Abrupt Changes in the Seasonal Cycle of North American Snow Cover

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ABSTRACT

Continental-scale snow cover extent has now been monitored from space for more than 20 yr in visible wavelengths. Here, the authors utilize weekly snow cover extent charts derived from such analyses to identify unusually rapid (1 week) spatially extensive snow cover accumulation and ablation events across the North American continent. Ancillary data are employed to describe the atmospheric patterns associated with the events. These episodes, which occur irregularly from year to year, bring about important changes in the total albedo of the continent.

Rapid extensive accumulation events occur during two preferred portions of the accumulation season. The early season accumulation events average 1-week snow cover increases of 3.9×10^6 km^2 and begin near the end of October. Late season accumulation events occur 1 month later and lead to average increases of 3.5×10^6 km^2. These rapid advances in the North American snowpack are associated with distinct and consistent atmospheric anomalies that are conducive to spatially extensive snowfalls.

Rapid ablation events also fall into two groupings based upon their timing within the annual cycle. Early season ablation episodes occur near the middle of March and account for snow cover losses averaging 2.1×10^6 km^2. Early ablation events are associated with fluxes of sensible and latent heat induced by atmospheric disturbances moving along the Canadian–U.S. border. Late season events occur near the middle of May and are generally associated with anomalous high pressure at the surface and aloft over eastern Canada. This category of ablation events is not associated with large sensible heat flux to the snowpack. The loss of snow cover is more likely associated with downwelling longwave radiation fluxes from cloudy skies or shortwave radiation fluxes under clear-sky conditions.

1. Introduction

The large-scale distribution of snow cover has been a topic of increasing interest over recent years. This interest has been spurred, at least in part, by concerns associated with potential changes in the global climate system associated with anthropogenic and natural causes. General circulation model studies have demonstrated that the earth's climate system is sensitive to the large-scale distribution of snow cover, primarily because of its radiative characteristics (Gray and Male 1981; Robinson 1986; Groisman et al. 1994). The well-known ice–albedo feedback argument suggests that large-scale increases in snow cover extent lead to increased hemispheric albedo and a cooling of the earth's lower troposphere. Alternatively, large-scale decreases in snow cover extent would lead to a lowering of the hemispheric albedo and increases in the surface air temperature.

Recent studies concerned with snow cover–temperature interactions seem to confirm these hypotheses at a variety of spatial scales ranging from hemispheric investigations (Foster et al. 1983; Ross and Walsh 1986; Walsh and Ross 1988; Robinson and Dewey 1990; Karl et al. 1993; Groisman et al. 1994), to those on continental scales (Walsh et al. 1982; Heim and Dewey 1984; Walsh et al. 1985; Leathers and Robinson 1993; Robinson and Leathers 1993), to more regional studies (Dewey 1977; Baker et al. 1992; Leathers et al. 1995).

The potential effects of snow cover on the large-scale atmospheric circulation, and vice versa, have also been studied at a variety of spatial and temporal scales (Namias 1978; Walsh et al. 1982; Heim and Dewey 1984; Gutzler and Rosen 1992). However, a detailed investigation of the atmospheric patterns associated with the annual cycle of continental-scale snow cover has not been initiated. Although monthly maps of mean snow cover have been published previously (Dewey and Heim 1982; Matson et al. 1986; Schutz and Bergman 1988;

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Robinson et al. 1993), little attention has been given to the atmospheric patterns associated with the advance and retreat of the continental snowpacks.

It is the purpose of this paper to examine rapid, large-scale snow cover accumulation and ablation events that take place on timescales of 1 week or less across the North American continent and the atmospheric patterns associated with them. The magnitude of these events, with snow cover extent changes of more than 3×10^6 km^2 in many cases, is important in the gross radiation balance of North America (Karl et al. 1993; Groisman et al. 1994). Moreover, the presence or absence of snow cover extent of this magnitude may also be important in airmass development and subsequently to surface air temperatures remote from the snow-covered regions (Leathers and Robinson 1993). In the following sections, we will discuss the data that are utilized in the study (section 2) and the techniques employed in the analysis of abrupt snow cover changes (section 3). In section 4, we will briefly address the annual cycle of North American snow cover on weekly timescales. Results concerning major accumulation and ablation events will be presented in sections 5 and 6. In section 7, case studies of individual accumulation and ablation events will be presented, while in section 8, we will discuss and summarize our findings.

2. Data

a. Weekly snow charts

Weekly snow cover extent data for North America are obtained from the National Oceanic and Atmospheric Administration (NOAA; Matson et al. 1986). This dataset covers the entire Northern Hemisphere dating back to 1966. To produce the charts, a visual interpretation of daily images is carried out on an operational basis by trained meteorologists to identify those areas of the hemisphere that are covered by snow on a given day (Robinson et al. 1993). The daily snow cover information is aggregated to produce weekly snow cover maps that depict the presence or absence of snow cover on the last day of the week that the surface of the earth in a given area is able to be identified (i e., cloud free). These maps are subsequently digitized within an 89×89 grid matrix covering the Northern Hemisphere, and weekly land-surface snow cover areas are calculated using a routine developed at Rutgers University (Robinson 1993; Robinson et al. 1993). We have found the weekly snow cover product to be most representative of the snow cover extent on the fifth day of a given chart week. This indicates that the fifth day of the week is, on average, the last day that the meteorologist is able to observe the earth's surface because of potential cloud cover effects. Moreover, it has been suggested that the earliest digitized weekly products underestimated the snow cover extent (Kukla and Robinson 1981; Ropelewski 1984). Thus, the weekly snow cover extent values for North America used in this study will cover only the time period from January 1971 to December 1990.

b. Atmospheric data

Atmospheric data used in the following analyses are derived from National Centers for Environmental Prediction (formerly the National Meteorological Center) octagonal grids (Jenne 1975) and include surface pressure, 850-mb temperature, and 500-mb height data. Departures are calculated based on the 1947 through 1990 period. In addition, radiosonde data are extracted from the ''Radiosonde Data of North America'' dataset compiled by the National Oceanic and Atmospheric Administration.

c. Storm tracks

Storm track information is derived from the National Climatic Data Centers *Global Tropical/Extratropical Cyclone Climatic Atlas.* Track information is collected for all cyclones that crossed the North American continent during the weeks encompassing the accumulation and ablation events studied below. The number of times that a cyclone center was found in a $5° \times 5°$ latitude–longitude box was summed, and these data were subsequently used to create the contour maps showing cyclone frequencies.

3. Analytic techniques

Differences in snow cover extent from one week to the next are calculated for the entire study period and subsequently ranked. The 20 largest accumulation and 20 largest ablation events (largest weekly differences) are selected for analysis. Not surprisingly, the abrupt accumulation events occur during the autumn months and ablation events in the spring. Furthermore, abrupt accumulation and ablation episodes are subdivided into early and late accumulation and ablation cases. This further stratification was carried out to eliminate any contamination of the composited atmospheric data because of annual cycle timing. The stratification into early and late cases was based upon events' timing during either the accumulation or ablation seasons (Table 1). An examination of the spatial characteristics of snow cover within each accumulation and ablation category shows considerable similarities.

Composite maps of the spatial distribution of 1-week snow cover changes are constructed for each category. First, the composite snow cover extent for the initial week of an accumulation or ablation event is constructed by identifying any NOAA grid cell with at least 50% snow coverage for those weeks under investigation (i.e., at least 6 of the 12 weeks in the early accumulation period). The same method is used to construct the composite map for weeks at the end of ablation or accumulation events. The composite area of snow cover

TABLE 1. Listing of all accumulation and ablation events. Table includes snow cover at the beginning of the event, snow cover at the end of the event, the snow cover change that took place, the date over which the change occurred, and the snow cover anomaly at both the beginning and end of the event. All values are given in 10^6 km^2.

Snow cover					
Week 1	Week 2	Change	Date	Week 1 anomaly	Week 2 anomaly
Early accumulation episodes					
3.05	6.65	3.60	4–10 October 1985	−1.00	1.52
4.48	8.24	3.76	13–19 October 1978	−0.65	2.05
5.97	9.23	3.25	11–17 October 1974	0.84	3.04
5.14	10.95	5.81	17–23 October 1981	−1.05	3.59
5.25	8.95	3.70	21–27 October 1988	−0.94	1.59
6.30	9.34	3.04	16–23 October 1971	0.11	1.98
7.16	10.20	3.04	26 October–1 November 1973	−0.20	2.05
5.98	10.34	4.36	1–7 November 1980	−2.17	0.30
7.44	11.33	3.89	3–9 November 1978	−0.71	1.29
7.59	10.80	3.21	4–10 November 1983	−0.56	0.76
8.32	13.54	5.22	5–11 November 1982	0.17	3.50
8.60	12.29	3.69	1–8 November 1986	0.45	2.25
6.27	10.15	3.88		−0.47	1.99
Late accumulation episodes					
8.47	11.50	3.03	13–19 November 1987	−2.39	−0.78
9.54	13.82	4.28	18–24 November 1977	−2.74	1.24
10.67	13.98	3.31	17–23 November 1989	−1.61	1.70
11.04	14.71	3.67	18–24 November 1983	−1.24	2.43
10.09	13.42	3.33	23–29 November 1979	−2.19	0.01
10.58	14.19	3.61	19–25 November 1976	−1.70	0.76
11.85	15.56	3.72	21–27 November 1975	−0.43	2.13
12.67	16.00	3.33	28 December 1978–3 January 1979	−1.95	0.72
10.61	14.15	3.54		−1.78	1.02
Early ablation episodes					
15.32	13.32	2.00	2–8 February 1990	−0.07	−1.98
16.42	14.11	2.31	15–21 February 1980	1.34	−0.47
14.92	12.79	2.14	1–6 March 1971	0.64	−1.25
15.44	13.16	2.28	1–6 March 1987	1.16	0.88
13.48	11.49	1.99	16–22 March 1973	−0.33	−1.77
14.36	12.13	2.23	24–30 March 1978	1.10	−0.63
15.03	12.81	2.22	25–31 March 1983	2.27	0.05
14.37	12.33	2.04	9–16 April 1982	1.93	0.66
10.06	7.92	2.13	9–16 April 1971	−1.61	−3.04
14.38	12.23	2.15		0.71	−1.03
Late ablation episodes					
11.29	8.24	3.05	20–26 April 1973	0.33	−1.56
13.27	11.01	2.26	18–24 April 1975	2.31	1.21
10.16	7.43	2.73	19–25 April 1980	0.36	−1.65
8.51	6.25	2.26	5–11 May 1972	−0.57	−2.11
8.87	6.16	2.70	5–11 May 1989	−0.21	−2.20
10.93	8.21	2.72	2–8 May 1975	1.85	−0.15
9.64	7.28	2.36	12–19 May 1978	1.28	−0.04
6.08	3.28	2.79	1–7 June 1971	0.06	−2.02
6.42	4.16	2.25	6–12 June 1975	1.12	−0.28
5.74	2.40	3.34	2–8 June 1974	1.30	−1.27
5.40	3.40	2.00	21–27 June 1985	1.73	0.35
8.76	6.17	2.59		0.86	−0.88

change is defined by the grid boxes that are considered not covered (covered) in the week prior to an accumulation (ablation) event and subsequently classified as covered (not covered) in the week after an accumulation (ablation) event.

The composite atmospheric patterns associated with these rapid accumulation and ablation episodes are constructed by calculation of the mean conditions during all days that fall within a given category. For example, all 84 days that occur in the 12 weeks included in early season accumulation events are composited to give the average atmospheric conditions during those events. Because the snow cover extent values for a given week are most representative of the fifth day of that week, the composite atmospheric patterns cover the 7-day period from the fifth day of the initial week to the fourth day of the ending week. The mean atmospheric conditions for the same 84 days, calculated with data for the 44-yr period from 1947 to 1990, are subtracted from the composite average to give the departure maps that follow in the analysis below. A *t* test for the difference between two means is utilized to gauge the statistical significance of the departure values (Leathers and Robinson 1993). All grid points that evidence differences between the composited values and the mean values significant at the 95% level are represented by asterisks.

4. The weekly annual cycle of North American snow cover

Before examining abrupt changes in the annual cycle of North American snow cover, a review of the mean annual cycle on a weekly basis is in order. Mean weekly snow cover extent values for North America are derived for the 20-yr period 1971 through 1990. Values for the continent (excluding Greenland) range from approximately 15×10^6 km^2 in January and February to just over 1×10^6 km^2 during August (Fig. 1a). The annual cycle is characterized by a rather slow ablation period in the spring and early summer and a relatively rapid accumulation period beginning in early September (week 36). Mean snow cover extent change values are calculated for the 20-yr period by averaging the 20 week-to-week snow cover differences over the period of record. The rapid accumulation period has larger week-to-week variations in snow cover change than are found in spring (Fig. 1b). As snow extent begins approaching a maximum in late November and December, an erratic pattern of mean week-to-week change is observed (Fig. 1b).

At least a portion of the variation in change from week to week is a function of the relatively short (20 yr) period of record. A somewhat different picture emerges when examining weekly standard deviations of snow cover extent. The weekly snow cover variance is relatively low (approximately 1×10^6 km^2) after the establishment of extensive snow cover in the early winter (Fig. 1c). The standard deviation continues at this level through the ablation period until the late summer, when it drops to lower values primarily because of the ablation of the previous winter's cover.

The variance begins to increase with the onset of the accumulation period in late August. The weekly standard deviations continue to increase through the accumulation period and reach their peak values at the end of October and the beginning of November (weeks 43 to 45), when the extent of North American snow cover is quite variable from one year to another. Within the accumulation period, large week-to-week snow cover changes (Fig. 1b) are not always directly associated with higher standard deviations. For instance, the standard deviation in week 44 (large mean change in snow cover) is within 0.2×10^6 km^2 of the standard deviation in week 50 (little mean change in snow cover), indicative of a relatively constant pattern of snow cover extent increases during the autumn and early winter.

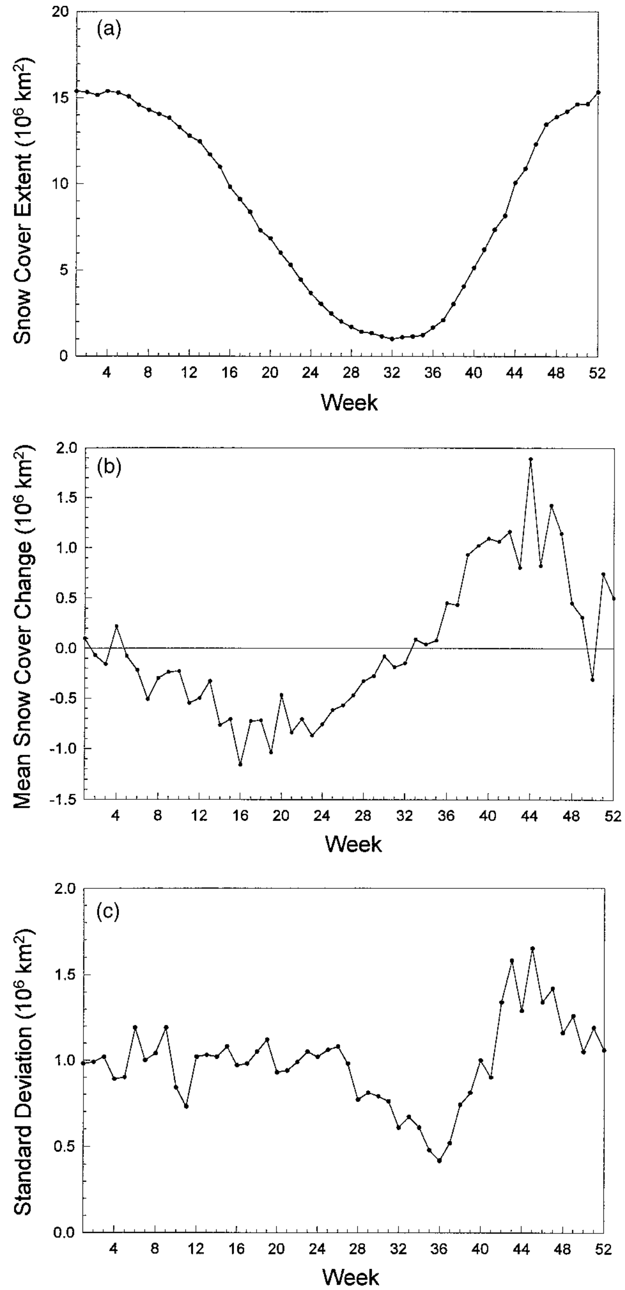

FIG. 1. Annual cycle of (a) mean weekly snow cover extent, (b) mean weekly snow cover extent change, and (c) standard deviation of weekly snow cover extent, all calculated for the period 1971–90.

5. Rapid accumulation events

a. Early season

Early season rapid accumulation events begin near the end of October when snow cover extent is still relatively small (approximately 6×10^6 km^2; Table 1). The average snow cover extent at the beginning of these events is confined mainly to the northern portion of northern Quebec, the Canadian Northwest Territories, the Yukon, and much of Alaska. Rapid early season accumulation events average 3.9×10^6 km^2 for a week, with snow accumulating primarily in northwestern and north-central Canada (Fig. 2a). At the onset of these events, snow cover extent across North America is generally below normal (Table 1).

The mean atmospheric pattern associated with these events includes a storm track oriented along the southern margin of the snow cover accumulation zone. Storms move onshore near the border of British Columbia and Alaska, travel through the Canadian prairie provinces, and then move north and east through northern Quebec (Fig. 2b). Surface pressures are below normal throughout eastern Canada, particularly in northeastern areas, with departures of -5 mb over that region (Fig. 2c), corresponding very well with the storm track orientation. At 850 mb, the temperatures are near the long-term mean, with the 850-mb 0°C isoline straddling the southern margin of the accumulation zone. At 500 mb, negative height departures are apparent north of the snow cover accumulation region in eastern Canada, while relatively strong positive height anomalies are found along the Pacific coast (Fig. 2d). In an anomaly sense, this upper-tropospheric flow would lead to anomalous northerly flow over much of the accumulation region.

In summary, it appears that large, rapid snow cover accumulation episodes in the middle of autumn are associated with the establishment of a zonally oriented storm track across central Canada. The movement of midlatitude cyclones through this area brings together the cold temperatures and atmospheric moisture needed for spatially extensive snowfall events.

b. Late season

Late season accumulation events take place approximately 1 month later than early season events (Table 1). The snow cover extent at the beginning of these late autumn events is nearly twice that of the early season accumulation episodes. At the beginning of these events, snow cover averages 1.8×10^6 km^2 below normal and is found across the majority of eastern Canada, within the boreal forest, across the tundra and mountains of central and western Canada, and in the U.S. Rocky Mountains. One-week snow cover accumulations averaging 3.5×10^6 km^2 take place during these events. The majority of the accumulation takes place along the southern periphery of Hudson Bay, across northern Quebec, and across the central Rocky Mountain region of the United States (Fig. 3a). Smaller, scattered areas of accumulation occur across the Yukon territory of Canada and southern Alaska. Mean atmospheric patterns associated with the late season accumulations are stronger than those found for early season events. A region of anomalously high surface pressure (+6 mb) is centered along coastal areas of southern Alaska and northern British Columbia (Fig. 3c). The dominant storm track during these events is characterized by storms making landfall along the southern coast of British Columbia and redeveloping in the high plains of the United States. Subsequent movement of these storms is eastward, through the Great Lakes and into eastern Canada (Fig. 3b). These surface characteristics lead to unusually strong cold advection and an abundant supply of Pacific moisture across the western one-third of North America. Moreover, this storm track parallels the main snow cover accumulation region along the southern periphery of Hudson Bay, northeast through northern Quebec. Temperature departures at 850 mb reach -2°C and lower across the accumulation region. Similar to the early season events, the 850-mb 0°C isoline defines the southern margin of the accumulation region. At 500 mb, a relatively strong trough, in the anomaly sense, is found centered across the central United States, a pattern consistent with the lower-tropospheric features (Fig. 3d).

6. Rapid ablation events

a. Early season

Early season ablation episodes typically occur prior to the vernal equinox (Table 1), with snow cover in place across all of Canada, the northern tier of the United States, and the mountains of the western United States. An average of 2.1×10^6 km^2 of snow cover, from an initial cover of approximately 14×10^6 km^2, disappears during early season events. The ablation takes place along the entire southern margin of the snow cover, in the Canadian Great Plains, and along the high plains of the United States. In addition, there is significant ablation throughout the Great Lakes region and extreme southeastern Canada (Fig. 4a). At the beginning of the ablation episodes, snow cover extent across North America is approximately 0.7×10^6 km^2 above the 20-yr mean.

The maximum surface pressure departures during these events are found along the coast of British Columbia (-9 mb; Fig. 4c). These negative departures extend across the Pacific Northwest and into the north-central United States. The predominant storm track brings cyclones onshore north of Vancouver Island, with an area of redevelopment in the southern Great Plains of the United States (Fig. 4b). The surface pressure pattern and storm track lead to the advection of relatively warm Pacific air across the northwestern United States and southwestern Canada. As the redeveloped storms move northeast out of central Colorado, they advect warm, moist air into the ablation area of eastern Canada. It should be noted that these storms sometimes produce heavy snowfall throughout the Rocky Mountains, actually increasing snow cover in these areas. However, the advective qualities of the events produce widespread

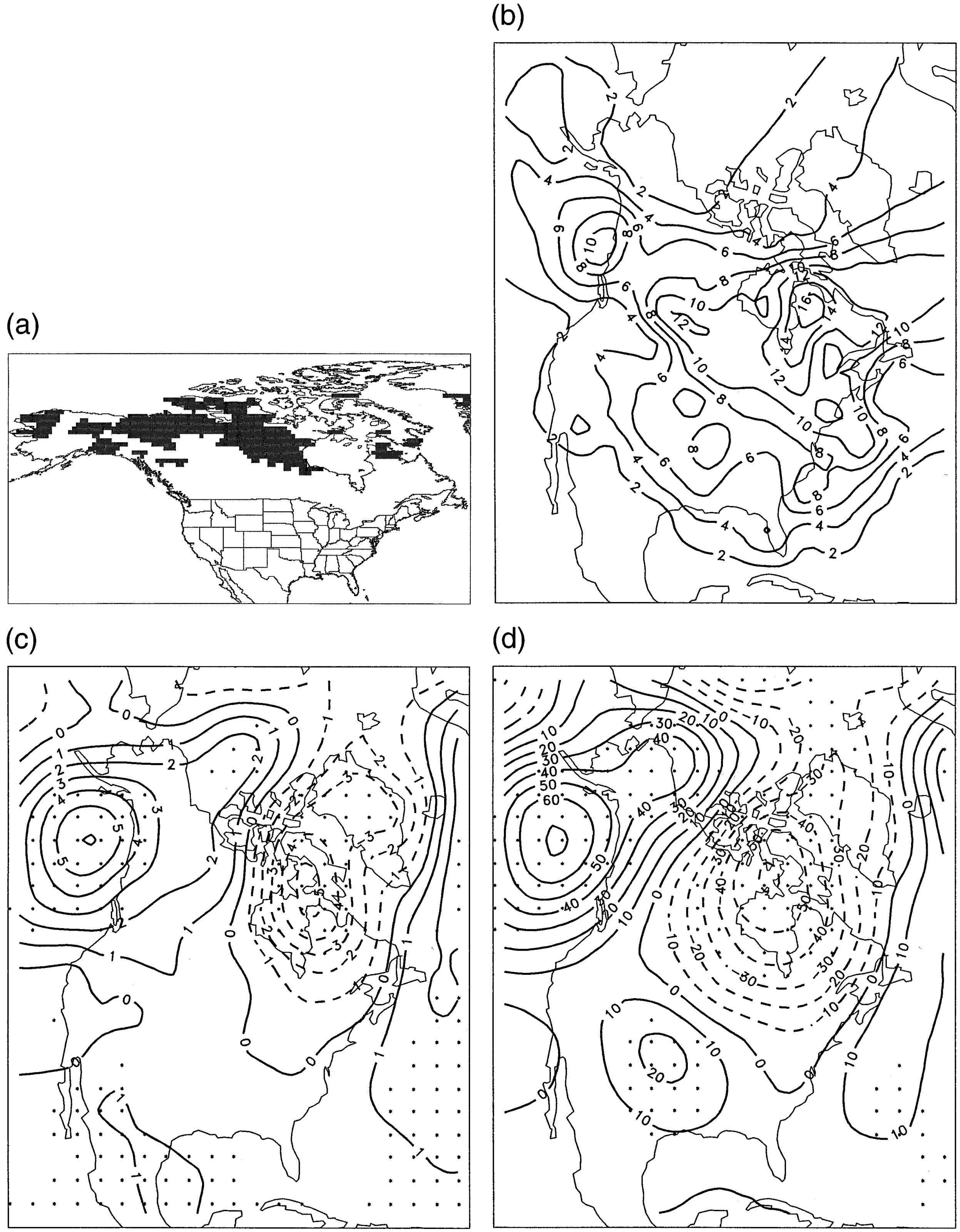

FIG. 2. Maps showing conditions during early season accumulation events. (a) Snow cover change (dark shading indicates accumulation areas), (b) cyclone frequencies within 5° × 5° latitude–longitude boxes, (c) sea level pressure departures (mb), and (d) 500-mb height departures (gpm). Asterisks on departure maps indicate grid points significant at the 95% level.

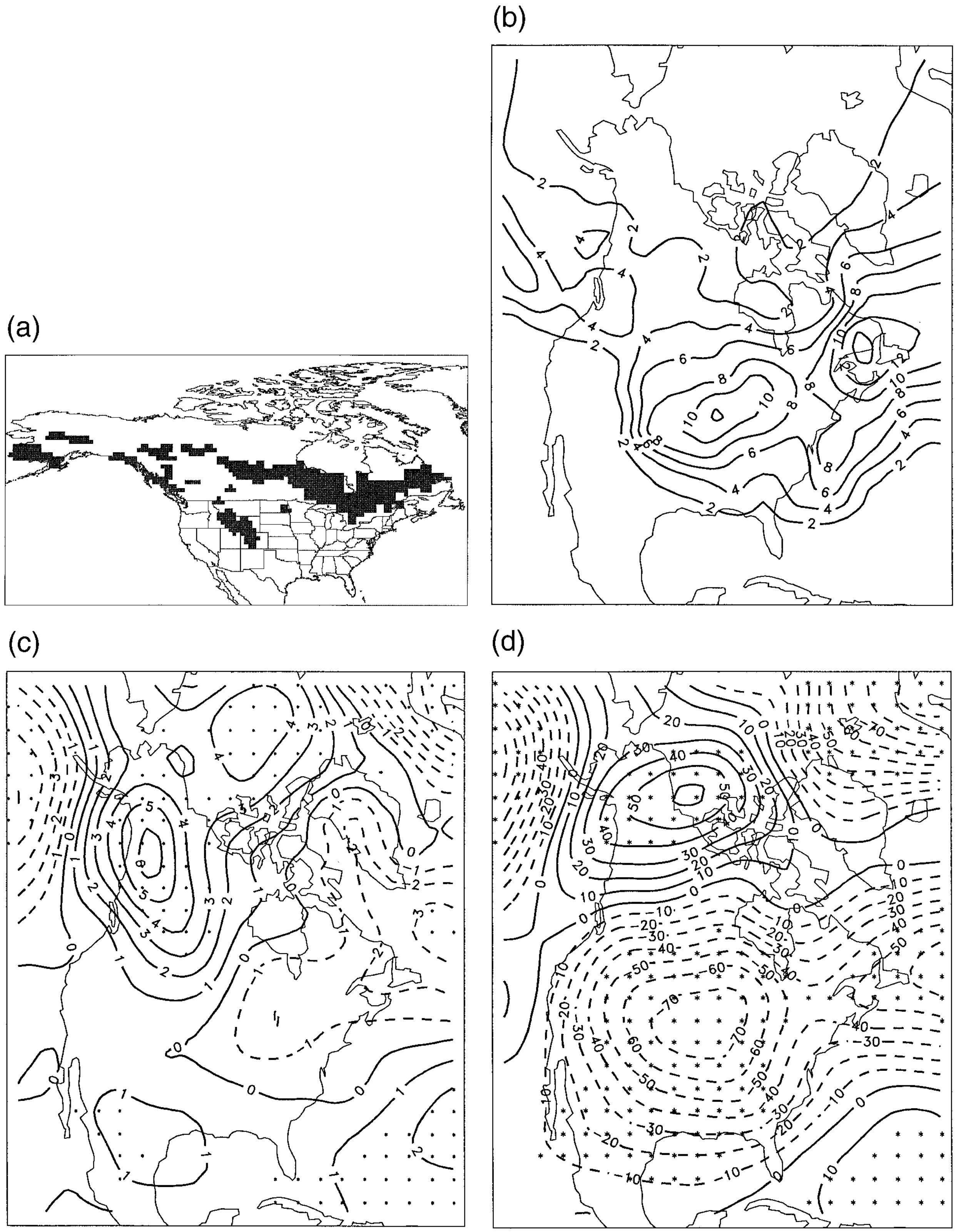

FIG. 3. Same as Fig. 2 except for late season accumulation events.

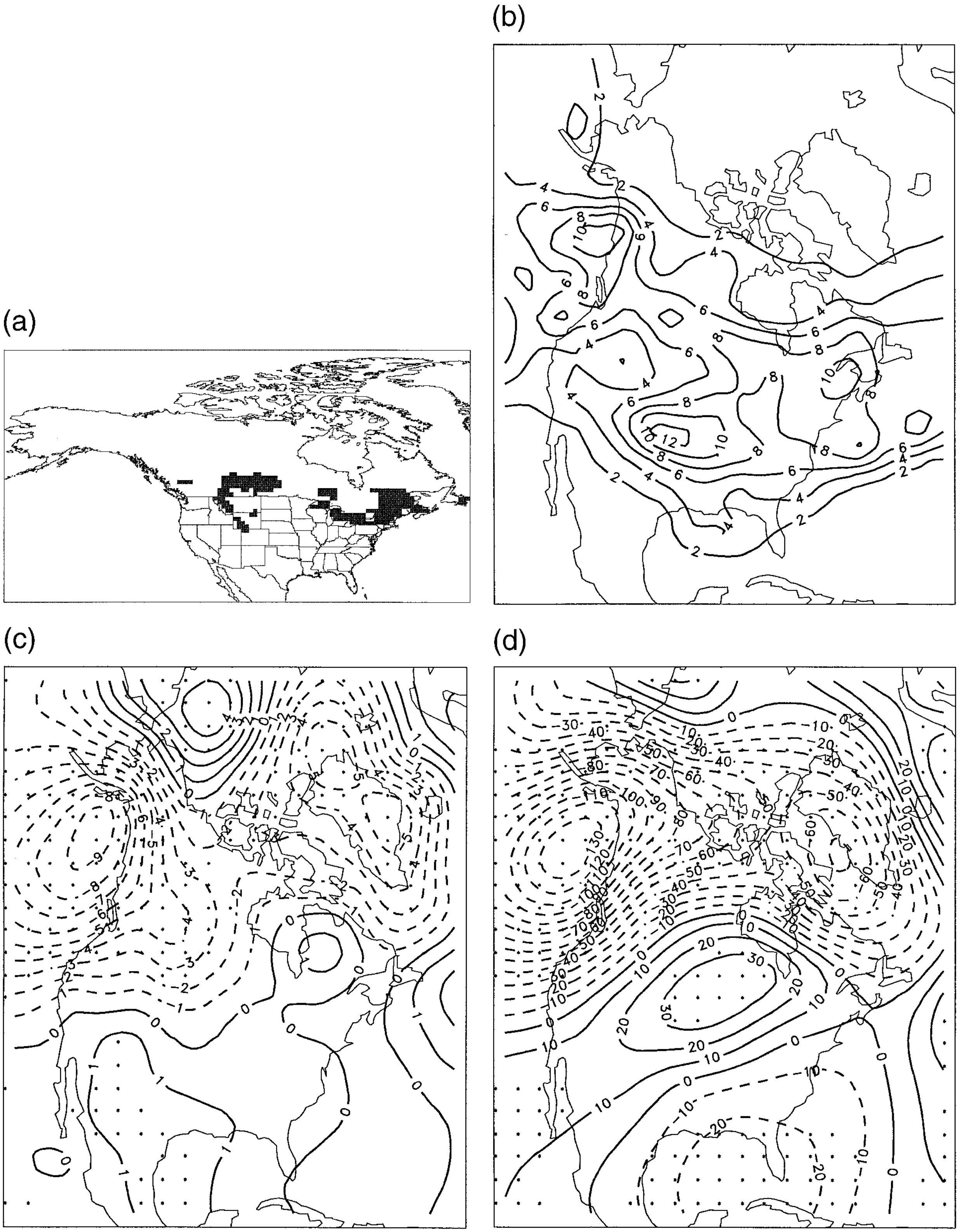

FIG. 4. Maps showing conditions during early season ablation events. (a) Snow cover change (dark shading indicates ablation areas), (b) cyclone frequencies within 5° × 5° latitude–longitude boxes, (c) sea level pressure departures (mb), and (d) 500-mb height departures (gpm). Asterisks on departure maps indicate grid points significant at the 95% level.

snow cover ablation at lower elevations. The warming across the western ablation area is evident in the 850-mb temperature field, while the 850-mb 0°C isoline lies along the northern boundary of the ablation region from the Pacific coast east to New England. At midtropospheric levels, large negative 500-mb height departures are found along the southern coast of Alaska, and these extend into the western United States and Canada (Fig. 4d). These height departures represent a weakening of the mean ridge across western North America and increased zonality across the continent.

b. *Late season*

Rapid, late season ablation events typically begin during mid-May, 2 months later than early season episodes (Table 1). These events begin with snow cover extents averaging 8.8×10^6 km^2, some 0.8×10^6 km^2 above normal. Snow cover at the beginning of late season ablation episodes typically extends from central Quebec and northern Ontario northwest to the Yukon, northern British Columbia, and Alaska. On average, more than 2.5×10^6 km^2 of snow cover is ablated during these abrupt late season events. The ablation takes place at lower elevations along the entire southern margin of the snow cover, primarily within regions of tundra (Fig. 5a).

Large positive surface pressure departures (+5 mb) are centered northeast of northern Quebec and are responsible for anomalous southeasterly flow across eastern Canada (Fig. 5c). Two storm tracks are apparent during the late season ablation events. One track is associated with storms originating in the central plains of the United States and moving to the northeast, toward James Bay. A second dominant track is found off of the mid-Atlantic coast, with movement northeast toward Newfoundland (Fig. 5b). The 850-mb 0°C isoline clearly delineates the southern margin of the melt region. At midtropospheric levels, strong 500-mb height anomalies are indicated over northern Quebec, with negative anomalies found over the Gulf of Alaska and along the Atlantic coast of the United States (Fig. 5d). This midtropospheric anomaly pattern indicates a weakening of the eastern North American trough and a more zonally oriented upper-level flow throughout northern Canada.

7. Case studies

Four case studies will be presented that represent typical atmospheric conditions during the diverse accumulation and ablation episodes. The early season accumulation case presented here occurred during the period from 1 to 7 November 1980, while an example of a late season accumulation episode is given for the period 18–24 November 1977. The early season ablation case occurred during the last week of March 1983, while the late season ablation example is for the period 2 through 8 June 1974.

a. *Early season accumulation case*

This system, responsible for snow cover accumulations of more than 4.3 million km^2, began to form as a low pressure area moved onshore across southern Alaska on 1 November 1980. A weak trough of low pressure pushed across the northern portion of western Canada over the next 48 h as it slowly intensified. By 12 UTC on 3 November 1980, a distinct trough of low pressure was evident from just east of Hudson Bay south into the United States (Fig. 6a). This trough of low pressure was associated with 850-mb temperatures of −4°C across the accumulation region (Fig. 6b). Over the next 24 h, the system had further intensified and moved to a position just east of Hudson Bay (Fig. 6c). The continued intensification of the system and cold advection to its west (Fig. 6d) resulted in widespread snowfall across the accumulation region over the next 48 h.

This storm represent a typical scenario during early season accumulation events. Storms move onshore in western Canada and intensify as they move eastward across central Canada. The result is cold advection behind the storm and widespread snowfall across the accumulation region (Fig. 2a).

b. *Late season accumulation case*

To represent typical conditions during late season accumulation events, a storm that developed over the central Rockies on 18 November 1977 will be investigated. This system quickly redeveloped over the southern plains on 19 November and began to move quickly northeastward. During this preliminary stage of development, significant snowfall occurred across the central and northern Rocky Mountains. By 1200 UTC 20 November 1977, a strong midlatitude cyclone with a central pressure of less than 1008 mb was moving through western Iowa into Minnesota (Fig. 7a). At this time, the low pressure area was associated with very strong areas of warm advection over the western Great Lakes states and strong cold advection over the high plains of Montana, Wyoming, and Nebraska, which lowered 850-mb temperatures in this area to far below 0°C (Fig. 7b). At 850-mb strong positive moisture advections were occurring over the Great Lakes region north toward James Bay, with snow falling across this general area. Negative moisture advections were occurring at the 850-mb level over the plains states and the Rocky Mountains at this time, but mountain snows continued across the central Rockies. At 500 mb, an intense trough was digging into the central United States, supporting the development of the surface storm. Over the next 24 h, the surface system weakened but continued to move to the northeast, crossing James Bay and causing heavy snow to fall around the periphery of Hudson Bay and throughout northern Quebec (Fig. 7c). The passage of the storm to the northeast allowed substantial cold advection throughout the typical accumulation region (Figs. 7d

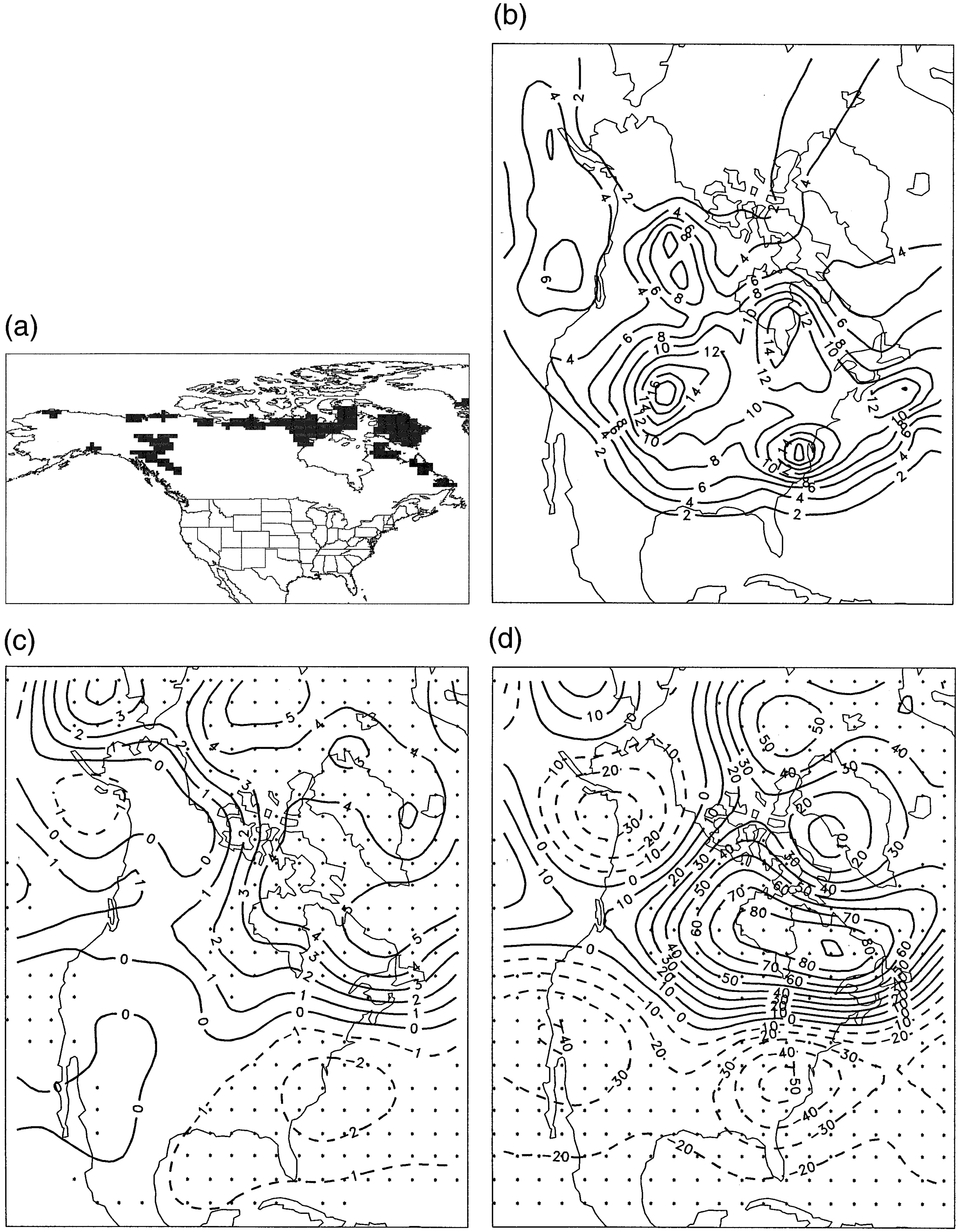

FIG. 5. Same as Fig. 4 except for late season ablation events.

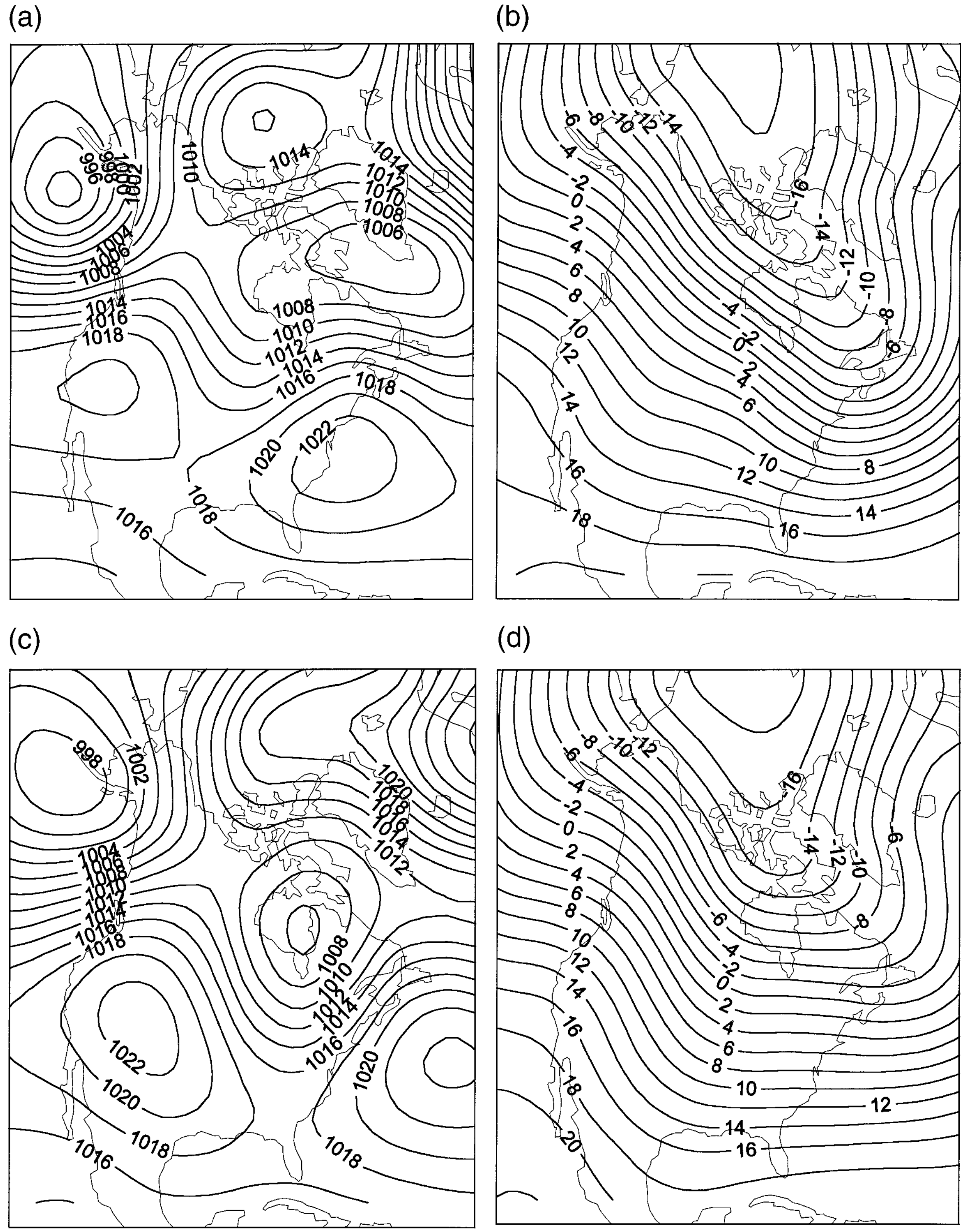

FIG. 6. Conditions during early season accumulation event of 1 through 7 November 1980. (a) Sea level pressure at 1200 UTC 3 November 1980 (mb), (b) 850-mb temperature at 1200 UTC 3 November 1980 (degrees Celsius), (c) sea level pressure at 1200 UTC 4 November 1980 (mb), and (d) 850-mb temperature at 1200 UTC 4 November 1980 (degrees Celsius).

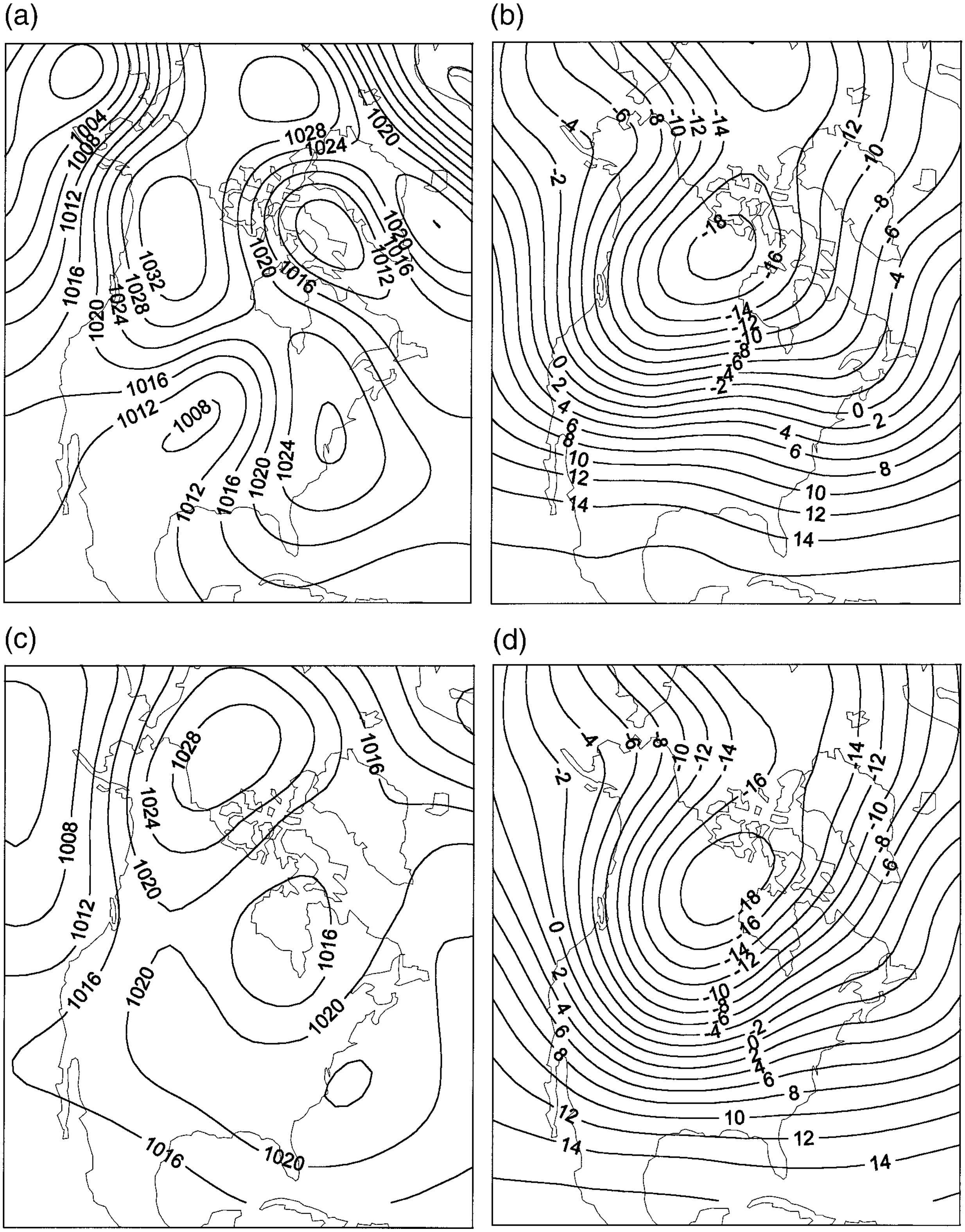

FIG. 7. Conditions during late season accumulation event of 18 through 24 November 1977. (a) Sea level pressure at 1200 UTC 20 November 1977 (mb), (b) 850-mb temperature at 1200 UTC 20 November 1977 (degrees Celsius), (c) sea level pressure at 1200 UTC 21 November 1977 (mb), and (d) 850-mb temperature at 1200 UTC 21 November 1977 (degrees Celsius).

and 3a). This storm represents the typical scenario for late season accumulation episodes, a system moving out of the central Rockies, redeveloping over the southern plains states, and moving northeastward. This atmospheric pattern typically brings heavy snowfall to the central and southern Rocky Mountains and eastward to the southern margin of Hudson Bay and across northern Quebec.

c. Early season ablation case

This early season ablation event began on 29 March 1983, when a relatively strong low pressure area came ashore along the coast of British Columbia, Canada. This storm moved to the east over the next 48 h across the southern portions of British Columbia, Alberta, and Saskatchewan, Canada, and was positioned over North Dakota by 1200 UTC 31 March 1983 (Fig. 8a). By this point, warm advection ahead of the cyclone had pushed early morning 850-mb temperatures above freezing as far north as Manitoba and Ontario, Canada (Fig. 8b), initiating snowmelt in many areas. By 0000 UTC 1 April 1983, a strong low pressure area had developed along the cold front, associated with the initial system (Fig. 8c). This new storm moved from northern Oklahoma northeastward over the next 72 h, bringing above-freezing temperatures (Fig. 8d) and rainfall to much of the northeast United States and eastern Canada, causing significant ablation of snow cover in these areas.

Thus, this storm represents a typical early season ablation episode that corresponds to the following general pattern. A weakening of the mean western North American ridge steers storms onshore in southwestern Canada. As these storms move eastward across the northern tier of the United States, warm advection to their east (and often liquid precipitation) lead to ablation of the snowpack (Treidl 1970). Moreover, a redevelopment of the low pressure area often occurs over the southern plains and the storms move northeast, resulting in significant ablations across much of southeastern Canada.

d. Late season ablation case

This late season ablation case has elements of the three possible mechanisms that are likely to lead to ablation of the subarctic snowpack during the late spring. A stationary front was located across much of northeastern Canada throughout the week of this event (2 through 8 June 1974). On 3 June 1974, a weak, undefined area of low pressure covered much of western Canada, while a high pressure area covered much of the eastern United States and eastern Canada. This general pattern of weak low pressure in the west and high pressure in the east is clearly evident at 12 UTC 5 June 1974 (Fig. 9a). The southerly flow between the two systems had pushed 850-mb temperatures above the freezing point as far north as northern Hudson Bay by this time (Fig. 9b). West of Hudson Bay, scattered precipitation, cloud cover, and southerly winds were dominant at this hour, while eastern Canada reported mainly clear skies. Over the next 24 h, the two systems continued a slow movement to the east, resulting in general southerly flow across most of eastern Canada and a mixture of clear and cloudy skies (Figs. 9c and 9d).

This case represents the general conditions typically found during large, late season snow cover ablation episodes. Weak systems lead to general southerly flow across the ablation region. This southerly flow results in the flux of sensible heat to the snowpack and varying sky conditions. During this portion of the annual cycle, either downwelling longwave radiation associated with cloudy-sky conditions (Zhang et al. 1996) or downwelling shortwave radiation associated with clear-sky conditions (Robinson 1986) can lead to significant snow cover ablation.

8. Discussion, summary, and conclusions

a. Reality of abrupt changes

As abrupt changes in snow cover extent have been recognized previously in the NOAA satellite record over the past 2 decades, a persistent concern has been whether these changes were actually occurring. Given that cloudiness, particularly in the accumulation season, obscures the surface from visible satellite image analysis, it was thought that more than a week of change could be displayed in a weekly chart over some regions if the previous chart week had been completely cloudy. While this concern has not been completely dispelled, our finding that the atmospheric patterns accompanying the charted changes logically explain or support an abrupt change strongly suggests that they are real and increases our confidence in the NOAA snow cover charts.

b. The nature of abrupt changes

An interesting question that arises from this analysis concerns the climatological nature of the abrupt changes in continental-scale snow cover extent. Are the abrupt changes associated with climatological preconditioning, or are they associated with more random extreme meteorological events? Table 1 gives the magnitude of the snow cover anomaly at the beginning of the abrupt changes (week 1) and at the end of the abrupt changes (week 2). These values represent anomalies from the 20-yr weekly snow cover means. For early accumulation episodes, average snow cover anomalies at the beginning of the abrupt change are negative (less snow cover than normal) and are positive at the end of the abrupt change (greater than normal snow cover; Table 1). At first glance, this would seem to indicate that climatological preconditioning was a major factor in the abrupt change. During the autumn season, with abundant cold air to the north and solar radiation receipt decreasing rapidly, an area that on average supports snow cover

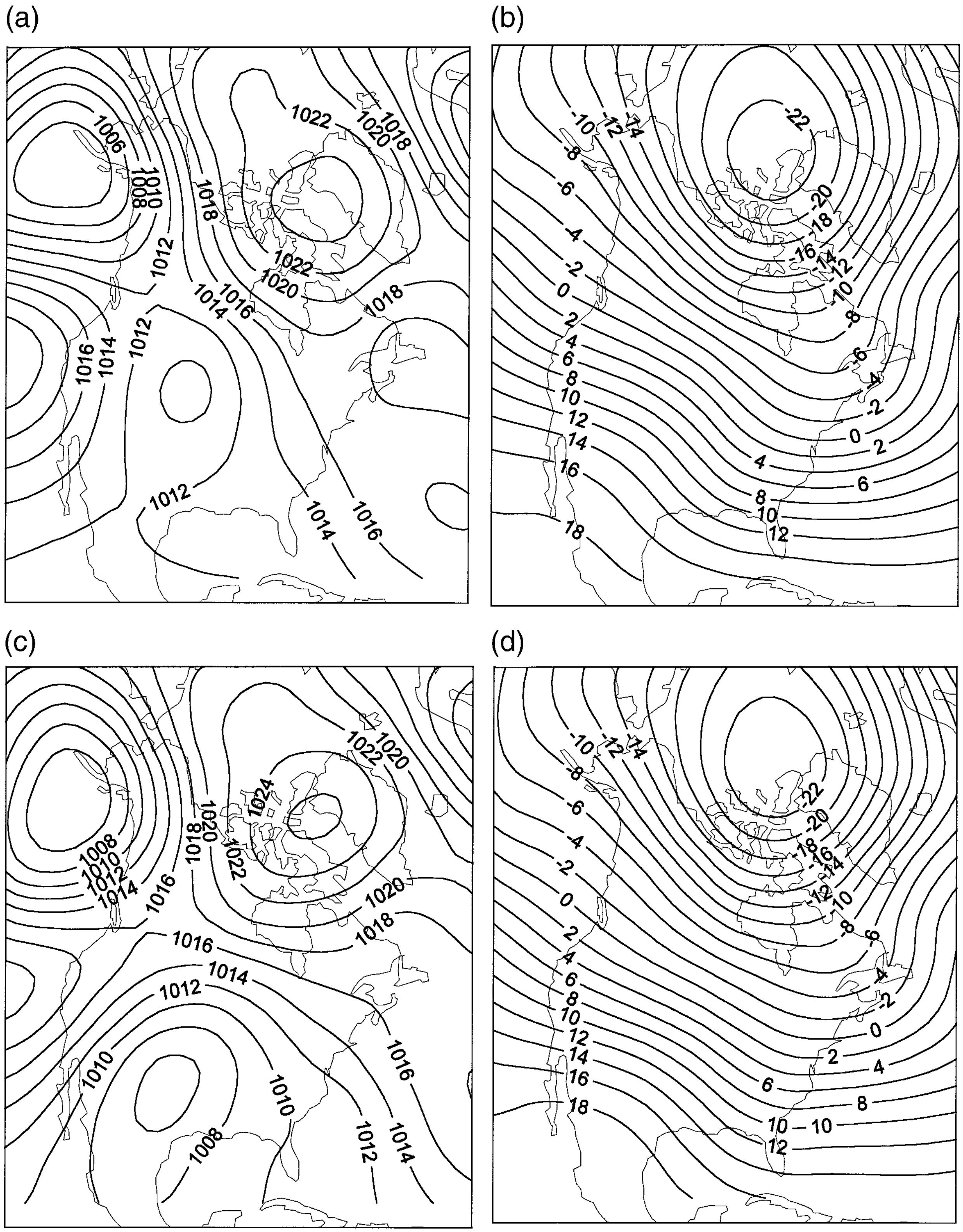

FIG. 8. Conditions during early season ablation event of 23 through 31 March 1983. (a) Sea level pressure at 1200 UTC 31 March 1983 (mb), (b) 850-mb temperature at 1200 UTC 31 March 1983 (degrees Celsius), (c) sea level pressure at 0000 UTC 1 April 1983 (mb), and (d) 850-mb temperature at 0000 UTC 1 April 1983 (degrees Celsius).

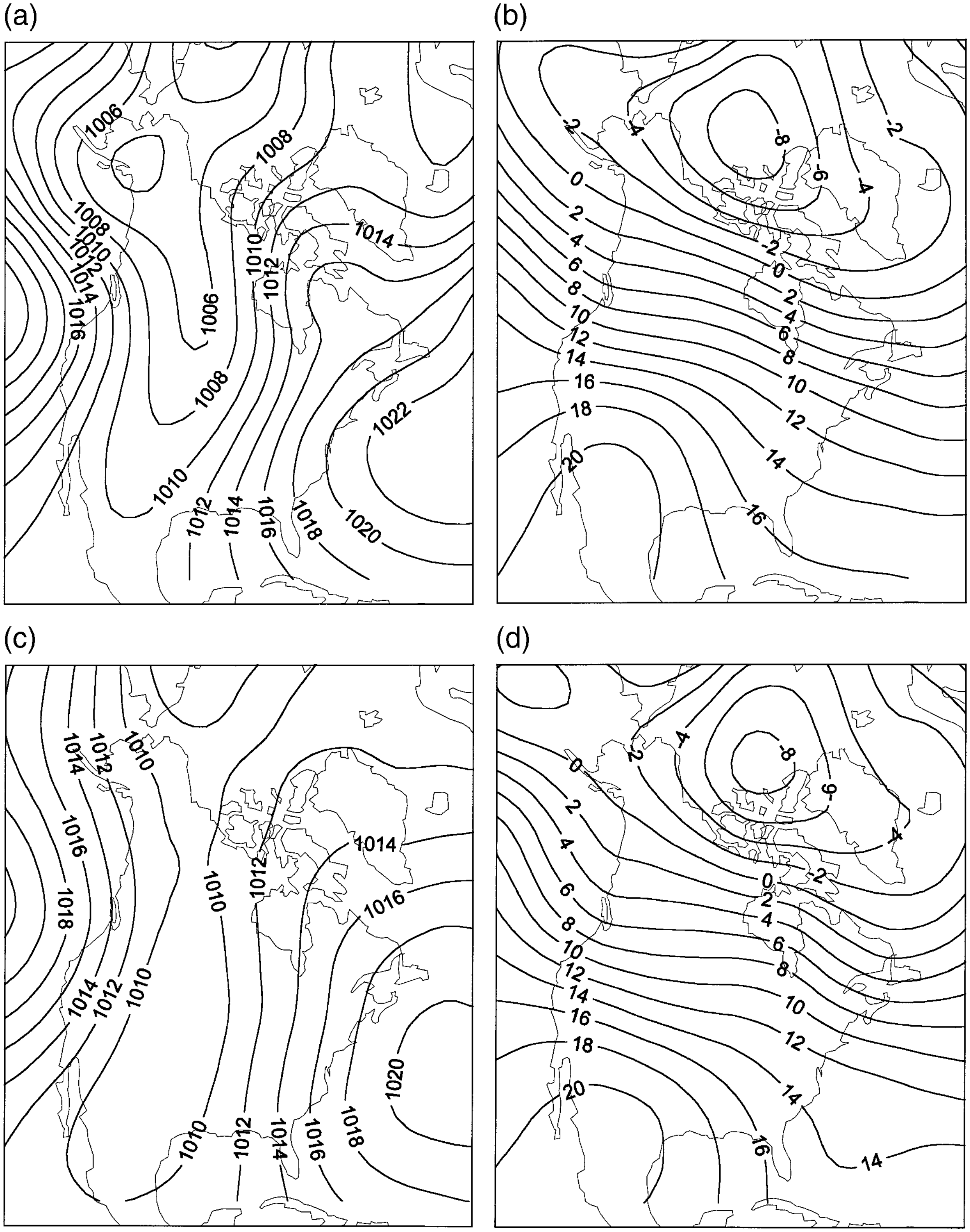

FIG. 9. Conditions during late season ablation event of 2 through 8 June 1974. (a) Sea level pressure at 1200 UTC 5 June 1974 (mb), (b) 850-mb temperature at 1200 UTC 5 June 1974 (degrees Celsius), (c) sea level pressure at 1200 UTC 6 June 1974 (mb), and (d) 850-mb temperature at 1200 UTC 6 June 1974 (degrees Celsius).

would be expected to become snow covered in the near future. However, a closer inspection of the individual events indicates that the snow cover anomalies at the beginning of early accumulation episodes are mixed; eight cases evidence below normal snow cover, while four indicate more extensive than normal snow cover (Table 1). Thus, this evidence indicates that abrupt early accumulation events are not necessarily a result of climatological preconditioning. Instead, several of the events are more likely the result of extreme but consistent meteorological events that lead to extensive snowfall over large areas.

For late season accumulation events, anomalies are strongly negative at the beginning of the abrupt change in each case. The strength and consistency of the negative snow cover anomalies before these large accumulation episodes suggests that climatological preconditioning may be important for these events, which occur later in the season (November). Large snow-free areas of North America that are usually snow covered by the late autumn will become snow covered as strong midlatitude cyclones move across the continent. In the case of late season accumulation events, the largest increases in snow cover extent occur in eastern Canada, around the southern periphery of Hudson Bay. Thus, an atmospheric pattern that leads to the establishment of a storm track that causes midlatitude cyclones to move from the central United States to eastern Canada results in large snow cover increases during this portion of the annual cycle. Although consistent atmospheric patterns are needed for the large accumulation episodes, the climate is preconditioned for the subsequent establishment of the snow cover.

At the beginning of early season ablation episodes, snow cover anomalies are generally positive. However, of the nine early ablation events three had snow cover anomalies below the 20-yr mean at the beginning of the event. This suggests that strong storms, with intense warm advection, are responsible for these large ablation events and that climatological preconditioning may not be important. In fact, much of the ablation that takes place during these early season events occurs in areas that are normally snow covered.

Late season ablation events are characterized by positive anomalies at the beginning of the abrupt ablation episodes in 9 of 11 cases. This suggests that in the majority of cases large, late season ablations are associated with a situation in which snow cover is found in areas where it is climatologically unusual. The atmospheric anomalies for these events suggest a lack of strong atmospheric disturbances in the ablation region. Thus, we hypothesize that general warm advection, solar radiation receipt, and/or persistent cloudiness may lead to large snow cover ablations without strong atmospheric disturbances or liquid precipitation (Robinson 1984, 1986; Zhang et al. 1996).

With snow cover ablation, there is also the factor of snow mass to be considered. An extensive yet shallow snowpack may result in an abrupt decrease in snow cover area, with little anomalous atmospheric forcing. Alternatively, an extensive, deep snowpack may evidence little change of extent, even with the movement of a strong system across the continent. For snow cover accumulation episodes, an atmospheric system may drop heavy amounts of snow on an area that is already covered with a thin layer of snow. In this case, the atmospheric system would not be classified as a major accumulation producer because the snow cover extent values for the continent would evidence little if any change. Thus, the information presented in this paper points to the general type of large-scale atmospheric pattern that is responsible for large accumulation and ablation episodes that are assumed to significantly change the continental albedo. Our analysis does not attempt to identify all heavy snowfall-producing or -ablating atmospheric systems. These complications will be investigated in future studies, incorporating station data and microwave satellite estimates of snow mass.

c. Summary and conclusions

This study represents a first step in understanding the role of atmospheric circulation variations on the annual cycle of continental-scale snow cover. A 20-yr record of satellite imagery is used to identify abrupt changes (1 week) in the annual cycle of snow cover extent across North America. Rapid accumulation events take place during the autumn. These events lead to an increase of nearly 4×10^6 km^2 in snow cover extent during a 7-day period. The accumulation events take place during a period when snow cover extent is typically below its mean value for that portion of the annual cycle. Relatively strong atmospheric anomalies are present during these episodes and are consistent with patterns that lead to spatially extensive snowfalls.

Rapid ablation events take place in the spring season. In the course of these events, greater than 2.0×10^6 km^2 of snow cover is ablated over a 1-week period. These episodes occur at times when North American snow cover extent is typically above its mean value for that time within the annual cycle. Early season ablation events, occurring near the vernal equinox, are associated with atmospheric anomalies that lead to strong sensible and latent heat fluxes in the ablation areas. Late season episodes, near the end of May, appear to be the result of a combination of anomalous heat fluxes and radiation induced melt.

The annual cycle of snow cover extent is an important component of the climate system because of the effect of snow cover on the global radiation balance. Recent results of Groisman et al. (1993, 1994) and Karl et al. (1993) have shown the importance of snow cover to the earth's radiative balance, especially in the spring. Thus, large-scale ablation events that occur after February may have a significant influence on continental-scale radiative balances and, hence, on temperature. In addition, large accumulation and ablation events could lead to important changes in the timing of seasonal temperature and moisture variations in middle- and high-latitude land areas of the Northern Hemisphere through effects on airmass modification (Leathers and Robinson 1993; Karl et al. 1993; Groisman et al. 1994). Thus, the synergistic relationship between hemispheric-scale atmospheric circulation variations and continental snow cover extent must be understood before any meaningful projections of future climatic states can be made. This study has provided an initial understanding of the influence of the atmospheric circulation on the annual cycle of snow cover across North America. This information will permit better evaluations of snow cover–atmosphere linkages in general circulation models and will increase the efficacy of utilizing snow cover as an indicator of global environmental change.

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