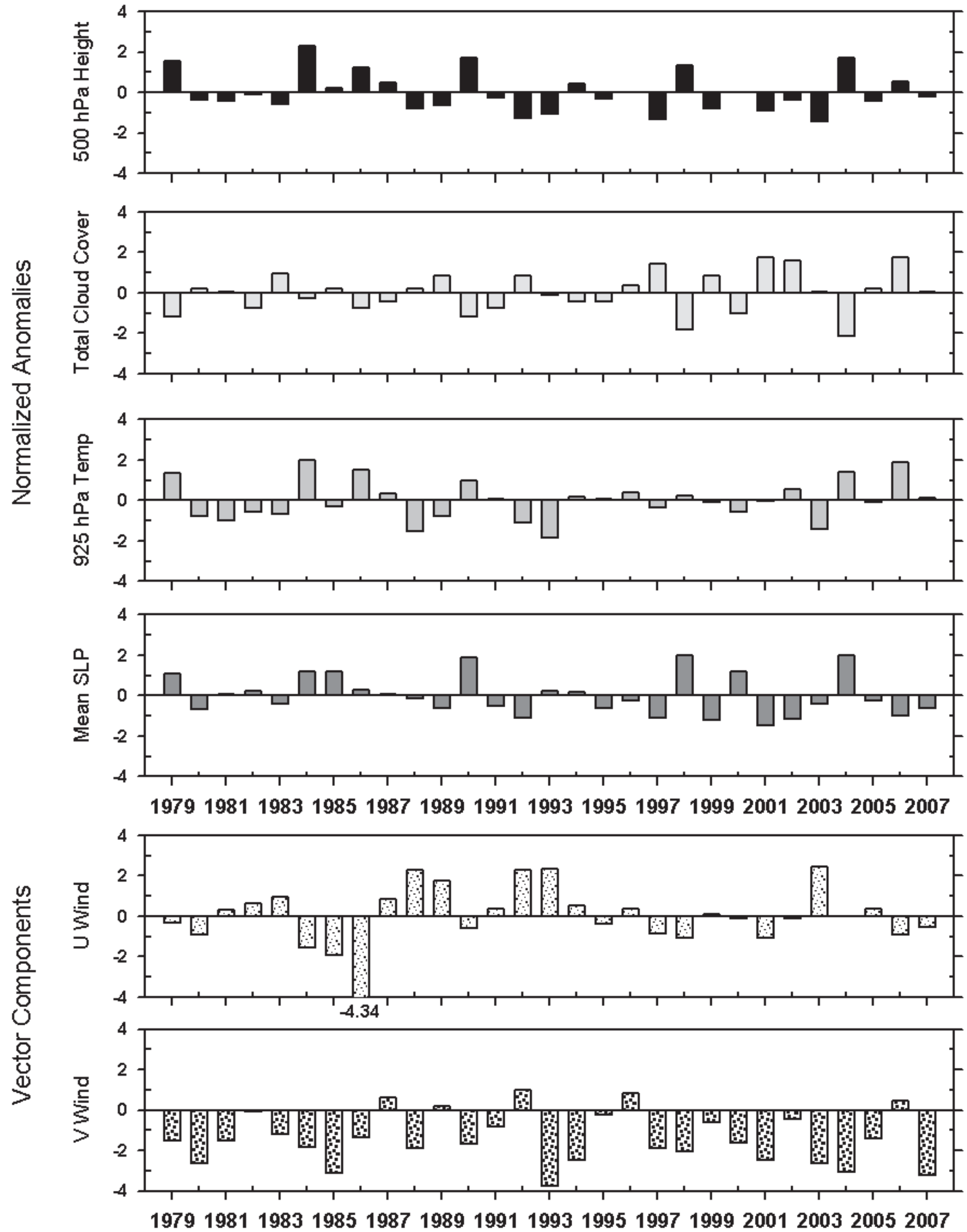


Figure 5.3 (e) July (continued).

f

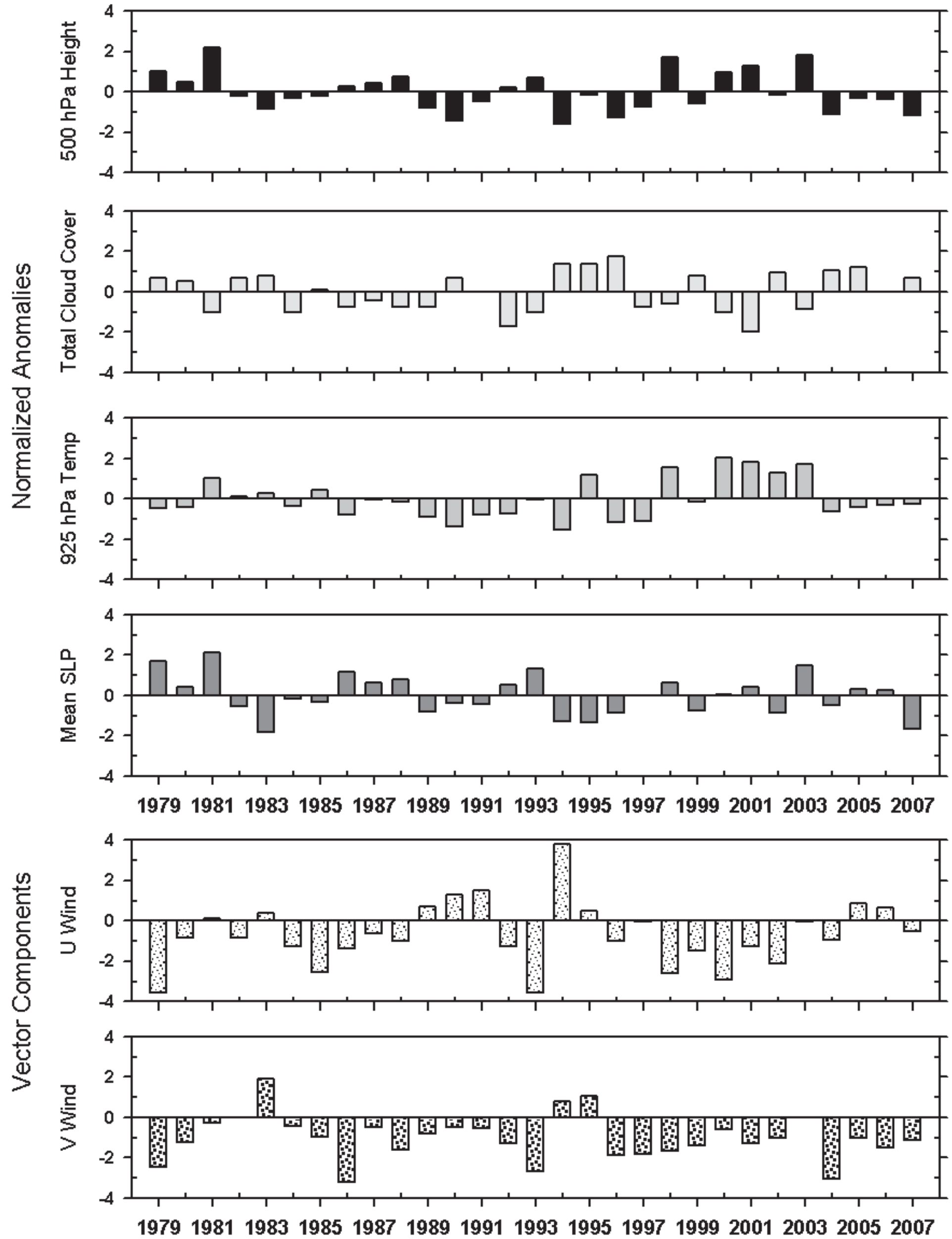
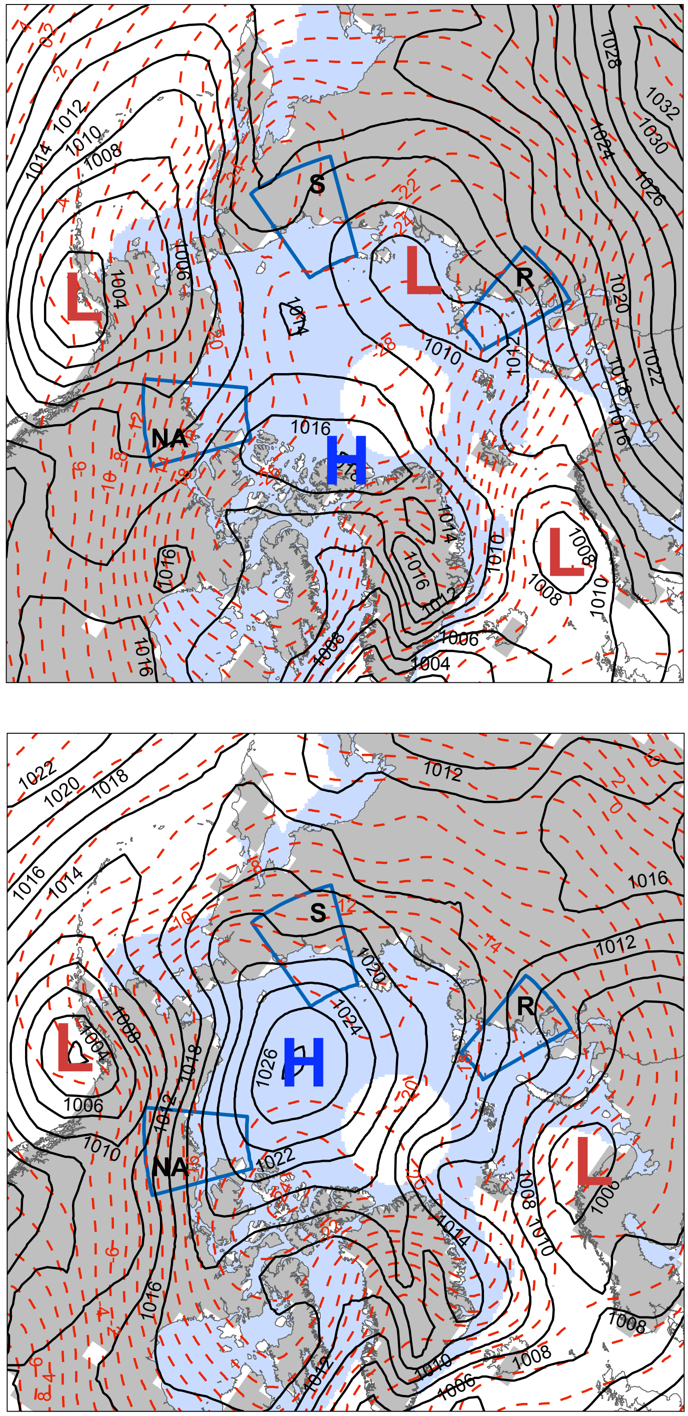


Figure 5.3 (f) August (continued).



a

b

Figure 5.4 1985 monthly MSLP in hPa (solid black), 925 hPa air temperature in ° C (dashed red), snow-covered area extent (gray shaded), and sea ice extent (blue shaded) for (a) March, (b) April, (c) May, (d) June, (e) July, and (f) August. The North American (NA), Siberian (S), and Russian (R) study regions are outlined in blue.

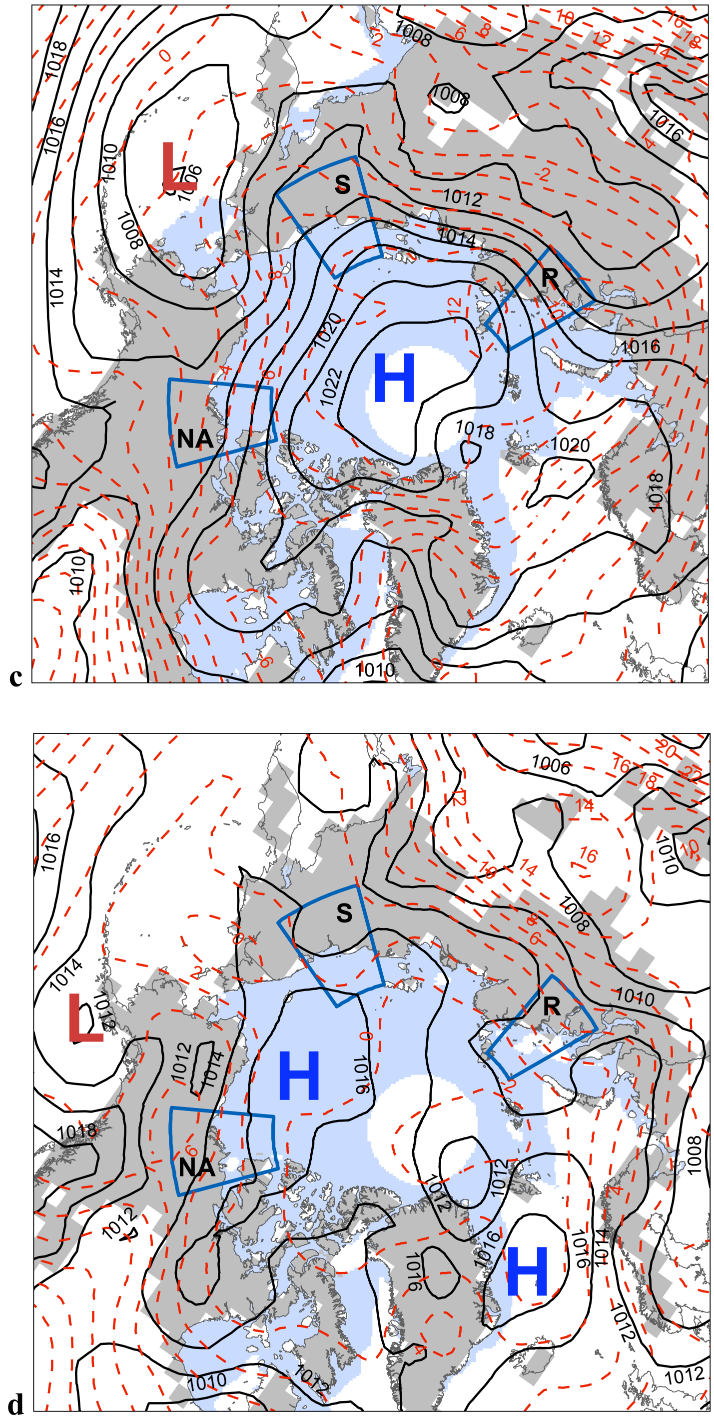


Figure 5.4 (c) May and (d) June (continued).

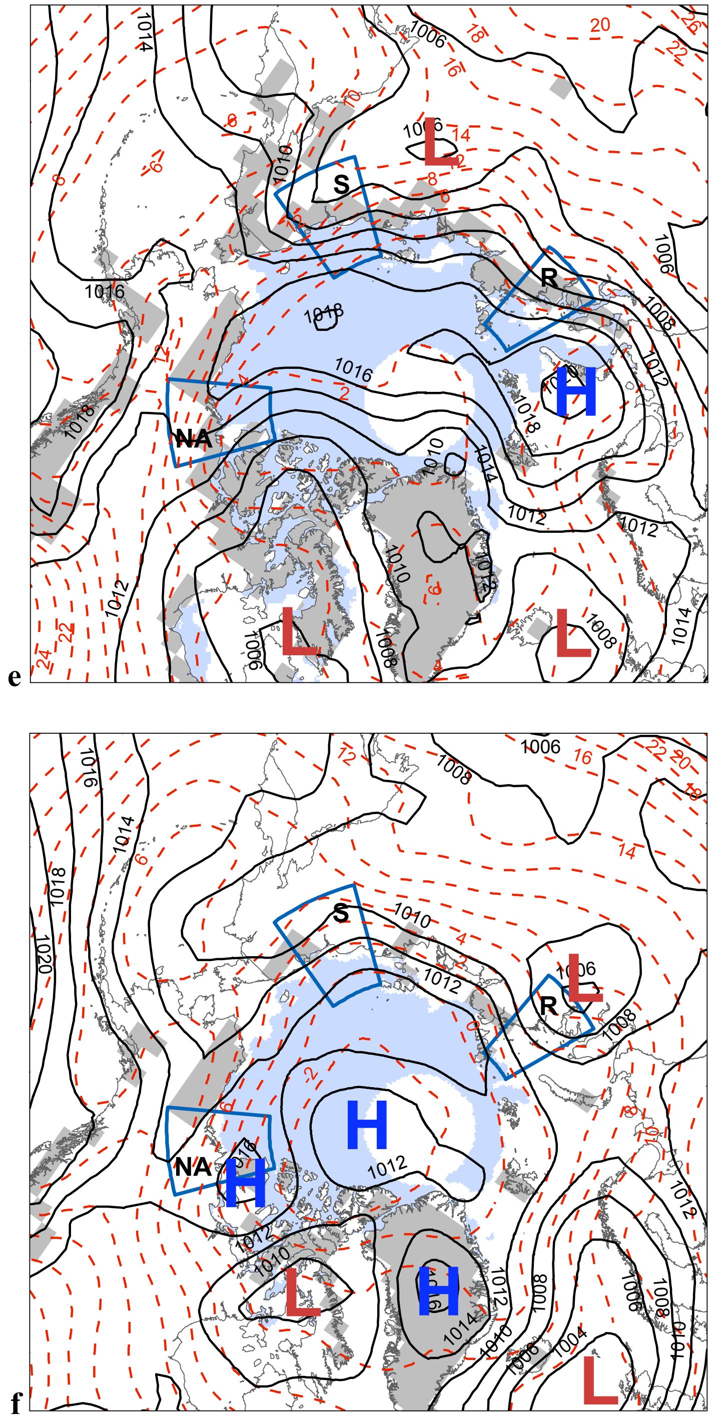


Figure 5.4 (e) July and (f) August (continued).

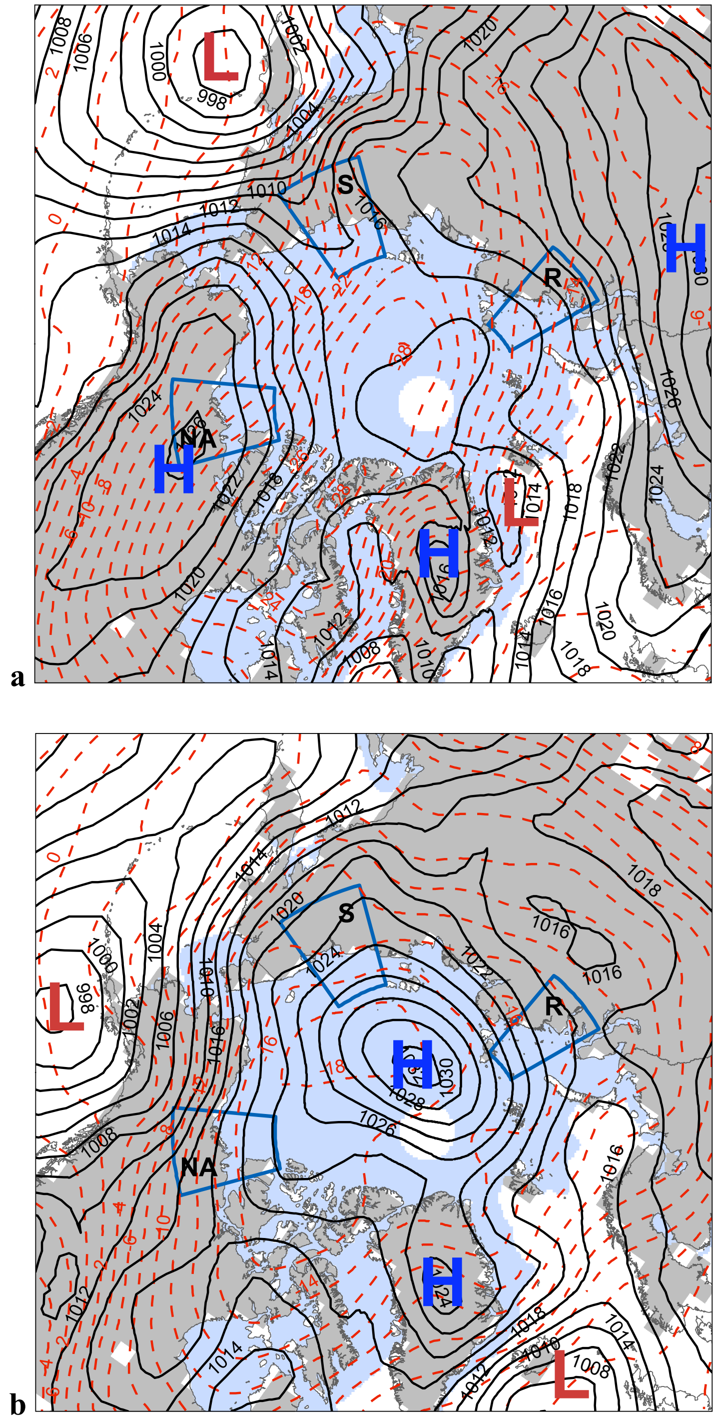


Figure 5.5 1996 monthly MSLP in hPa (solid black), 925 hPa air temperature in ° C (dashed red), snow-covered area extent (gray shaded), and sea ice extent (blue shaded) for (a) March, (b) April, (c) May, (d) June, (e) July, and (f) August. The North American (NA), Siberian (S), and Russian (R) study regions are outlined in blue.

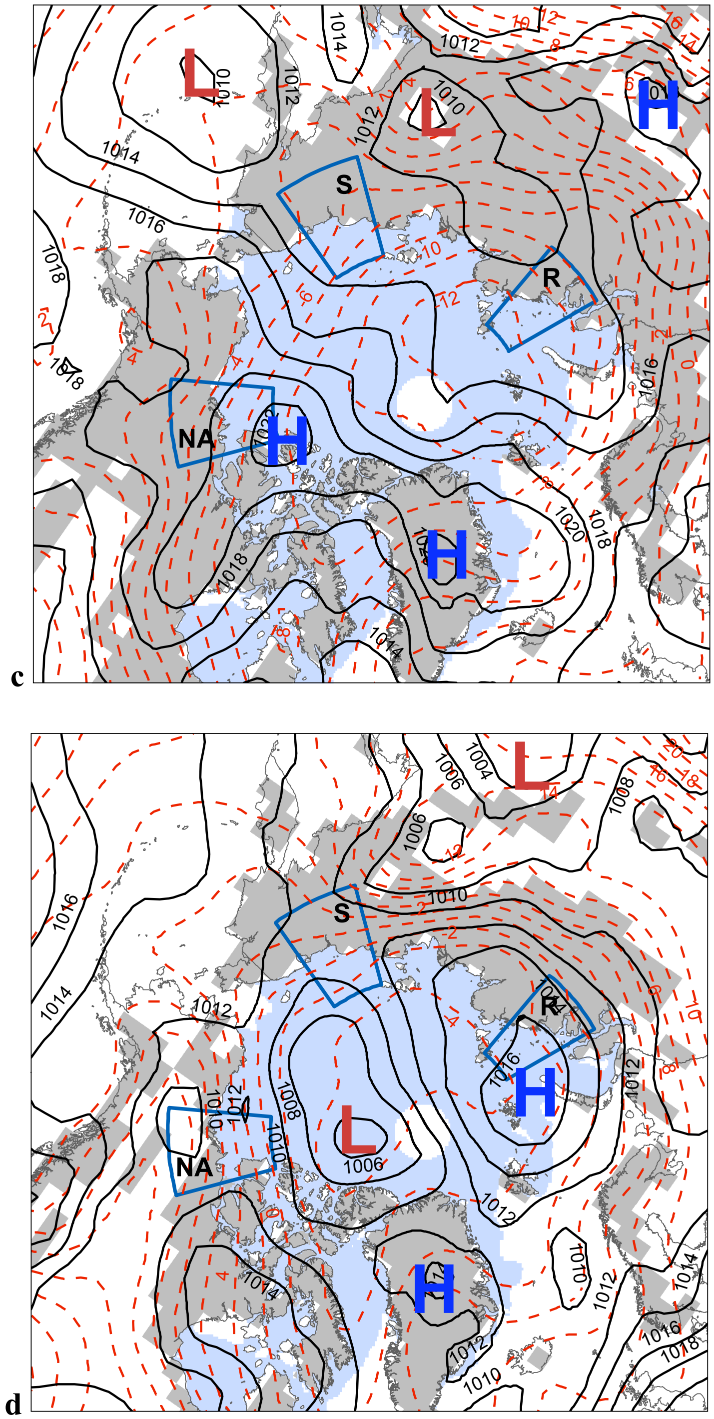


Figure 5.5 (c) May and (d) June (continued).

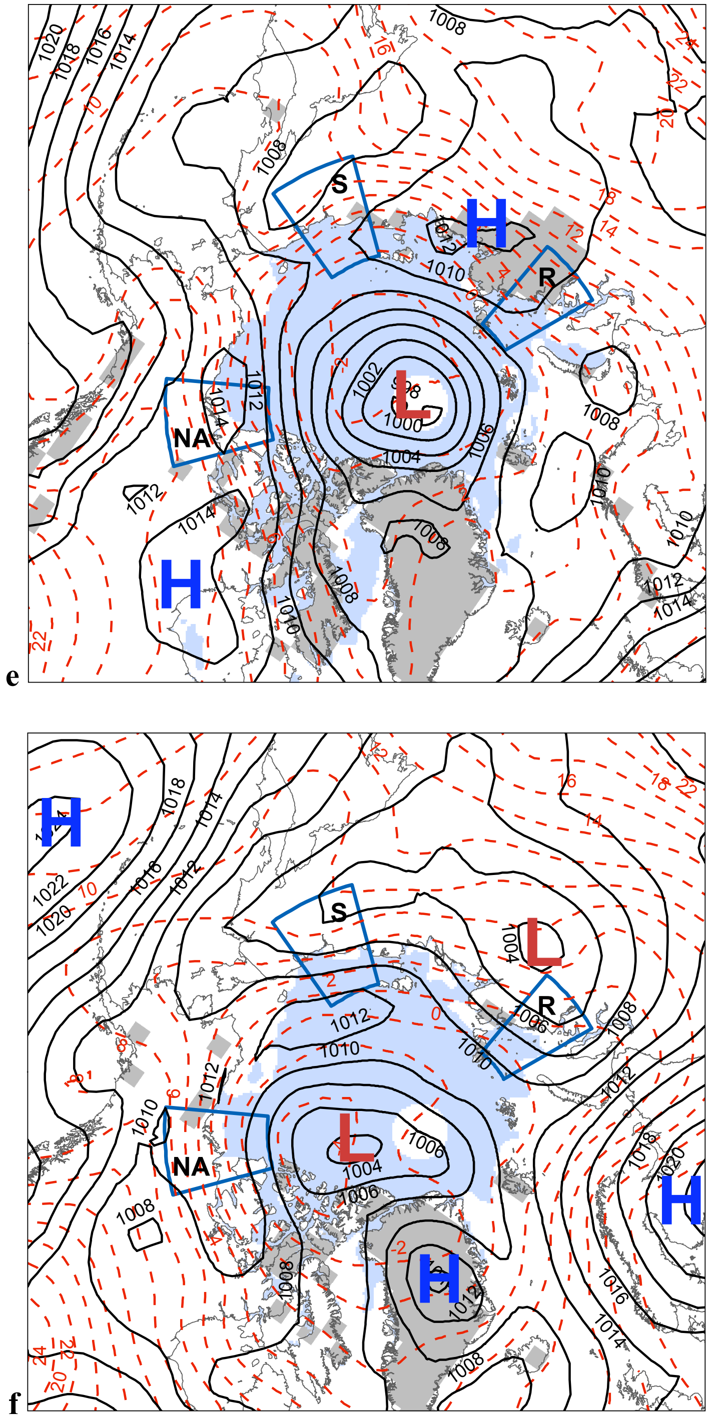


Figure 5.5 (e) July and (f) August (continued).

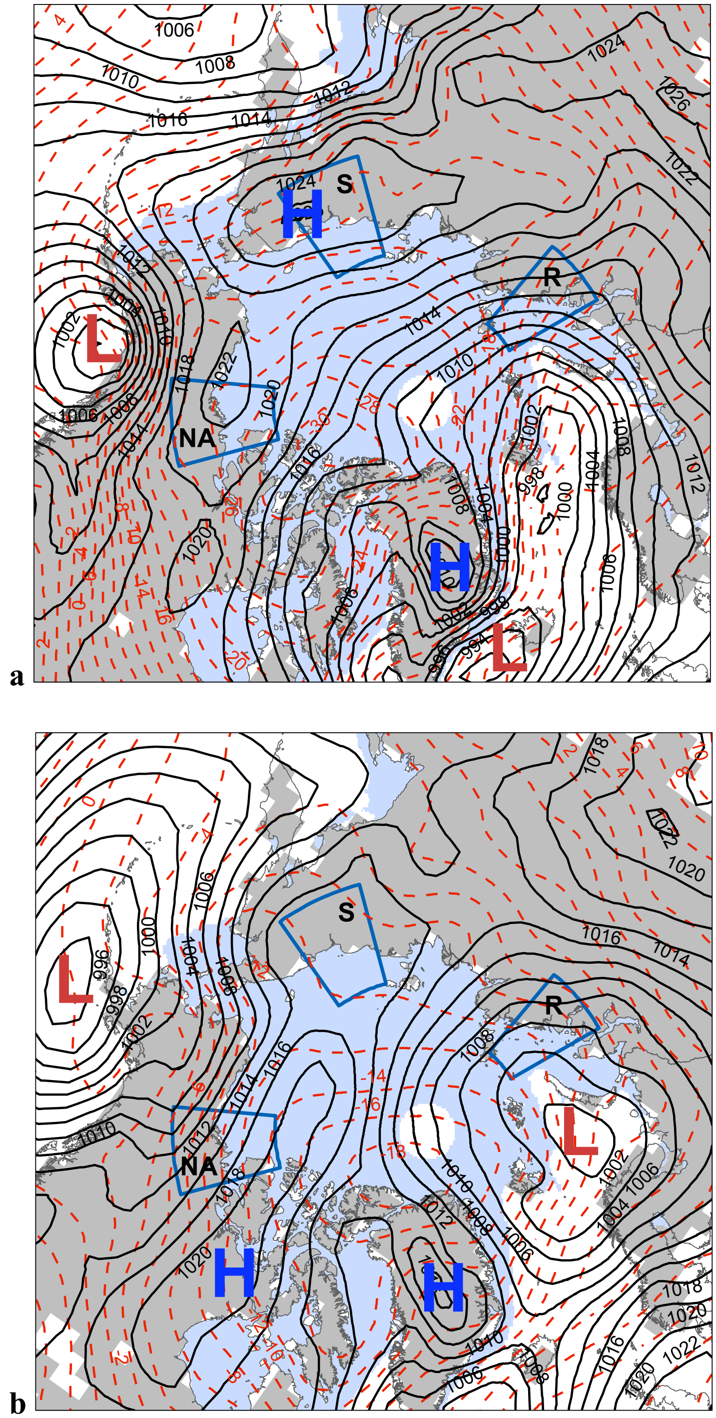


Figure 5.6 2007 monthly MSLP in hPa (solid black), 925 hPa air temperature in ° C (dashed red), snow-covered area extent (gray shaded), and sea ice extent (blue shaded) for (a) March, (b) April, (c) May, (d) June, (e) July, and (f) August. The North American (NA), Siberian (S), and Russian (R) study regions are outlined in blue.

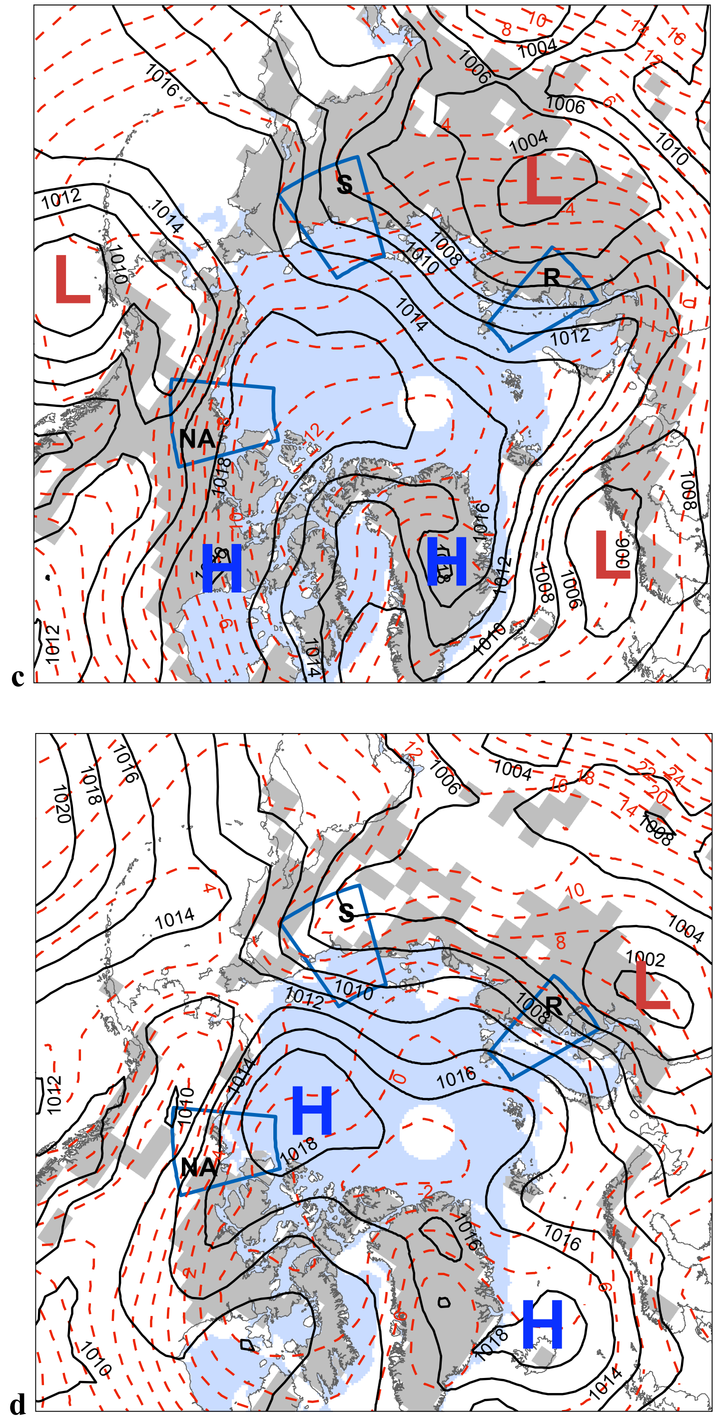


Figure 5.6 (c) May and (d) June (continued).

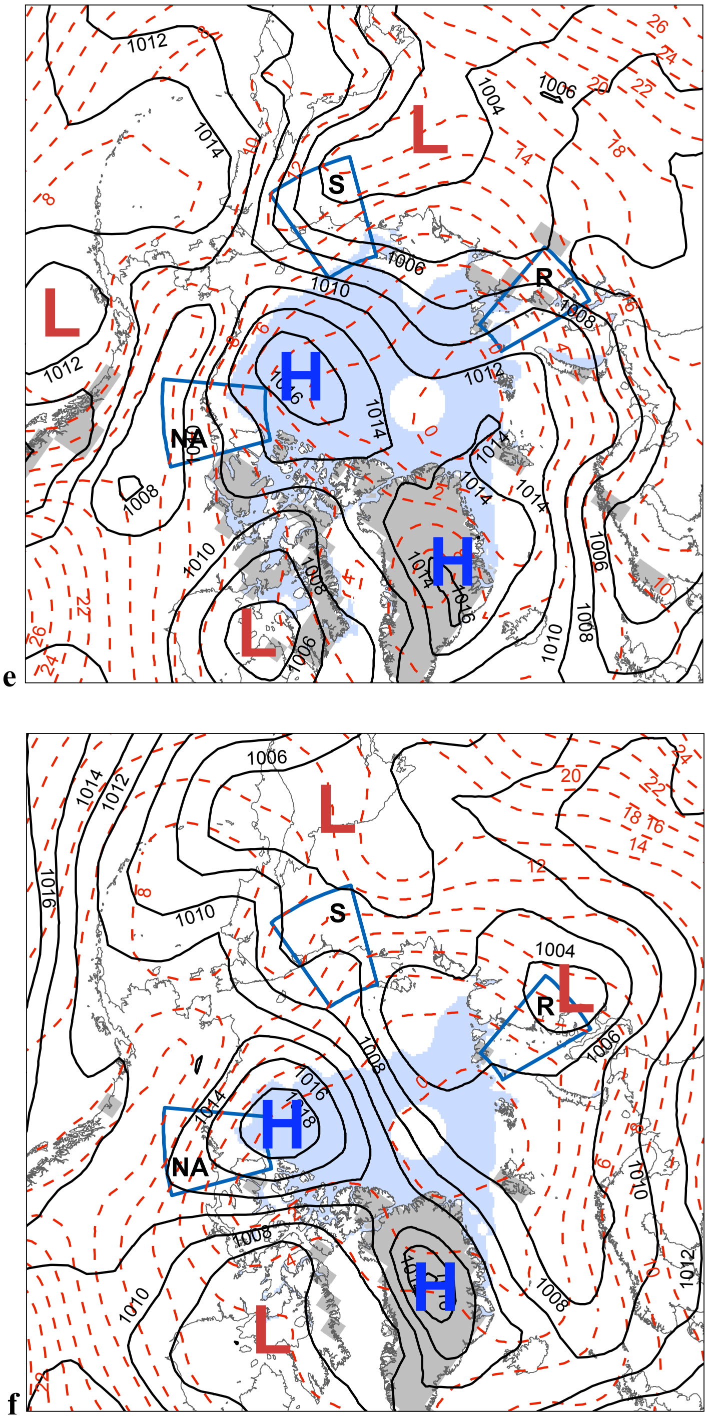


Figure 5.6 (e) July and (f) August (continued).

Regions (Figures 4.2-4.4). The Russian Region during 1985, however, is out of phase with the other two regions, having early snow cover and sea ice extent losses (negative anomalies) in June, July, and August (Figures 4.2-4.4). August sea ice cover is almost completely gone except for the farthest northern portion of the Russian Region (Figures 4.8a, 5.4f), whereas the Siberian and North American Regions are almost completely ice covered in August except for near the coastal areas of both regions (Figures 4.8a, 5.4f). Snow cover persists abnormally late in the North American and Siberian Regions in August and is completely absent from the Russian Region (Figures 4.4b, 5.4f).

During March, low pressure centers exist to the northwest of the Siberian Region and to the east of the region, centered over the Gulf of Alaska resulting in anomalously lower MSLP (Figures 5.1a, 5.4a). Although there is a mean southwesterly wind direction, which would commonly indicate warm air advection, the temperature over the region is anomalously colder since the flow is from cold, continental Siberia (Figures 5.1a, 5.4a). The lower MSLP and increased cloud cover in the Siberian Region indicates strong or frequent cyclones which may have deposited new snow cover, thickening the existing continental snowpack (Figure 5.1a). However, colder temperatures during March when the mean temperature is well below freezing (-19.31°C) and very low 500 hPa geopotential heights would restrict the amount of moisture available for precipitation (Table 5.1, Figure 5.1a). It is also likely that periods of warming via advection from southerly surface winds are lost in the monthly average and short periods of strong advection are not apparent at the monthly scale but could still increase precipitation.

Table 5.1 Monthly means and standard deviations of 500 hPa geopotential height (in gpm), total cloud cover (in %), 925 hPa air temperature (in °C), and MSLP (in hPA) for the Siberian, North American, and Russian study regions (1979-2007).

500 hPa Geopotential Height						
	Siberian Region		North American Region		Russian Region	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
March	5195.68	56.41	5212.19	46.94	5152.62	59.49
April	5257.70	34.20	5306.41	48.31	5194.84	60.78
May	5376.03	31.04	5429.28	39.51	5315.67	46.88
June	5500.31	24.33	5541.41	30.50	5463.64	56.67
July	5574.96	38.63	5590.60	34.10	5572.80	47.54
August	5528.32	47.66	5541.20	40.61	5520.82	49.31

Total Cloud Cover						
	Siberian Region		North American Region		Russian Region	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
March	50.5	8.3	38.9	6.6	53.8	6.8
April	43.9	8.7	34.9	8.6	50.1	9.6
May	40.1	7.4	30.4	5.6	46.4	7.2
June	40.0	5.5	29.5	5.9	44.2	7.7
July	45.4	6.1	38.0	5.3	42.7	6.4
August	48.1	5.7	45.1	6.4	50.2	7.2

925 hPa Air Temperature						
	Siberian Region		North American Region		Russian Region	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
March	-19.31	2.74	-19.01	3.20	-18.69	2.52
April	-13.71	2.52	-11.54	2.83	-15.34	3.01
May	-4.19	1.77	-3.73	2.13	-8.35	1.59
June	4.27	1.60	5.03	1.35	-0.25	2.11
July	7.99	2.00	8.21	1.76	5.11	1.94
August	5.02	2.34	5.58	1.85	3.68	1.74

Table 5.1 (continued).

MSLP						
	Siberian Region		North American Region		Russian Region	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
March	1019.75	3.82	1019.46	3.89	1014.49	6.65
April	1017.78	3.90	1018.16	2.68	1013.77	6.35
May	1013.47	2.43	1017.51	2.32	1012.92	4.25
June	1009.90	2.09	1014.00	2.02	1010.27	3.06
July	1009.39	1.80	1012.73	1.77	1010.64	2.88
August	1010.35	2.55	1012.01	2.61	1010.32	3.54

In April, high pressure builds into the Central Arctic and persists through the remainder of the melt season resulting in anomalously higher MSLP for 1985 (Figures 5.1b 5.4b). This high pressure system results in an east-northeasterly wind direction and anomalously colder temperature in the Siberian Region (Figure 5.1b). The colder temperature and higher MSLP conditions persist into May, during which northwesterly winds increase in strength (Figure 5.1c). In May, snowmelt onset on the sea ice cover occurs over approximately 33% of the ice area although no loss of snow or sea ice occurs during this month (Figure 5.7a). Similar higher MSLP and colder temperature conditions also occur in June; however, during June, the high pressure system shifts to the northeast of the Siberian Region (Figure 5.4d) causing the shift in wind direction from northeasterly in May to southeasterly during June (Figures 5.1c-d). No area of snow cover extent is lost during June; however, the normal June temperature in the Siberian Region is 4.27°C and even anomalously colder temperatures are above the freezing point (Table 5.1). Thus anomalously colder temperature, though still above freezing, during June is most likely thinning the continental snow cover prior to actual removal of snow cover in July, resulting in later than normal snow cover extent loss (Figures 5.2, 5.4e).

As in June, mean July MSLP is anomalously higher (Figure 5.1e), except a low pressure center is located to the west-southwest of the Siberian Region (Figure 5.4e). The pressure gradient over the region results in strong easterly winds (Figure 5.1e). The warmer temperature is caused by the presence of the low pressure center and the advection of warm air into the region (Figure 5.1e), inducing normal snow cover extent losses for July (Figure 4.3b). The northern portion of the Siberian Region is still located

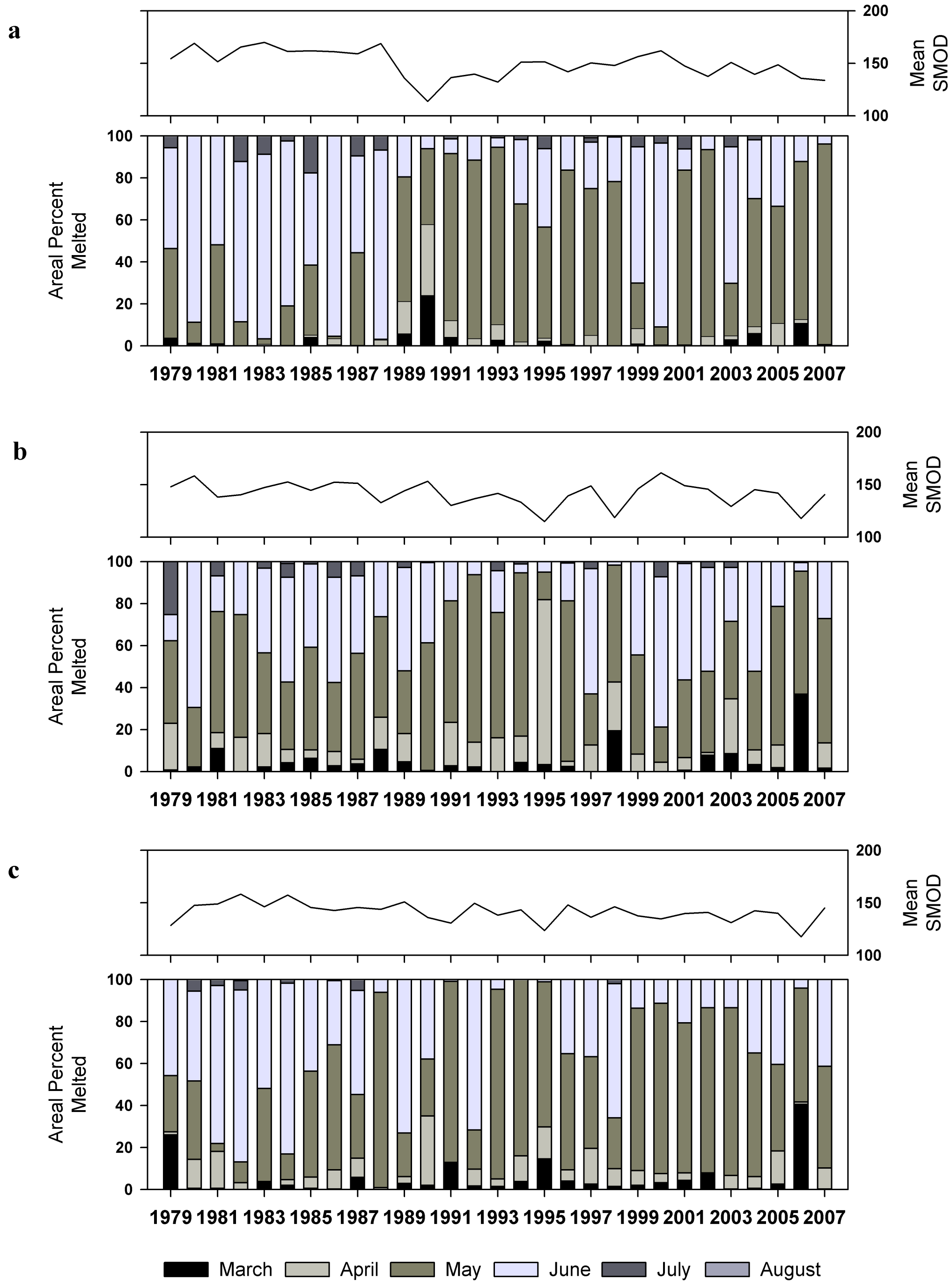


Figure 5.7 Mean Julian date of snow melt onset and areal percent snow cover on sea ice melted by month for the (a) Siberian, (b) North American, and (c) Russian study regions.

under higher MSLP and an easterly wind with a fetch over completely sea ice-covered ocean causes sea ice extent to have later than normal loss in July (Figures 4.3a, 5.4e), while local warming effects of the low pressure system cause melt in an already thin continental snow cover. By August, MSLP is still higher over the Siberian Region but temperature is anomalously cooler again (Figure 5.1f). Lower MSLP to the south and southwest of the region is slightly weakened and coincides with a mean northeasterly wind direction (Figures 5.1f, 5.4f). Some snow cover remains in the eastern portion of the region, resulting in later than normal snow cover extent loss for August (Figures 4.4b, 5.4f). The shift to northeasterly winds likely thinned the sea ice making it easier for the loss of ice near the coast to occur, anomalously later than normal (Figures 4.4a, 5.1f, 5.4f).

In-phase with the Siberian Region in 1985 is the North American Region (Table 4.3). March in the North American Region has an anomalously lower MSLP and warmer temperature (Figure 5.2a), a result of the deep low pressure center in the Gulf of Alaska (Figure 5.4a). The March pressure pattern results in the mean southeasterly wind direction over the region (Figure 5.2a), which advects warmer temperatures into the region allowing for greater moisture content in the air mass and likely causes the deposition of new snow, deepening the existing snow cover. During April, low pressure over the Gulf of Alaska remains while a strong high pressure center builds to the northwest of the North American Region, creating strong northeasterly winds across the region, leading to the anomalously colder conditions (Figures 5.2b, 5.4a-b). In May, the high pressure system over the Central Arctic weakens, resulting in anomalously lower pressure and weaker northeasterly winds (Figures 5.2c, 5.4c). In June the pressure pattern over the Arctic further weakens (Figure 5.4d). MSLP over the North American Region is slightly higher than normal, and the area of higher pressures to the north of the study region results in a northeasterly wind direction (Figures 5.2d, 5.4d). The winds are the likely cause for the colder than normal temperature over the region (Figure 5.2d), and also the loss of some sea ice extent via sea ice divergence and thinning (Figures 4.6a, 5.4d). Although the June temperature in the North American Region is anomalously cold, June is the earliest month that normal mean temperature is above freezing (Table 5.1). Thus cooler than normal June temperatures can still melt or thin the snowpack; however, in this year did not remove the continental snow cover and still allows for some loss of sea ice extent, but not a large decline (Figures 4.6a, 5.4d), resulting in later than normal snow cover and sea ice extent loss (Figure 4.2).

In July, the atmospheric pattern shifts, resulting in high pressure to the west of the North American Region (Figure 5.4e), changing the mean wind direction to northwesterly (Figure 5.2e). Some additional sea ice extent is lost during July (Figures 4.7a, 5.4e). However, the sea ice extent for the regions is still anomalously late for July (Figure 4.3a). The anomalously colder temperature also prevents the complete loss of snow cover within the region, resulting in a highly anomalous late snow cover extent loss (Figure 4.3b). By August MSLP is still anomalously high and the temperature is cooler than normal; however, the location of a high pressure center over the eastern portion of the study region results in a weaker southeasterly wind (Figures 5.2f, 5.4f). The cooler August temperature prevents the complete loss of snow cover in the region and with weaker winds, likely cause little sea ice loss due to southward transport and thinning, resulting in anomalously late loss of snow and sea ice cover in the North American Region at the end of the melt season.

The Russian Region during the 1985 melt season is out-of-phase with the Siberian and North American Regions since anomalously early melting takes place in the snow cover and sea ice extent for this region. In March, the Russian Region is influenced by a low pressure system located over the Laptev Sea (Figure 5.4a), causing slightly lower MSLP and a colder temperature (Figure 5.3a). Although the mean wind direction is southwesterly, which would suggest the advection of warmer temperatures from latitudes to the south, March temperatures are anomalously colder (Figure 5.3a). The colder temperature is likely caused by the winds advecting cold continental air into the Russian study region located along the coast. In April, MSLP is normal with a low pressure center located to the west of the study region and high pressure located over the Central Arctic (Figures 5.3b, 5.4b). The wind direction is southeasterly and the temperature is slightly below normal (Figure 5.3b). In May, the atmospheric pattern shifts and the Russian Region is under anomalously higher MSLP and lower temperature (Figure 5.3c). The pressure pattern shift results in a change in the wind direction from having a southerly wind component during March and April to strong northeasterly winds in May (Figure 5.3). Although no sea ice loss occurs during May, the strong northeasterly winds would aid in thinning the sea ice cover, setting up the region for the anomalously early loss of a large portion of sea ice cover during June (Figures 4.2a, 5.4d). In June, the Russian Region is still under anomalously higher MSLP, but the pressure gradient over the region weakens, weakening the winds and likely causing the anomalously warmer temperature (Figures 5.3d, 5.4d).

In July, a high pressure center has built just to the west of the Russian Region causing anomalously higher MSLP, strong northeasterly winds, and slightly below normal temperature (Figures 5.3e, 5.4e). Although the temperature is cooler than normal, normal July temperatures in all three study regions are well above freezing (Table 5.1), thus melting results in the loss of some snow cover in the region and additional sea ice extent loss (Figure 5.4e). The atmospheric conditions in July result in normal loss in the sea ice extent and anomalously late loss of snow cover extent (Figure 4.3). During August, a low pressure center is located over the southern portion of the Russian Region causing a mean northeasterly wind direction, slightly below normal MSLP, and warmer than normal temperature (Figures 5.3f, 5.4f). Although the pressure pattern is very different in the months of July and August, the resulting wind direction is the same through both months (Figures 5.3e-f, 5.4e-f). The warmer temperature during August is enough to melt all remaining snow cover within the Russian Region resulting in a normal snow cover extent anomaly (Figure 4.4b). The warm temperatures in addition to the persistent northeasterly wind direction through both July and August (Figure 5.3), thinning and diverging the sea ice cover, resulted in almost complete loss of sea ice within the study region (Figures 4.8a, 5.4f). The complete loss of snow and extensive loss of sea ice in August results in the normal snow cover loss and the anomalously early loss of sea ice cover in contrast to the late losses of sea ice and snow cover in both the Siberian and North American Regions during 1985 (Figure 4.4).

In summary, the North American and Siberian Region anomalously late losses of snow and sea ice extent during the 1985 melt season are primarily a result of cooler temperatures through June, July, and August in the North American Region and in July and August in the Siberian Region and possibly deep continental snow cover which is able to persist longer into the melt season (Figures 5.1, 5.2, 5.4). An anomalously warmer June and August in association with the strengthening of northeasterly winds through July and August acted to spread out and thin the sea ice cover, leading to rapid and extensive sea ice cover loss in the Russian Region (Figures 5.3, 5.4). The atmospheric pattern over the entire Arctic Region and the varied influences on different sub-hemispheric regions result in the mixed responses of the sea ice and snow cover in the three study regions during this case year.

5.2 In-Phase Late Sea Ice and Snow Cover Anomaly Case Year: 1996

The sea ice extent anomalies of the 1996 melt season have a later than normal loss of sea ice extent (all positive anomalies) through the melt season in all three study regions (Figures 4.1-4.4). The earliest loss of snow cover during the melt season occurs in the North American Region in June while the Siberian and Russian Regions remain completely snow-covered (Figures 4.6b, 5.5d). Snow cover over the entire extent of the Russian Region during June is not abnormal; however, in the Siberian Region this is an anomalously late loss of snow cover (Figures 4.2b, 4.6b). Although the sea ice conditions of the three study regions are in-phase, the same atmospheric conditions do not apply to all three regions during the months of the 1996 melt season.

The Siberian Region during March 1996, like March of 1985, has anomalously lower MSLP, but unlike March 1985 has an anomalously warmer temperature (Figure 5.1). Although there is no snow depth information, it is likely that lower MSLP and warmer temperature conditions could produce new snowfall, adding to the snow cover depth over the region. In April of 1996, like 1985, higher MSLP and colder temperatures in the Siberian Region would help preserve the snow cover from March into April (Figure 5.1). During May and June of 1996, the MSLP patterns over the Siberian Region are weak (Figure 5.5) and in the absence of a strong low pressure pattern during May and June (Figure 5.5) there might not be any significant deposition of new continental snow cover within any of the study regions. However, a normal temperature in May and colder temperature in June result in anomalously extensive snow cover extent in the region through June (Figures 4.2b, 5.1c-d). With weak pressure gradients over the Siberian Region, calm winds are observed in May and weak northwesterly winds observed in June (Figure 5.1). The weak pressure patterns and winds would make sea ice transport and loss difficult, resulting in a persistent sea ice cover through these two months covering normal extents, which during these months are completely sea ice-covered (Figures 4.1, 4.2a, 4.5a, 4.6a, 5.5c-d).

Slightly below normal MSLP in July and anomalously colder temperatures through June and July likely helped postpone the loss of sea ice cover (Figures 5.1, 5.5d-e). In July, sea ice extent loss should occur (Figures 4.3a, 4.7a); however, there is no actual loss of sea ice cover within the Siberian Region until August 1996 resulting in the late sea ice extent loss anomaly (Figures 4.4a, 4.8a, 5.5). Although the temperature in the Siberian Region during July is anomalously colder like in June, mean 925 hPa air temperatures are well above freezing in both months, 4.27°C in June and 7.99°C in July (Table 5.1). In addition, the snowpack is likely very thin by June and does not need much forcing to melt completely in July (Figures 5.1, 5.5). In August, low pressure to the west-southwest of the Siberian Region (Figure 5.5f) is able to advect warm air into the region causing the warmer August temperature anomaly and allowing for some loss of coastal sea ice, though much less than normal (Figures 4.4a, 5.1f, 5.5f).

The temperature in the North American Region during March 1996 is anomalously warmer (Figure 5.2a). In the mixed-phase case year 1985, the North American Region also has anomalously warmer temperatures, but is under anomalously lower MSLP (Figure 5.2a). However, in 1996 the North American Region is centered under a large high pressure system causing southwesterly anticyclonic winds (Figures 5.2a, 5.5a). This warming in March induces some melting of the snowpack on the sea ice cover over a small portion of the study region (Figure 5.7b) although the mean snowmelt onset date for the region does not occur until 18 May (Julian date 139) (Table 5.2).

In April, the North American Region is under normal MSLP conditions around 1018 hPa (Figure 5.2b, Table 5.1); however, the region is influenced by both a high pressure center located in the Central Arctic and a low pressure center over the Gulf of Alaska (Figure 5.5b). The interaction between these two systems results in the northeasterly mean wind direction and an anomalously colder temperature over the North American Region (Figures 5.2b, 5.5b). By May, the atmospheric pattern breaks down and a weak high pressure system is located over the northeastern portion of the North American Region (Figure 5.5c). The weak pressure gradient results in weaker southeasterly winds across the region (Figure 5.2c). Although there is anomalously higher MSLP present in May for the North American Region, temperatures are very near normal, likely a result of warm air advection from the southeasterly winds (Figure 5.2c).

Table 5.2 Mean date of snowmelt onset on sea ice for the Siberian, North American, and Russian study regions from the first of the year.

Year	Siberian Region	North American Region	Russian Region
1979	154.4	148.0	128.5
1980	168.9	158.1	147.5
1981	151.3	138.1	148.9
1982	165.4	140.3	158.3
1983	169.9	147.1	146.1
1984	161.3	152.6	157.3
1985	161.8	144.4	145.5
1986	161.0	152.2	142.5
1987	159.0	151.3	145.7
1988	168.8	132.8	143.7
1989	135.5	144.1	150.9
1990	113.5	153.1	136.1
1991	136.4	130.1	130.8
1992	139.5	136.6	149.5
1993	132.0	141.6	138.1
1994	151.0	133.2	143.4
1995	151.5	114.8	123.5
1996	141.8	139.2	147.9
1997	150.2	148.8	136.4
1998	147.8	118.5	146.2
1999	156.3	145.9	137.6
2000	162.0	161.1	134.7
2001	147.4	149.0	139.7
2002	137.4	145.7	141.0
2003	150.8	129.2	131.1
2004	139.5	145.1	142.5
2005	148.5	142.0	139.9
2006	135.7	117.6	117.6
2007	133.7	140.6	145.1
Mean	149.4	141.4	141.2
Std. Dev.	13.4	11.4	9.1

As a result, the largest areal percentage of snowmelt onset on sea ice occurs during May, although actual loss of sea ice cover does not occur until July (Figures 5.5, 5.7b).

During June, the region is influenced by a weak low pressure system to the north (Figure 5.5d). The pressure gradients are very weak and as a result so are the winds (Figures 5.2d, 5.5d). Without a strong influence from the winds, it is likely that the anomalously warmer temperature alone resulted in the earlier than normal loss of snow cover in June (Figure 4.2b). No sea ice extent loss occurs in June; however, it is likely that the warmer temperature contributed to the loss of sea ice cover that is observed in July by thinning the ice (Figure 5.5).

In July, snow cover extent is reduced to zero within the North American Region and sea ice cover is lost near the coastline (Figures 4.7, 5.5e). The Arctic is dominated by a strong low pressure region in the Central Arctic; however, MSLP is higher than normal in the North American Region, a result of a high pressure region over Northern Canada (Figures 5.2e, 5.5e). Although the study region is under higher MSLP, the mean wind direction during July 1996 is southwesterly (Figure 5.2e). Southwesterly winds and warm air advection resulting in a slightly warmer than normal temperature remove the remaining continental snow cover and some coastal sea ice in the region (Figures 5.2e, 5.5e).

By August, the low pressure center located over the Central Arctic in July has weakened and has shifted towards the Canadian Arctic (Figure 5.5). The pressure gradients over the North American Region are very weak and as a result the mean wind is weak and from a northwesterly direction (Figures 5.2f, 5.5f). The shift in wind direction caused an anomalously colder August temperature and a lower 500 hPa geopotential height (Figure 5.2f). These August atmospheric conditions prevent a precipitous decline in the sea ice cover and also produced some new snow cover in the western portion of the North American Region resulting in the above normal extent anomalies at the end of melt season for sea ice and snow cover (Figures 5.2f, 5.5f).

The Russian Region is under anomalously higher MSLP with a warmer than normal temperature during March and April of 1996 (Figure 5.3). The high pressure center spanning the Eurasian continent to the south of the Russian study region during March results in a mean southwesterly wind direction which causes the warmer temperature and higher 500 hPa geopotential heights (Figures 5.3a, 5.5a). Although high pressure in the Arctic is generally associated with cold temperatures, this high pressure system is located to the south of the study area, in a lower latitudinal band that can have higher mean temperatures. Increased temperatures early in the melt season, increase the ability of the atmosphere to hold moisture and will likely produce more precipitation in the form of snow. In this case, new snow cover would add to the depth of snow cover on the ground in the region and help lengthen its persistence into later months of the melt season. In April, however, a high pressure center is located to the northeast of the Russian Region causing a 180° shift in mean wind direction from southwesterly during March to northeasterly in April (Figures 5.3, 5.5). The shift in wind direction concurred with a near normal although slightly warmer temperature, which could also result in more available moisture to produce precipitation (Figure 5.3b).

During May 1996, the Russian Region is under normal MSLP and a colder temperature (Figure 5.3c). There is almost no pressure gradient across the region with slightly lower pressure to the east-southeast of the region (Figure 5.5c). Despite there being weak winds in May, there is an anomalously higher percentage of cloud cover, likely contributing to the high areal percentage of snowmelt on sea ice during the month and a mean snowmelt onset date of 27 May (Julian date 148) (Figure 5.3c, 5.7c). During June, MSLP is higher than normal and the temperature is cooler than normal (Figure 5.3d). Both May and June each have a northerly component to the mean wind direction (Figure 5.5). These constant cold temperatures allowed the sea ice cover in the Russian Region to persist through June and most of the snow cover extent to also persist through July resulting in later than usual snow cover loss (Figure 5.5).

The July loss of sea ice extent coincides with a shift in the location and intensity of MSLP over the Russian Region. The mean wind direction in July is southwesterly (Figure 5.3e), a result of the strong low pressure center located north of Greenland and the weaker region of high pressure located to the east of the study region (Figure 5.5e). The shift in mean wind direction in addition to normal warm July air temperatures (Table 5.1) resulted in the first losses in sea ice cover and continental snow cover in the Russian Region where the ice and snow cover likely had been thinning, but had not opened up earlier in the melt season (Figures 5.3, 5.5).

Anomalously lower MSLP occurs during August in the Russian Region like in July (Figure 5.3e-f). However, the August low pressure center is located just to the southeast of the Russian Region, resulting in a northeasterly mean wind direction over the study region (Figures 5.3f, 5.5f). The shift to northeasterly winds coincides with a colder than normal temperature which likely restricted the amount of sea ice cover lost during the month of August, as observed by the later than normal loss of August sea ice extent (Figures 4.4a, 5.3f, 5.5f). Snow cover in the Russian Region is completely removed in

August, although mean temperature is colder than normal (Figures 4.8b, 5.3f, 5.5f). This is due to the above-freezing normal August temperature (Table 5.1) and also because any snow cover remaining at the end of July is likely to be very thin and easily melted. Considering that some coastal fast ice cover has previously been lost in the month of July (Figure 5.5e), a northeasterly wind fetch, although generally indicative of cold air advection, would be able to pick up warm moist air from the areas of open ocean to the north of any remaining continental snow cover, easily warming the local temperature enough to melt a thin, late-season snowpack. The observed Russian Region sea ice and snow conditions include a normal (snow-free) continental snowpack and a less than normal amount of sea ice cover lost in August (Figures 4.4b, 4.8b, 5.5f).

In summary, during the 1996 melt season, all three study regions are in-phase with late sea ice and snow cover loss conditions (Table 4.3, Figures 4.1-4.4). The late loss of Siberian sea ice cover is the result of very weak pressure patterns and thus weaker winds during May and June making it difficult to transport ice and the anomalously colder temperature during the months of June and July, preventing the loss of sea ice extent until August (Figures 5.1, 5.5). The North American Region during the 1996 melt season is under anomalously warmer temperatures during May, June, and July (Figure 5.2) forcing the early loss of snow cover in June and near-normal sea ice extents in July (Figures 4.2, 4.3). However, a precipitous decline in sea ice extents from July to August is prevented by a shift in the MSLP pattern and cooler temperatures (Figures 5.2, 5.5). The Russian Region has anomalously colder temperatures in the months of May, June, and August of 1996 (Figure 5.3). The anomalously warmer temperature in July coincides with the first losses in both sea ice and snow cover;

however, August temperatures become anomalously colder like in the North American Region, preventing extensive August sea ice loss (Figures 5.2, 5.3, 5.5e). Although the pressure pattern is not the same for the Russian and North American Regions during August 1996, the resulting affects on temperatures and the northerly wind component are similar in both regions, preventing a large loss of the sea ice extent during August (Figures 5.2f, 5.3f, 5.5). The resulting sea ice extent anomalies in the 1996 melt season are the same for each study region; however, the specific atmospheric forcing is not exactly the same in any region.

5.3 In-Phase Early Sea Ice and Snow Cover Anomaly Case Year: 2007

At the end of the 2007 melt season, the sea ice cover across the Arctic reached its lowest extent on record. In each of the three study regions, earlier than normal sea ice extent losses are observed during June, July, and August (Figure 4.1-4.4). Anomalous loss of snow cover begins in June in the North American and Siberian Regions and during July in the Russian Region (Figures 4.2b, 4.3b, 5.6). A one-month lag in snow cover loss for the Russian Region is not unusual; however, there is a large loss of sea ice extent in the Russian Region in June (Figure 5.6d) while the adjacent land is still completely snow-covered (Figure 4.6b). In the North American and Siberian Regions, however, snow cover and sea ice extent losses occur simultaneously during June (Figure 5.6d).

The Siberian Region is anomalously warmer throughout the entire melt season (Figure 5.1). The temperatures are influenced by the presence of low pressure centers to the west, southwest, and south-southwest during May and June, July, and August respectively (Figure 5.6). During March, however, the region is under an area of high pressure centered over the southern portion of the study region (Figure 5.6a). The location of this high pressure center produces a mean southwesterly wind direction in the Siberian Region, resulting in a similar warmer temperature anomaly to months of lower MSLP (Figure 5.1). The anomalously warm temperatures observed through the melt season are aided by warm air advection from the persistent southerly component to the wind direction in all months except April when winds are very weak due to the lack of any pressure gradient over the extent of the Siberian study region (Figures 5.1, 5.6). The conditions during this persistently warm melt season would easily melt the snow cover and sea ice as well as aid in the northward transport of sea ice out of the study region (Figure 5.1). By August, observed sea ice cover has been completely removed in the East Siberian and Chukchi Seas and completely out of the extent of the Siberian study region (Figures 5.6f, 4.8a).

The North American Region is under an area of higher MSLP during March 2007 (Figure 5.6a). Temperatures are anomalously cold and since the pressure gradient across the region is weak, the winds are weak and from the northwest (Figures 5.2a, 5.6a). Colder temperatures early in the melt season restrict the ability of air masses to hold more moisture and do not promote the accumulation of new snow cover especially since the North American Region is still completely sea ice-covered (Figure 5.6a). During April 2007, the low pressure center located in the Gulf of Alaska has strengthened as compared to March and high pressure, although still present over the northern portion of the study region has weakened slightly (Figure 5.6). The relative location of the high and low pressure centers during April put the North American Region in the southeasterly wind flow (Figures 5.2b, 5.6b). The southeasterly winds coincide with anomalously warmer April temperatures and higher 500 hPa geopotential heights, indicating warm air advection into the study region from lower latitudes (Figure 5.2b). Although no sea ice or snow cover extent is lost this early in the year, approximately 10% of the sea ice cover has a snowmelt onset date during April 2007 (Figure 5.7b). The advection of warm temperatures via southeasterly winds also can begin to melt and thin the continental snowpack, although no extent is removed until later months (Figure 5.6). The pressure pattern in May 2007 over the North American Region is similar although much weaker than the pressure pattern in April (Figure 5.6). May temperatures are cooler than normal, coinciding with the shift to northeasterly wind direction, since MSLP is slightly below normal (Figure 5.2c). The cooler temperatures over the study region help prevent melting or removal of the snow cover.

An early loss of snow cover extent and slightly early loss of sea ice extent occurs in the North American Region during June 2007 (Figure 4.2). During this month, a high pressure center is located over the northern portion of the North American Region resulting in the mean northeasterly wind direction (Figures 5.2d, 5.6d). The warmer temperature observed in June (Figure 5.2d), however, is not caused by warm air advection associated with a low pressure system that is commonly seen in the anomaly record. The warmer temperature indicates that this high pressure center in June 2007 (Figure 5.6d) is likely more dynamically induced by air descending and warming rather than thermodynamically induced by a cold, dense air mass near the surface. Higher 500 hPa geopotential heights are also associated with the warmer temperatures and the dynamic high during June (Figure 5.2d).

This high pressure system persists to the north of the North American Study Region through the remaining melt season months of July and August although it is slightly weaker in July resulting in anomalously lower MSLP in the region (Figures 5.2e, 5.6). The presence of the persistent high pressure system results in a continuous northeasterly wind direction through June, July, and August and anomalously warmer temperatures through June and July in the North American Region (Figures 5.2, 5.6). Both warm temperatures and the northeasterly winds spreading and thinning the ice southward results in an anomalously lower observed sea ice extent at the end of the 2007 melt season in the North American Region. The presence of remaining sea ice cover in the northern portion of the North American Region, in contrast to the complete loss of sea ice cover in the Siberian Region, is due to the greater multiyear ice fraction present in the Beaufort Sea (Figures 5.6, 2.3).

In the beginning of the 2007 melt season, regions of low pressure are located to the west of the Russian Region in March and April (Figure 5.6). The Russian Region sits in the warm sector of the mean low pressure center, and anomalously warmer temperatures occur along with south-southwesterly winds during March and April (Figure 5.3). Warmer temperatures associated with lower MSLP this early in the melt season could increase moisture and result in the deposition of new snow cover over the study region. Some melting takes place in the snow cover on sea ice in the Russian Region as early as March and April (Figure 5.7c); however, the mean snowmelt onset date across the study region does not occur until 25 May (Julian date 145), although May temperatures are anomalously colder (Figure 5.3). During May a mean low pressure center is located to the southeast of the study domain (Figure 5.6c), resulting in a northeasterly wind direction (Figure 5.3c), advecting cooler temperatures into the region from over the sea ice cover to the north (Figure 5.6c) and likely thinning the Russian Region sea ice cover by transporting it southward where the ice is more easily melted later in the season. Anomalously warmer temperatures during June in combination with a northeasterly wind direction forcing sea ice divergence and thinning (Figure 5.3) resulted in the anomalously early loss of June sea ice extent and the observed loss of sea ice cover through the central portion of the Russian sea ice study domain (Figures 4.2a, 5.6d).

Although sea ice cover is reduced during June in the Russian Region, snow cover extent is not lost until July (Figure 5.6). The anomalously warmer temperatures in March and April (Figure 5.3) when mean 925 hPa air temperatures are still well below freezing would allow more moisture (Table 5.1), resulting in the accumulation of thicker snow depths in the Russian Region, especially during April when a low pressure center is located just to the west of the region (Figure 5.6b). The addition of new snow cover would deepen the continental snowpack and take longer to melt completely away. This accumulation of additional snow could explain why the snow cover extent in the Russian Region during the 2007 melt season persisted later than portions of the thin, first-year sea ice cover (Figures 2.3, 5.6).

After the anomalous loss of sea ice extent during June in the Russian Region (Figures 4.2a, 5.6d), areas of lower MSLP are located to the south of the study region during July and August (Figures 5.6e-f). The lower pressures put the region in northeasterly flow, which could act to spread sea ice southward, thinning the ice further. Temperatures are just slightly above normal, during July in the Russian Region and slightly below normal during August (Figure 5.3). Although not anomalously warm, the months of July and August are normally 5.11°C and 3.68°C, well above the freezing point (Table 5.1). The thin, southward-transported sea ice is able to melt almost completely away within the study region boundary by August (Figure 5.6f).

The most extreme sea ice extent losses occur during the 2007 melt season. Sea ice extent losses occur anomalously early through the months of June, July, and August in all three study regions, fitting the in-phase and early melt phase category (Table 4.3). Although each region has the same resultant sea ice conditions, the atmospheric conditions vary by region. The Siberian Region lost all sea ice cover by August due to winds with a southerly component in almost all months advecting warm air, resulting in persistent anomalously warmer temperatures (Figures 5.1, 5.6). The North American Region was also subject to warm temperatures during June and July; however, the mean wind direction through the later three months of the melt season are northeasterly, spreading and thinning the sea ice cover southward where it can be more easily melted (Figure 5.2). The Russian Region lost a large amount of sea ice extent anomalously early, earlier than any loss of continental snow cover extent occurs. The loss of sea ice before snow cover also occurs in the Russian Region during 1985, a mixed-phase year (Figure 4.2). During March and April, anomalously warmer temperatures likely contributed to snowfall in the region, thickening the snow cover and making it resistant to melt during June (Figure 5.3). Northeasterly winds, like in the North American Region during this year, through the months of May, June, July, and August in the Russian Region likely resulted in thinning and divergence of sea ice southward where extensive melting is more easily accomplished (Figures 5.2, 5.3).

5.4 Summary of Case Years

Hemispheric-scale MSLP and 925 hPa air temperature patterns at the monthly scale agree with the MSLP and temperature anomaly patterns and mean wind direction throughout the melt season months of the three case study years 1985, 1996, and 2007. Although no snow cover depth data are available for this study, it is apparent that depth plays a role in the persistence of snow cover extent through the melt season. It is assumed that conditions of anomalously warmer temperatures and lower pressures early in the melt season, during March and April, would deepen the snow cover, making the cover more resistant to melt forcing conditions later in the season. Through the melt season snow cover thins, although thinning does not affect the snow cover extent observations until the snow cover melts completely. Anomalously cooler temperatures likely slow the loss of snow cover extent; however, thinning of the snow pack occurs leading to precipitous losses when temperatures warm.

During the three case years, anomalously warmer temperatures generally cause anomalously early losses of sea ice extent, especially when the warming occurs with strong northeasterly winds as is observed in the Russian Region during 1985 and 2007 and in the North American Region in 2007. However, conditions of anomalously warmer temperatures can also be associated with winds from a more southerly direction and result in anomalously early losses of sea ice extent as occurs in the Siberian Region in 2007. In many ways, mean southerly winds advecting warmer temperatures into the study regions are intuitively assumed to be the primary condition necessary to promote melting and the early loss of sea ice extent. However, the observed atmospheric and sea ice conditions suggest that strong northeasterly winds with or without anomalously warm conditions in the later melt season months, July and August when mean temperatures are above freezing, are as effective at forcing anomalously early melt conditions, most likely via thinning and ice transport.

Anomalously late losses of sea ice extent are typically associated with cool conditions and weak winds as occurs in the North American Region in 1985 and the Siberian and North American Regions in 1996. However, anomalously late losses of sea ice extent tend to carry over into later months since the sea ice cover from month to month is not independent of the conditions in the previous months as appears in the Siberian Region during 1996. Anomalously late loss of sea ice also occurs in regions that are on track to reach anomalously low sea ice extents through the melt season until a shift in the atmospheric pattern cools temperatures and changes the wind direction, reducing the decline in sea ice extent as is observed in the Siberian Region in 1985 and the North American and Russian Regions in 1996.

Overall, strong winds tend to force more sea ice loss while weak winds tend to reduce the reduction of sea ice cover. Anomalously warmer temperatures promote sea ice loss, but are not necessary to cause extensive ice loss during July and August when mean temperatures are above freezing. The effects of sea ice extent in previous months impact the sea ice condition in later months, i.e. once the ice cover is removed either anomalously early or late, the anomaly of the sea ice cover in the later month is calculated from the normal ice extent for the month regardless of the area of sea ice cover present at the beginning of the month which is dependant on the conditions of the previous month. Although anomalies in the sea ice extent are not completely independent from month to month, the monthly condition does respond to the present atmospheric forcing. Thus a study of snow and sea ice conditions in response to atmospheric forcing at the monthly scale can be used to assess the response of snow and sea ice cover to specific atmospheric conditions across independent study regions throughout the 29-year study period.

Chapter 6

Results III: Atmospheric Forcing of Snow Cover and Sea Ice Conditions Through the 29-Year Study Period

Melt seasons over the study period have been classified based on the snow and sea ice loss anomaly patterns in each of the three study regions across the Arctic. These classified patterns include: both late (positive) or early (negative) in-phase anomalies and mixed-phase anomalies (Table 4.3). However, when looking at each study region independently, the annual melt season snow cover and sea ice loss conditions can be attributed to specific patterns present in the atmosphere within study regions at the monthly scale. Three atmospheric parameters, anomalous MSLP and 925 hPa air temperature and mean wind direction spatially averaged over the study domain (Figures 5.1-5.3), have been chosen to represent the general atmospheric forcing for anomalous monthly sea ice and snow cover conditions (Figures 4.1-4.4). As described in Chapter 5, individual regions may have very different atmospheric patterns that result in the same MSLP and temperature anomaly conditions as observed over the study region. In these cases, mean wind direction can better identify the location of high and low pressure centers relative to the study region, and help resolve the atmospheric influence on sea ice and snow conditions. Using a ±0.25 threshold to define normal versus anomalous conditions, the concurrent anomalous MSLP and temperature can be classified into four atmospheric conditions. These conditions include: higher than normal MSLP and colder than normal temperature, higher than normal MSLP and warmer than normal temperature, lower than normal MSLP and warmer than normal temperature, and lower than normal MSLP and colder than normal temperature. However, not all years fall into these categories, in some cases, either the MSLP or temperature fall within the ±0.25 threshold and are considered normal. During June and July, both snow cover and sea ice extents are most highly variable across all three study regions (Tables 4.1, 4.2; Figures 4.6, 4.7). Therefore, atmospheric conditions during these two months are analyzed and summarized to determine what snow and ice anomalies are taking place to see how well given atmospheric conditions will be able to forecast resultant ice and snow conditions. The case study years 1985, 1996, and 2007 described in Chapter 5 are used to provide a starting point for future, more thorough analyses of the sea ice and snow conditions through the entire study period.

6.1 June Anomalous Conditions

In all anomalous cases of June snow cover and sea ice extent in the study regions through the 29-year study period, the most frequent condition was the late loss of both sea ice and snow cover, representing 34 cases or 39.1% of all possible monthly June cases (Table 6.1). By region, late snow and late sea ice loss is the most frequent condition in the Siberian and Russian Regions (Table 6.1). In the Russian Region, there is almost no variability in June snow cover and in the Siberian Region, there is less snow cover lost during June than in the North American Region (Figure 4.6b, Table 4.2)). Thus more cases of anomalously late snow cover loss appear during June in the Siberian and Russian Regions and conversely, fewer cases of anomalously early snow cover loss are observed in these two regions (Figure 4.2b, Table 6.1). The most common snow and

Table 6.1 Summary of June cases of snow cover and sea ice extent loss anomaly conditions over the 29-year study period and in each study region.

	Siberian Region Cases		North American Region Cases		Russian Region Cases		All Region Cases	
	Count	%	Count	%	Count	%	Count	%
Late Snow & Late Ice	11	37.9	7	24.1	16	55.2	34	39.1
Early Snow & Early Ice	3	10.4	5	17.2			8	9.2
Early Snow & Late Ice	7	24.1	6	20.7	1	3.5	14	16.1
Late Snow & Early Ice			1	3.5	7	24.1	8	9.2
Normal Snow and/or Ice	8	27.6	10	34.5	5	17.2	23	26.4
Total	29	100.0	29	100.0	29	100.0	87	100.0

sea ice condition in the North American Region during June is a normal loss of snow cover or sea ice extent at 34.5% (Table 6.1). More cases of normal snow and sea ice conditions occur due to the greater variability in North American June snow and sea ice, i.e. fewer outliers skewing the anomalies late or early (positive or negative) through the study period (Figure 4.2). This analysis will focus on attributing anomalous sets of atmospheric conditions to the snow and sea ice conditions, although many cases of normal MSLP and/or 925 hPa temperature do occur during the study period (Table 6.2).

6.1.1 Anomalously Higher MSLP and Colder 925 hPa Temperature

Conditions of anomalously higher MSLP and colder 925 hPa air temperature during June occur in a total of 19 cases during the study period (Table 6.3). The most typical wind direction under these atmospheric conditions is from the northeast, nine cases total (Table 6.3). A total of 13 cases have a northerly wind component (Table 6.3). The most common response in the snow and sea ice to these higher MSLP and colder temperature conditions is a later than normal loss of snow cover and sea ice extent, 11 cases or 57.9% (Table 6.4). Excluding cases of normal June snow cover in the Russian Region which represent completely snow-covered conditions (realistically a positive anomaly), higher MSLP and colder temperature produce a normal loss of snow cover in three cases, one in the Siberian Region and two in the North American Region (Table 6.4). However, including all normal cases of snow cover and sea ice, 31.6% of higher MSLP and colder temperature conditions result in normal snow or sea ice extent conditions, the second most frequent (Table 6.4). The only other snow and ice conditions that occur under these atmospheric conditions are an anomalously early loss of both snow and sea ice cover and early loss of snow cover with a late loss of sea ice extent

Table 6.2 June cases with normal MSLP and/or 925 hPa air temperature. MSLP and temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction and anomalously early (negative) and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal conditions are identified by the * symbol.

Region	Case	MSLP	925 hPa Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1981	*	-	W	+	+
	1982	-	*	NE	*	+
	1984	-	*	NE	-	+
	1990	-	*	N	-	-
	1998	+	*	NE	+	+
	1999	-	*	SE	+	+
	2000	-	*	S	-	+
	2002	*	+	E	-	-
	2004	*	+	SE	-	+
	2006	-	*	W	-	+
North American Region	1983	-	*	SE	+	+
	1988	*	+	NE	+	-
	1989	*	+	E	-	+
	1990	-	*	NE	-	+
	1992	+	*	SE	+	+
	1997	-	*	E	+	*
	1999	+	*	NE	*	+
	2003	-	*	NE	+	*
Russian Region	1981	+	*	NW	*	+
	2005	+	*	NE	*	*
	2007	*	+	NE	*	-

Table 6.3 June cases of anomalously higher MSLP and colder 925 hPa air temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction and anomalously early (negative) and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal conditions are identified by the * symbol.

Region	Case	MSLP	925 hPa Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1979	+	-	NE	+	+
	1983	+	-	NW	*	+
	1985	+	-	E	+	+
	1988	+	-	NE	+	+
	1992	+	-	SE	+	*
	1996	+	-	NW	+	+
	2001	+	-	NE	-	+
North American Region	1979	+	-	W	+	*
	1982	+	-	NE	-	-
	1985	+	-	NE	+	+
	1991	+	-	NE	*	-
	2001	+	-	E	+	+
	2005	+	-	NE	*	-
Russian Region	1982	+	-	E	*	+
	1983	+	-	SW	*	+
	1987	+	-	N	*	*
	1991	+	-	NW	*	+
	1996	+	-	NE	*	+
	1998	+	-	NE	*	+

Table 6.4 Summary of June snow cover and sea ice loss conditions under anomalously higher MSLP and colder 925 hPa air temperature conditions at the ±0.25 threshold for the Siberian, North American, and Russian study regions.

	Siberian Region	North American Region	Russian Region	All Regions	
				Total	%
Late Snow & Late Ice	4	2	5	11	57.9
Early Snow & Early Ice		1		1	5.3
Early Snow & Late Ice	1			1	5.3
Late Snow & Early Ice					
Normal Snow and/or Ice	2	3	1	6	31.5
Total	7	6	6	19	100.0

(Table 6.4). Each of these snow and ice conditions occur only once during the study period. Since the early loss of snow cover occurs less frequently under anomalously colder conditions than cases of normal or late snow cover extent loss, it is likely that these early loss cases are pre-conditioned by the atmospheric and resulting snow cover conditions (i.e. thinning snow depth) in the preceding month which is lost anomalously early when temperatures warm in June (Table 5.1).

Anomalously higher MSLP and colder temperature resulting in anomalously late snow cover and late sea ice area loss can be represented by the case study of June 1985 in the North American and Siberian Regions and June 1996 in the Russian Region (Table 6.3). This pattern of anomalies in the North American Region in June 1985 and June 1996 in the Russian Region indicates the location of a high pressure center to the north of the study region causing a northeasterly wind, cooler temperature, and later than normal loss of snow cover and sea ice extent (Figures 5.4d, 5.5d; Table 6.3). Although, a cooler temperature would inhibit melt, the northeasterly wind direction indicates the divergence and transport of sea ice cover southward where it is more easily melted. Since the snow and sea ice anomalies indicate later than normal loss in both the North American Region in 1985 and the Russian Region in 1996 (Table 6.3), it is more likely that the conditions in the preceding months contributed greatly to the extensive June snow and sea ice cover, i.e. weaker winds in the North American Region in May 1985 and in the Russian Region during May 1996 reducing melting in the snow and sea ice cover (Figures 5.2c, 5.3c, 5.4, 5.5). The atmospheric anomalies and resultant snow and sea ice conditions are the same for the Siberian Region in June 1985; however, in this case the mean wind direction is easterly (Table 6.3). The region of high pressure located north of the North American Region in June 1985 is influencing the Siberian Region as well (Figure 5.4d). In this case, the high pressure region is located to the northeast of the northern portion of the Siberian Region, resulting in the observed easterly wind (Figure 5.4d). Cooler than normal temperatures are associated with the influence of the atmospheric pattern over the Siberian Region (higher MSLP and easterly winds), resulting in anomalously late June snow and sea ice loss.

6.1.2 Anomalously Higher MSLP and Warmer 925 hPa Air Temperature

Atmospheric conditions of anomalously higher MSLP and warmer 925 hPa air temperature during June occur in 17 cases (Table 6.5). Unlike the higher MSLP and colder temperature conditions described in the previous section, there is a more mixed response in the snow and sea ice cover conditions under higher MSLP and warmer temperature conditions (Tables 6.4, 6.6). The most common snow and sea ice response included either normal snow cover or sea ice extents, in 41.1% of all cases (Table 6.6). In order of decreasing prevalence the snow and ice conditions include: late loss of snow and sea ice (23.5%), late loss of snow cover and early loss of sea ice (17.7%), early loss of snow and sea ice (11.8%), and early loss of snow cover with late loss of sea ice (5.9%) (Table 6.6). It is worth noting that all cases of late loss of snow cover and early loss of sea ice occur in June in the Russian Region (Table 6.6). This is most likely due to the 5° in latitude farther north position of the Russian Region as compared to the other two study regions. Less overall solar radiation results in a one month lag in the loss of snow cover, the exception being June 2000 (Figure 4.6b). The most cases of June late snow cover loss and early sea ice extent loss occur in the Russian Region (Tables 6.1, 6.6),

Table 6.5 June cases of anomalously higher MSLP and warmer 925 hPa air temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction and anomalously early (negative) and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal conditions are identified by the * symbol.

Region	Case	MSLP	925 hPa Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1991	+	+	SE	+	*
	1993	+	+	SE	*	+
	1994	+	+	E	*	+
	1995	+	+	E	-	+
North American Region	1980	+	+	SE	*	+
	1993	+	+	NE	-	-
	1998	+	+	NE	-	-
	2004	+	+	NE	*	*
	2007	+	+	NE	-	*
Russian Region	1984	+	+	S	*	+
	1985	+	+	E	*	-
	1990	+	+	N	*	+
	1993	+	+	NE	*	*
	1994	+	+	SE	*	+
	2001	+	+	NE	*	-
	2003	+	+	SW	*	+
	2004	+	+	SE	*	-

Table 6.6 Summary of June snow cover and sea ice loss conditions under anomalously higher MSLP and warmer 925 hPa air temperature conditions at the ±0.25 threshold for the Siberian, North American, and Russian study regions.

	Siberian Region	North American Region	Russian Region	All Regions	
				Total	%
Late Snow & Late Ice			4	4	23.5
Early Snow & Early Ice		2		2	11.8
Early Snow & Late Ice	1			1	5.9
Late Snow & Early Ice			3	3	17.7
Normal Snow and/or Ice	3	3	1	7	41.1
Total	4	5	8	17	100.0

since snow cover is not typically lost until July in the Russian Region (Table 4.2) and sea ice cover loss begins as early as May in all three study regions (Table 4.1).

During June cases with anomalously higher MSLP and warmer temperature, the most common wind component is easterly and the cases are evenly split north and south with 7 cases from a more northerly direction and 7 cases from a more southerly direction (Table 6.5). The highly variable case-to-case wind direction corresponds with the high variability of snow and sea ice responses under conditions of higher MSLP and warmer temperature. Thus there is not as clear of a predictable pattern during June in the atmospheric, snow, and sea ice anomalies as under conditions of higher MSLP and colder temperature as discussed previously (Tables 6.3, 6.5).

Two months from the case study years appear under the higher MSLP and warmer temperature conditions, June 1985 in the Russian Region and June 2007 in the North American Region (Table 6.5). The Russian Region in June 1985 under atmospheric conditions of higher MSLP and warmer temperature has an observed normal snow cover with an early loss of sea ice condition (Table 6.5). Warmer temperatures during June 1985 are likely the result of the weakening of the pressure gradient over the region during June and associated shift to weak easterly winds that led to the anomalous loss of sea ice (Figures 5.3d, 5.4d). During 2007 in the North American Region, higher MSLP and warmer temperature results in earlier than normal loss of snow cover and normal June sea ice conditions (Table 6.5). The high pressure region located north of the North American Region in June 2007 resulted in a mean northeasterly wind direction (Figure 5.6d, Table 6.5). The wind direction provided a fetch over newly open coastal ocean water, which would warm the atmosphere and aid in early melting of the continental snow cover within the region (Figure 5.6d). The resultant snow and sea ice conditions under higher MSLP and warmer temperature are highly variable (Table 6.6), thus the 1985 and 2007 cases do not have the same snow and sea ice response although the atmospheric situation is similar (Table 6.5).

6.1.3 Anomalously Lower MSLP and Warmer 925 hPa Air Temperature

June cases of anomalously lower MSLP and warmer temperature result in all possible snow and sea ice conditions excluding late loss of snow cover and early loss of sea ice (Table 6.7, 6.8). In cases under these atmospheric conditions, 35.7% result in late losses of snow cover and sea ice, 28.3% result in either a normal snow cover or sea ice extent, 21.4% result in the early loss of snow cover and the late loss of sea ice, and 14.3% result in the early loss of both snow cover and sea ice (Table 6.8). Eight of the months with lower MSLP and warmer temperature have a southerly direction to the wind which indicate some advection of warmer temperatures from latitudes farther south (Table 6.7). However, only two cases under this atmospheric pattern occur with earlier than normal loss of sea ice cover (negative anomalies), 2007 in the Siberian Region and 1995 in the North American Region (Table 6.7). This is most likely due to the influence that atmospheric conditions and resultant snow and sea ice conditions in previous months have on later sea ice and snow conditions. Later than normal melt conditions due to persistent cold temperatures in early melt months can carry into later months resulting in a greater than normal amount of snow and/or sea ice cover to be melted during the month to reach normal melt conditions for June. Also, the two cases with normal June sea ice cover loss in the Siberian and North American Regions occur with anomalously early snow cover loss and southeasterly winds (Table 6.7). Of the four cases (two normal and

Table 6.7 June cases of anomalously lower MSLP and warmer 925 hPa air temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction and anomalously early (negative) and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal conditions are identified by the * symbol. Instances of weak winds are indicated by the / symbol.

Region	Case	MSLP	925 hPa Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1986	-	+	S	+	+
	1989	-	+	SE	-	*
	1997	-	+	SE	+	+
	2005	-	+	SE	-	*
	2007	-	+	SE	-	-
North American Region	1984	-	+	NE	-	+
	1995	-	+	E	-	-
	1996	-	+	/	-	+
	2000	-	+	SE	+	+
	2006	-	+	/	-	+
Russian Region	1979	-	+	SE	*	+
	1988	-	+	NE	*	*
	2002	-	+	N	*	+
	2006	-	+	SW	*	*

Table 6.8 Summary of June snow cover and sea ice loss conditions under anomalously lower MSLP and warmer 925 hPa air temperature conditions at the ±0.25 threshold for the Siberian, North American, and Russian study regions.

	Siberian Region	North American Region	Russian Region	All Regions	
				Total	%
Late Snow & Late Ice	2	1	2	5	35.7
Early Snow & Early Ice	1	1		2	14.3
Early Snow & Late Ice		3		3	21.4
Late Snow & Early Ice					
Normal Snow and/or Ice	2		2	4	28.6
Total	5	5	4	14	100.0

two early) of sea ice extent loss in the Siberian and North American Regions, three occurred with southeasterly winds indicating that lesser than normal continental snow cover extents in the wind fetch could have contributed to sea ice extent losses, both at normal and earlier than usual loss rates (Table 6.7).

Two cases with anomalously lower MSLP and warmer temperature appear during the case study years 1996 and 2007 (Table 6.7). These include: June 1996 in the North American Region and June 2007 in the Siberian Region (Table 6.7). During June 1996, a center of low pressure is located north of the North American Region (Figure 5.5d). However, the pressure gradient across the region is very weak, resulting in the weak observed winds (Figure 5.5d, Table 6.7). The snow cover in the North American Region in June 1996 is lost anomalously early while the sea ice cover is lost anomalously late (Table 6.7). Given that there is little influence on melting from wind and the wind direction in this case, a large area of continental snow cover is lost from May to June; however, the sea ice within the study region has not yet been lost. In the case of June 1996, radiational heating over a thinning snowpack resulted in the loss of snow cover and likely contributed to the anomalously warmer air temperature over the entire study region (Figure 5.5c, d; Table 6.7).

The anomalously lower MSLP and warmer temperature of June 2007 in the Siberian Region along with a southeasterly wind direction resulted in anomalously early loss of both snow and sea ice cover (Table 6.7). Low pressure in the western portion of the North American study region in June 2007 caused a typical situation where warm air advection in the warm sector of cyclonic systems resulted in an anomalously warmer temperature and significant melting in the snow and sea ice pack causing the early snow and sea ice loss anomalies (Figure 5.6d, Table 6.7). The main difference between the North American 1996 and Siberian 2007 June case months are the winds and the resulting sea ice conditions (Table 6.7). Winds advect warmer air in the Siberian Region in June 2007 melting the sea ice cover while weak winds in the North American Region in June 1996 allow more sea ice cover to persist longer into the melt season than usual.

6.1.4 Anomalously Lower MSLP and Colder 925 hPa Air Temperature

June cases of anomalously lower MSLP and anomalously colder 925 hPa air temperature produce all five possible snow and sea ice conditions (Table 6.9). Of all cases of lower MSLP and colder temperature in June, 50% produced late snow cover and late sea ice extent loss conditions (Table 6.10). Early loss of snow cover concurrent with late loss of sea ice cover occurred during one June case of lower MSLP and colder temperature in each of the study regions, representing 18.8% of all cases (Table 6.10). Cases of lower MSLP and colder temperature (18.8%) also occur with anomalously late snow cover and early sea ice extent loss; however, every case of this snow and ice condition occurs only in the Russian Region (Table 6.10). Since, snow cover loss in the Russian Region does not typically occur until July (Table 4.2) and sea ice cover loss can begin as early as May in all study regions (Table 4.1), the case where sea ice is removed during June, prior to losses of continental snow cover most commonly occurs in the Russian Region (Table 6.10). Early loss of snow cover and late loss of sea ice also occurs in the Russian Region under conditions of anomalously higher MSLP and warmer temperature with an easterly wind direction in three other cases (Tables 6.5, 6.6).

In all but three cases of lower MSLP and colder temperature, there is a northerly direction to the wind indicating that the low pressure system is located to the south,

Table 6.9 June cases of anomalously lower MSLP and colder 925 hPa air temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction and anomalously early (negative) and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal conditions are identified by the * symbol. Instances with weak winds are indentified by the / symbol.

Region	Case	MSLP	925 hPa Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1980	-	-	E	-	+
	1987	-	-	NE	+	+
	2003	-	-	SE	+	+
North American Region	1981	-	-	NE	+	+
	1986	-	-	NE	+	+
	1987	-	-	NE	-	-
	1994	-	-	/	-	+
	2002	-	-	NE	*	+
Russian Region	1980	-	-	NW	*	-
	1986	-	-	NW	*	+
	1989	-	-	NW	*	+
	1992	-	-	NE	*	+
	1995	-	-	N	*	-
	1997	-	-	NE	*	-
	1999	-	-	NW	*	+
	2000	-	-	NW	-	+

Table 6.10 Summary of June snow cover and sea ice loss conditions under anomalously lower MSLP and colder 925 hPa air temperature conditions at the ±0.25 threshold for the Siberian, North American, and Russian study regions.

	Siberian Region	North American Region	Russian Region	All Regions	
				Total	%
Late Snow & Late Ice	2	2	4	8	50.0
Early Snow & Early Ice		1		1	6.3
Early Snow & Late Ice	1	1	1	3	18.7
Late Snow & Early Ice			3	3	18.7
Normal Snow and/or Ice		1		1	6.3
Total	3	5	8	16	100.0

relative to the location of the study region and to the east or west, opposite to the east-west wind direction (Table 6.9). A westerly wind component indicates an eastern position of the low pressure center and an easterly wind component indicates a more westerly position of the low relative to the study region. The northerly wind direction likely influences the temperature via advection of cold air masses from the north. However, during cases with anomalously early sea ice extent loss, stronger northerly winds would likely aid the southward transport and melting of sea ice cover resulting in anomalously early melt anomalies despite a colder temperature (Table 6.9).

6.1.5 June Anomaly Summary

Anomalously colder 925 hPa air temperature, regardless of MSLP anomalies, are most likely to produce late snow and sea ice cover losses during June, representing 57.9% of all cases of higher MSLP and colder temperature and 50% of all cases of lower MSLP and colder temperature (Tables 6.4, 6.10). Atmospheric conditions of higher MSLP and higher temperature are most likely to produce a normal snow or sea ice response (41.2% of the time), though any type of snow and sea ice response can be produced (Table 6.6). Although warmer temperatures would intuitively indicate early loss of the snow and ice cover, in combination with lower MSLP 35.7% of cases result in late losses of snow cover and sea ice (Table 6.8) and under higher MSLP and warmer temperature, 23.5% of cases result in late snow and sea ice loss (Table 6.6), likely due to the influence of atmospheric conditions in previous months and the resulting snow and sea ice conditions present at the beginning of June, based on prior in-depth analysis of the melt seasons of the three case study years.

6.2 July Anomalous Conditions

In July, the most common snow cover and sea ice anomaly cases differ from the June cases in all three study regions (Tables 6.1, 6.11). Equally frequent during July, are cases of early loss of both snow and sea ice extent and normal snow and/or sea ice conditions, each representing 25.3% of all July cases (Table 6.11). Frequency of normal snow or sea ice loss cases is almost the same in July (25.3%) as in June (26.4%) (Tables 6.1, 6.11). The most frequent July anomaly case involves the early loss of snow cover with a later than normal loss of sea ice extent in 35.6% of all July months (Table 6.11), while in June it is most common to have a case with later than normal snow cover and sea ice loss (Table 6.1). The difference in most typical snow and sea ice condition in these two months is most likely due to the precipitous loss of snow cover from June to July in all three study regions (Table 4.2; Figures 4.6b, 4.7b). The atmospheric conditions associated with July snow and sea ice conditions are again split into the four major atmospheric conditions represented by anomalous MSLP and anomalous 925 hPa air temperature. However, July cases with normal MSLP or temperature are not described further (Table 6.12).

6.2.1 Anomalously Higher MSLP and Colder 925 hPa Air Temperature

During July there are only a few cases with anomalously higher MSLP and colder temperature, three cases each in the North American and Siberian Regions and two in the Russian Region (Table 6.13). In all cases of July higher MSLP and colder temperature, there is a northerly component to the winds indicating that a region of higher MSLP is located in the Central Arctic, north of the three study regions (Table 6.13). Under these atmospheric conditions, 50% of the cases result in normal July snow cover or sea ice

Table 6.11 Summary of July cases of snow cover and sea ice extent loss anomaly conditions over the 29-year study period and in each study region.

	Siberian Region Cases		North American Region Cases		Russian Region Cases		All Region Cases	
	Count	%	Count	%	Count	%	Count	%
Late Snow & Late Ice	1	3.5	2	6.9	7	24.1	10	11.5
Early Snow & Early Ice	7	24.1	9	31.0	6	20.7	22	25.3
Early Snow & Late Ice	11	37.9	13	44.8	7	24.1	31	35.6
Late Snow & Early Ice	1	3.5			1	3.5	2	2.3
Normal Snow and/or Ice	9	31.0	5	17.3	8	27.6	22	25.3
Total	29	100.0	29	100.0	29	100.0	87	100.0

Table 6.12 July cases with normal MSLP and/or 925 hPa air temperature. MSLP and temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction and anomalously early (negative) and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal conditions are identified by the * symbol. Instances of weak winds are identified by the / symbol.

Region	Case	MSLP	925 hPa Air Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1980	*	-	NE	*	+
	1982	+	*	NE	-	+
	1990	-	*	NE	-	-
	1995	-	*	NE	-	+
	1997	*	*	NE	-	+
	1998	+	*	NE	-	+
	2000	+	*	NE	-	-
	2001	*	+	SE	-	+
	2002	-	*	SE	-	-
	2006	*	*	NE	*	+
North American Region	1980	*	-	NE	-	+
	1982	*	+	NE	-	-
	1989	*	+	SW	-	+
	1991	*	-	N	-	+
	1994	*	+	/	-	+
	1995	+	*	NE	-	-
	2001	-	*	NE	-	+
	2003	-	*	SW	-	*
	2004	-	*	S	-	*
Russian Region	1981	*	-	NW	+	+
	1982	*	-	W	-	+
	1987	*	+	SW	+	+
	1988	*	-	NW	-	+
	1991	-	*	NW	*	+
	1993	*	-	NW	-	-
	1994	*	*	NW	+	+
	1995	-	*	E	+	-
	1998	+	*	NE	-	+
	1999	-	*	N	-	+
	2001	-	*	NE	-	-
	2005	-	*	NW	-	-
	2007	-	*	NE	-	-

Table 6.13 July cases of anomalously higher MSLP and colder 925 hPa air temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction, anomalously early (negative), and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal conditions are identified by the * symbol.

Region	Case	MSLP	925 hPa Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1984	+	-	NE	-	+
	1986	+	-	NE	-	*
	1999	+	-	NE	-	+
North American Region	1985	+	-	NW	+	+
	1986	+	-	NE	-	+
	1999	+	-	NW	-	*
Russian Region	1985	+	-	NE	+	*
	2000	+	-	N	*	-

extent conditions (Table 6.14). The other 50% of cases with higher MSLP and colder temperature in July result in late losses of sea ice cover with either early or late snow cover loss (Table 6.14). Early loss of snow cover in 37.5% of cases (Table 6.14) could be a result of the northerly wind component advecting warmer temperatures from over coastal sea ice-free ocean, locally removing any remaining thin continental snow cover resulting in earlier than normal July snow cover extent loss (Table 6.13, Figures 4.3b, 4.7b). Although, with the dominant northerly wind direction, the local advection of warmer marine air into the continental portion of the study regions would not warm temperatures enough across the entire study region to result in anomalously warmer temperatures in these cases (Table 6.13). However, even cooler than normal July temperatures are above freezing and will produce melt (Table 5.1).

The one case of late snow cover and late sea ice loss during July under the condition of higher MSLP and colder temperature occurs in the North American Region during July 1985 (Table 6.13). In July 1985, a center of high pressure is located just to the west of the Russian Region, over the Barents Sea, and the region of high pressure extends eastward across the Central Arctic to the western portion of the North American Region (Figure 5.4e). The influence of the high pressure on the North American and Russian study regions results in northwesterly and northeasterly winds in each region respectively (Table 6.13). In the case of the North American Region in July 1985, there is later than usual sea ice loss (Table 6.13), thus there is less open ocean than normal (Figure 5.4e). The northwesterly wind fetch over the sea ice cover keeps the temperature anomalously colder which would allow continental snow cover to persist longer into the melt season as observed by the later than normal loss of July snow cover for the region

Table 6.14 Summary of July snow cover and sea ice loss conditions under anomalously higher MSLP and colder 925 hPa air temperature conditions at the ±0.25 threshold for the Siberian, North American, and Russian study regions.

	Siberian Region	North American Region	Russian Region	All Regions	
				Total	%
Late Snow & Late Ice		1		1	12.5
Early Snow & Early Ice					
Early Snow & Late Ice	2	1		3	37.5
Late Snow & Early Ice					
Normal Snow and/or Ice	1	1	2	4	50.0
Total	3	3	2	8	100.0

(Table 6.13). In the Russian Region, the high pressure center has a stronger influence. The pressure gradient over the Russian Region is stronger than over the North American, which indicates a stronger northeasterly wind (Figure 5.4e). Northeasterly winds keep the temperature cooler than normal and stronger winds would better transport sea ice southward and promote reductions in extent. The combination of higher MSLP, colder temperature, and northeasterly winds allow the snow cover to persist later in the Russian Region, like in the North American Region (Table 6.13, Figure 5.4e). However, the stronger winds in the Russian Region likely increased the transport of sea ice to the south and caused more sea ice loss than is observed in the North American Region during the same month, resulting in a normal sea ice extent (Table 6.13). It is apparent that slight differences in the atmospheric conditions can impact the response of sea ice and snow cover differently in the study regions over the same time period.

6.2.2 Anomalously Higher MSLP and Warmer 925 hPa Air Temperature

Under conditions of anomalously higher MSLP and warmer 925 hPa temperature during July (Table 6.15), the most common response in the snow and sea ice cover conditions is a normal snow cover and/or sea ice cover loss, in 35.3% of cases (Table 6.16). Overall, in cases of higher MSLP and warmer temperature the snow and sea ice response is almost equally distributed in the early snow and late sea ice loss and early snow and early sea ice loss (Table 6.16). No cases of late snow cover and early sea ice loss occur under these atmospheric conditions since more than 90% of snow cover is gone by the month of July in the Siberian and North American Regions and almost 70% of snow is gone in the Russian Region (Tables 4.2, 6.16). In all cases with remaining July snow cover, the anomalously warmer temperature during July, the month of highest

Table 6.15 July cases of anomalously higher MSLP and warmer 925 hPa air temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction and anomalously early (negative) and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal conditions are identified by the * symbol.

Region	Case	MSLP	925 hPa Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1985	+	+	E	+	+
	1987	+	+	SE	*	+
	1991	+	+	E	*	*
	2003	+	+	SW	-	+
North American Region	1979	+	+	SE	+	+
	1987	+	+	NE	-	-
	1988	+	+	E	-	-
	1990	+	+	N	-	*
	1992	+	+	N	-	+
	1993	+	+	NE	-	-
	1996	+	+	NW	-	+
	1998	+	+	NE	-	-
Russian Region	1979	+	+	NE	-	*
	1984	+	+	NE	-	+
	1986	+	+	NE	*	+
	1990	+	+	NE	*	+
	2004	+	+	N	-	-

Table 6.16 Summary of July snow cover and sea ice loss conditions under anomalously higher MSLP and warmer 925 hPa air temperature conditions at the ±0.25 threshold for the Siberian, North American, and Russian study regions.

	Siberian Region	North American Region	Russian Region	All Regions	
				Total	%
Late Snow & Late Ice	1	1		2	11.7
Early Snow & Early Ice		4	1	5	29.5
Early Snow & Late Ice	1	2	1	4	23.5
Late Snow & Early Ice					
Normal Snow and/or Ice	2	1	3	6	35.3
Total	4	8	5	17	100.0

mean air temperature in all three study regions (Table 5.1), would quickly melt any remaining continental snow cover.

During July of 1985, a mixed-phase year (Table 4.3), the North American and Russian Regions are under conditions of anomalously higher MSLP and anomalously colder temperature (Table 6.13). The Siberian Region at this time, however, is under anomalously higher MSLP and anomalously warmer temperature (Table 6.15). The same expansive high pressure region spread over the majority of the Arctic Ocean that influences the Russian and North American Regions impacts the Siberian Region as well (Figure 5.4e). However, there is a weak low pressure center located to the west-southwest of the Siberian Region at this time (Figure 5.4e). The location of the high and low pressure regions results in a mean easterly wind direction in the Siberian Region (Figure 5.4e, Table 6.15). During this case, snow cover and sea ice extent losses are both later than normal, despite the anomalously warmer July temperature (Table 6.15). The July snow and sea ice conditions likely carry over from June, when snow cover and sea ice losses were anomalously late under atmospheric conditions of anomalously higher MSLP and anomalously colder temperature (Table 6.3).

During July 1996 in the North American Region, there is no remaining continental snow cover (Figures 4.7b, 5.5e) and there is an observed anomalously late loss of sea ice cover (Table 6.15). A deep low pressure center is located over the Central Arctic while the North American Region is located under a region of higher pressure centered over Northern Canada, resulting in the mean west-northwesterly wind direction (Figures 5.5e, 5.2e). The anomalously high amount of sea ice cover present in the region likely carries over from the high amount of sea ice during June when the region is under lower MSLP and warmer temperature conditions (Table 6.7); however, winds are weak resulting in a later than normal sea ice loss rate despite higher July temperature (Table 6.15). Although temperature is anomalously warm in June and July, June winds are weak (Table 6.7), making it harder to transport and reduce sea ice in the North American Region where thick multiyear sea ice is present (Figure 2.3).

6.2.3 Anomalously Lower MSLP and Warmer 925 hPa Air Temperature

By July, the most common response in the snow cover is early loss (Table 6.11) and under an anomalously warmer temperature with anomalously lower MSLP this is still the case since most snow cover has already been removed (Tables 4.2, 6.17). Under these atmospheric conditions, the most common response in snow and sea ice, in 46.2% of cases, is anomalously early loss in both snow and sea ice (Table 6.18). Both early loss of snow cover with late loss of sea ice and cases with normal snow or sea ice cover occur in 23.1% of cases and only one occurrence of late snow and sea ice loss (7.7%) is observed under these atmospheric conditions (Table 6.18).

July 1996 in the Russian Region is the only case, under lower MSLP and warmer temperature conditions, which has a late loss of both snow cover and sea ice extent (Table 6.17). During this month there is a deep low pressure center located in the Central Arctic (Figure 5.5e). Although there is a region of higher pressures over the eastern portion of the Russian Region, overall MSLP is lower than normal (Figure 5.5e, Table 6.17). The relative location of the high and low pressure areas result in the mean southwesterly wind direction (Table 6.17). This is the only case under lower MSLP and warmer temperature with a westerly wind direction (Table 6.17). These conditions are known to promote rapid melting, via the advection of warm air from the south. However,

Table 6.17 July cases of anomalously lower MSLP and warmer 925 hPa air temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction and anomalously early (negative) and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal snow cover are identified by the * symbol.

Region	Case	MSLP	925 hPa Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1983	-	+	NE	-	+
	1988	-	+	SE	*	+
	1992	-	+	SE	-	-
	1993	-	+	S	-	-
	2005	-	+	SE	-	-
	2007	-	+	SE	-	-
North American Region	1983	-	+	NE	-	+
	1997	-	+	NE	-	-
	2000	-	+	E	-	+
	2007	-	+	NE	-	-
Russian Region	1996	-	+	SW	+	+
	2002	-	+	N	*	+
	2006	-	+	SE	*	-

Table 6.18 Summary of July snow cover and sea ice loss conditions under anomalously lower MSLP and warmer 925 hPa air temperature conditions at the ±0.25 threshold for the Siberian, North American, and Russian study regions.

	Siberian Region	North American Region	Russian Region	All Regions	
				Total	%
Late Snow & Late Ice			1	1	7.7
Early Snow & Early Ice	4	2		6	46.1
Early Snow & Late Ice	1	2		3	23.1
Late Snow & Early Ice					
Normal Snow and/or Ice	1		2	3	23.1
Total	6	4	3	13	100.0

the snow and sea ice conditions during July in the Russian Region are heavily influenced by the atmospheric conditions in the early melt season. Due to the anomalously colder temperature in May and June, little melting is observed in the region (Figures 5.3, 5.5). The first losses of snow cover and sea ice do not occur until July and occur over small areas, resulting in later than normal July snow and sea ice extent anomalies (Figures 4.3, 4.7, 5.5e).

In July 2007 anomalously early snow and sea ice losses are observed in both the Siberian and North American Regions (Table 6.17) following early snow cover losses and normal North American sea ice and early Siberian sea ice extent losses in June (Tables 6.5, 6.7). The 2007 melt season is consistently warmer in all months of the season in the Siberian Region (Figure 5.1) and in April, June, and July in the North American Region (Figure 5.2). The southeasterly wind direction in the Siberian Region could effectively advect warm air northward, causing melt, and aid in the northward transport of sea ice out of the study region (Table 6.17). The high pressure center located over the northwest corner of the North American study region results in a northeasterly wind direction which, in addition to warmer air temperatures, would thin the sea ice by transporting it southward where it is more easily melted (Figure 5.6e, Table 6.17).

6.2.4 Anomalously Lower MSLP and Colder 925 hPa Air Temperature

Under conditions of anomalously lower MSLP and colder 925 hPa temperature all snow and sea ice conditions occur except for the late loss of snow cover with an early loss of sea ice (Table 6.19). In 41.2% of cases under lower MSLP and colder temperature, an early loss of snow cover with a late loss of sea ice cover occurs (Table 6.20). Normal snow or sea ice conditions occur in 23.5% of cases and 17.7% of

Table 6.19 July cases of anomalously lower MSLP and colder 925 hPa air temperature are given by the direction of the anomaly at the ±0.25 threshold for the Siberian, North American, and Russian study regions. Cardinal wind direction and anomalously early (negative) and anomalously late (positive) snow cover and sea ice loss are given. Instances of normal conditions are identified by the * symbol. Instances with weak winds are indentified by the / symbol.

Region	Case	MSLP	925 hPa Temp	Wind Direction	Snow Cover	Sea Ice
Siberian Region	1979	-	-	N	*	+
	1981	-	-	N	+	*
	1989	-	-	W	-	-
	1994	-	-	N	*	+
	1996	-	-	N	-	+
	2004	-	-	/	-	+
North American Region	1981	-	-	SW	-	*
	1984	-	-	NW	-	+
	2002	-	-	W	-	+
	2005	-	-	NE	-	-
	2006	-	-	SE	-	+
Russian Region	1980	-	-	NE	+	+
	1983	-	-	NW	-	+
	1989	-	-	W	+	+
	1992	-	-	SW	+	+
	1997	-	-	NE	-	-
	2003	-	-	NW	-	+

Table 6.20 Summary of July snow cover and sea ice loss conditions under anomalously lower MSLP and colder 925 hPa air temperature conditions at the ±0.25 threshold for the Siberian, North American, and Russian study regions.

	Siberian Region	North American Region	Russian Region	All Regions	
				Total	%
Late Snow & Late Ice			3	3	17.7
Early Snow & Early Ice	1	1	1	3	17.7
Early Snow & Late Ice	2	3	2	7	41.1
Late Snow & Early Ice					
Normal Snow and/or Ice	3	1		4	23.5
Total	6	5	6	17	100.0

cases result in both early snow and late sea ice loss and late snow and late sea ice conditions (Table 6.20). All three of the late snow and late sea ice loss cases under these atmospheric conditions occur in the Russian Region (Table 6.20). Late snow cover losses in July occur most often in the Russian Region because more snow cover remains in this region in July than does in the Siberian or North American Region since the Russian Region sits 5° in latitude farther north (Figure 4.7b).

The Siberian Region in 1996 fits in the early snow and late sea ice loss category under anomalously lower MSLP and colder temperature conditions (Table 6.19). Snow cover extent within the region in July is gone, while there is still complete sea ice coverage (Figure 4.7). Since there is complete sea ice coverage in July, the June sea ice extent anomalies also indicate later than normal sea ice loss (Table 6.3, Figure 5.5e). However, the region is also completely snow-covered in June, resulting in the later than normal snow cover anomaly observed during June (Table 6.3, Figure 5.5d). The snow cover is likely very thin in June since the snow completely disappears from June to July within the Siberian Region (Figure 5.5). Although the July temperature is anomalously colder, normal July temperatures are well above freezing, easily melting the thinning snowpack (Tables 5.1, 6.19). The northerly July wind direction would keep the temperature cool, and since the sea ice is present even near the Siberian coastline, there is likely no significant southward sea ice transport resulting in the removal of the sea ice cover (Table 6.19, Figure 5.5).

6.2.5 July Anomaly Summary

The only snow and ice condition that does not appear during July anomalous atmospheric conditions is the late loss of snow cover with an early loss of sea ice

(Tables 6.14, 6.16, 6.18, 6.20). Since July is late enough in the melt season that Russian Region snow cover has reached peak variability (Table 4.2, Figure 4.7b), there are no cases where sea ice extent is lost prior to some loss of snow cover as is seen during June (Tables 6.6, 6.10). Under higher MSLP and colder temperature conditions in July, aside from normal snow or sea ice extents, late sea ice loss occurs, in most cases with the anomalously early loss of snow cover (Table 6.14). When the temperature is anomalously warmer, the most frequent snow and ice response under both higher and lower MSLP is an early loss of snow cover and early loss of sea ice extent (Tables 6.16, 6.18). When the temperature is anomalously colder, the most frequent condition, excluding normal snow or sea ice extents, is the early loss of snow cover and late loss of sea ice (Tables 6.14, 6.20). This is likely due to the thinning of snow cover through the early melt season months and although temperature is anomalously colder, July temperatures in all three study regions are well above freezing (Table 5.1). In addition to late sea ice losses in previous months, a cooler July temperature prevents anomalously early loss of sea ice in these cases (Figures 4.1, 4.2a; Tables 6.13, 6.19).

6.3 Summary

During June, it is most common to have a late loss of snow cover and sea ice extent when temperature is anomalously cooler (Tables 6.4, 6.10); however, these snow and ice conditions are not independent of conditions in preceding months. In most of these cases, the wind direction has a northerly component (Tables 6.4, 6.10) and although temperature is anomalously cooler, mean June temperatures are above 0°C (Table 5.1). Strong northerly winds with above freezing temperatures can induce melting via sea ice thinning and southward transport. However, these cases with anomalously cooler temperature, most often produce late snow cover and late sea ice extent losses, 57.9% of cases under higher pressure (Table 6.4), and 50% of cases under lower pressure (Table 6.10). The snow and sea ice response under these conditions is most likely a result of the atmospheric conditions during the preceding months, for example, weak winds and/or a colder than normal temperature. Under anomalously warmer temperature conditions in June, there is a more mixed response in the snow and sea ice cover, the result of the mixed atmospheric patterns in these cases and thus mixed wind directions (Tables 6.5-6.8).

In July, snow cover is mostly gone in the Siberian and North American Regions and during some years in the Russian Region (Figure 4.7b). The absence of snow cover appears as an early loss of snow cover extent in the July anomaly analysis (Figure 4.3b) and since this is the case in many occurrences, early loss of snow cover is the most typical anomalous snow condition during July (Tables 6.13-6.20). As a result of little July snow cover, the sea ice cover shows the best response to the atmospheric conditions. In general, in the cases with anomalously early loss of snow cover (no snow cover) conditions with a warmer temperature generally result in more cases of early sea ice loss and conditions with a colder temperature result in more cases of late sea ice loss (Tables 6.13-6.20).

Chapter 7

Conclusions and Future Work

The analysis of snow cover and sea ice extent anomalies in three regions, the Siberian, North American, and Russian Regions, spanning the land-ocean boundary through the 29-year study period indicates that sea ice extent is lost earlier in the year, in May, than continental snow cover extent, in June, in all three study regions. This suggests that at the regional scale over the land-ocean boundary, the assumption that loss of the snow and sea ice cover progresses northward through the melt season is false. Instead, it appears that although the snow and sea ice areas are subject to the same atmospheric conditions across the region, the snow cover and sea ice respond differently to melt forcing and that conditions in earlier months play a role in how the cryosphere responds to current atmospheric conditions.

The timing of annual continental snow cover loss varies by latitude since, there is a one-month lag in first snow cover loss in the Russian Region which is located 5° in latitude farther north than the Siberian and North American study regions. However, variation in the extent of snow cover in the Siberian and North American Regions suggests that local geographic features also play a role in the annual melt of snow cover. Larger extents of snow cover are lost earlier in the year in the North American Region than in the Siberian Region, most likely due to cooler mean 925 hPa air temperature in the Siberian Region caused by continentality and mountains to the south and west of the region trapping Arctic air masses. The depth of snow cover most certainly plays a role in the timing of annual loss; however, those data are not available for the 1979-2007 study period. The biggest atmospheric contributor to anomalous snow cover extent loss appears to be warmer 925 hPa air temperature in months with below freezing mean 925 hPa air temperatures; however, depth of snow also appears to be critical to the persistence of snow cover.

The total extent of sea ice lost annually by the month of August depends on the sea ice thickness since mean August extent is highest in the North American Region, which has the highest multiyear ice fraction of the three study regions. Atmospherically, the greatest contributors to sea ice loss appear to be strong winds and warmer 925 hPa air temperatures during mid-melt season months when mean 925 hPa air temperatures are still below 0°C. Although one would expect a southerly wind component to advect warmer 925 hPa air temperatures into the study region leading to more melt and sea ice loss, a cooler 925 hPa air temperature coincident with a northeasterly wind direction is also very effective at forcing anomalous sea ice extent loss, via thinning and sea ice transport southward. Under conditions with weak winds, sea ice loss does not occur easily due to a lack of sea ice transport. Comparing the atmospherically anomalous conditions with the snow and sea ice response during the melt season both embedded within the hemispheric circulation pattern and through the study regions independently verifies the influence that specific atmospheric conditions including different combinations of MSLP, 925 hPa air temperature, and the strength and direction of the wind have on the snow and sea ice cover when individual differences between regions are taken into account.

This research provides a guide for future studies and establishes that mean sea level pressure, 925 hPa air temperature, and wind direction provide a good explanation for many cases throughout the study period; however, additional factors that have not been verified here likely contribute to melt conditions across the land-ocean boundary. In particular, deep continental snow cover can only be inferred from atmospheric conditions in the early melt season and the later persistence of snow cover within the study regions. Also, the reduction in snow cover depth cannot be accounted for in this study since, only the loss of 50% snow coverage is represented in the data. Information on the changes in snow cover depth at a shorter time scale can further resolve the direct response of snow cover to atmospheric forcing. It is still unknown what affects the loss of continental snow cover has on the continuing reduction in sea ice extents during the melt season; however, with further study the direct influence of snow cover on sea ice extent and vice versa can be explored more thoroughly. Additionally, further resolving the loss of snow cover and sea ice extent within the melt season both spatially and temporally could lead to determining the predictability of the potential conditions in the Arctic cryosphere to a more complex degree in response to modeled future climatic conditions.

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