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ASSOCIATIONS BETWEEN CONTINENTAL-SCALE SNOW COVER ANOMALIES AND AIR MASS FREQUENCIES ACROSS EASTERN NORTH AMERICA

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ABSTRACT

The spatial extent of snow cover has been shown to affect diverse meteorological variables, including surface air temperatures, atmospheric moisture, longwave and shortwave radiation budgets, and sensible and latent heat fluxes. However, little research has directly addressed the role of snow cover extent in the production and/or maintenance of diverse air mass types. The major hypothesis of this study is that continental-scale snow cover anomalies should influence air mass frequencies because of their important effects on land-surface energy budgets. To test this hypothesis, satellite-derived Northern Hemisphere snow cover data were used in conjunction with a unique air mass classification routine to ascertain the association between air mass frequencies and snow cover anomalies across eastern North America.

Results indicate that continental-scale snow cover anomalies are strongly associated with changes in the frequency of air masses over eastern North America. However, strong mid-tropospheric circulation anomalies are often associated with the snow cover and air mass frequency changes, making it difficult to judge the relative importance of the snow cover anomaly to the variations in air mass frequency. During the months of November, December, January and April, circulation patterns are present that would lead to the observed snow cover anomalies and associated air mass frequency changes. Thus, we hypothesize that snow cover anomalies (resulting from the strong circulation anomalies) help to enhance changes in the air mass frequencies of the region. However, during the months of February and March no strong circulation anomalies are apparent, suggesting that during these months snow cover may play a dominant role in air mass frequency variations. Copyright © 2002 Royal Meteorological Society.

KEY WORDS: North America; air mass classification; snow cover

1. INTRODUCTION

The spatial extent of snow cover has been shown to affect many diverse meteorological variables, including surface air temperatures (Dewey, 1977; Walsh *et al*., 1982; Heim and Dewey, 1984; Namias, 1985; Baker *et al*., 1992; Wojcik and Wilks, 1992; Groisman *et al*., 1993; 1994; Leathers and Robinson, 1993; Robinson and Leathers, 1993; Leathers *et al*., 1995), atmospheric moisture, longwave and shortwave radiation balances, and sensible and latent heat fluxes (Grundstein and Leathers 1997, 1999; Ellis and Leathers 1998a,b, 1999). Each of the variables mentioned above, which are modified by the presence of a snow cover, determine air mass characteristics within a source region and the subsequent modification of an air mass as it moves

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across the land surface. Therefore, it is reasonable to assume that snow cover extent should be associated with variations in the air mass climatology of a given region.

Little research has directly addressed the role of snow cover extent in the production and/or maintenance of air mass types. Ellis and Leathers (1998a, 1999) adapted a one-dimensional snow pack model, SNTHERM (Jordan 1991), to predict surface air temperatures, and sensible and latent heat fluxes within the core of a suite of cold, high-pressure systems moving from their source region over Canada into the central USA under varying snow cover conditions. The model was modified such that the thermal characteristics of a cold air mass could be derived solely from the equation governing the heat balance between the surface and the lower atmosphere. The modified model included the synergistic interactions between the overlying air mass and the surface. Ellis and Leathers (1998a, 1999) found that mean daytime surface air temperatures were 6 to 10 °C warmer over bare ground compared with snow cover and that mean night-time temperatures were from 1 to 2 °C warmer over bare ground. Changes in the radiation budget and in fluxes of sensible and latent heat were found to be responsible for the large temperature depressions over snow-covered surfaces. Variations in the temperature and convective fluxes of the magnitude identified by Ellis and Leathers (1998a, 1999) would certainly lead to significant changes in the character of air masses that were forming or moving over an area of ephemeral snow cover.

2. DATA AND METHODOLOGY

A major difficulty in defining a relationship between snow cover and air mass characteristics has been the lack of information on daily air mass types at a large number of stations. Kalkstein *et al.* (1998) and Sheridan (2000, 2002) have developed a methodology to identify air mass types in an automated manner for an extended period of record. The spatial synoptic classification 2 (SSC2; Kalkstein *et al.*, 1998; Sheridan, 2000; 2002) uses hourly meteorological data to identify air mass types for each day for a given station. The SSC2 identifies each day as one of seven air mass types: dry polar (DP), dry moderate (DM), dry tropical (DT), moist polar (MP), moist moderate (MM), moist tropical (MT), and transition (Tr). Although these air mass designations are not the 'classic' definitions found in previous literature, they describe the overall character of the air mass existing at a station on a given day.

The DP air mass type of the SSC2 classification corresponds closely to cP air masses of the traditional scheme. These air masses are usually associated with the lowest temperatures at a location for a particular time of the year, and are almost always found in association with the movement of strong high pressure from central Canada. DT air mass types are very similar to the classic cT. These air masses normally give the highest temperatures and the lowest dew points of any of the types. This air typically originates in the southwestern USA or northern Mexico and is subsequently advected into the central USA. A DM air mass has generally warm, dry characteristics and is similar to the so-called 'Pacific' air mass type. These air masses are usually advected from the Pacific Ocean and are adiabatically warmed and dried as they cross the Rocky Mountains. MP air in the SSC2 system is very similar to the traditional mP. Cool, cloudy conditions with high relative humidities are found with this type. MM air masses are generally similar to MP, but with higher dew points and warmer temperatures. On days with this air mass type a warm front is generally found near the station with overrunning taking place. Finally, MT air masses are very similar in character and formation to classic mT air. The SSC2 also provides for a Tr day. On Tr days there is a distinct change from one air mass type to another, often associated with a frontal passage. Table I shows an example of the mean 1500 LST temperatures associated with diverse air mass types at Birmingham, AL, and Kapuskasing, ON. Note that the SSC2 system identifies an air mass based upon the relative surface conditions at a given station. Thus, air mass characteristics are very different during the same month from one station to another.

Air mass calendars are available for 327 North American stations (USA and Canada), generally for the period from 1948 through 2000. A subset of 54 stations has been selected covering the eastern two-thirds of North America, east of the Rocky Mountains (Figure 1; Table II). These 54 stations were chosen to represent a homogeneous distribution that adequately covers the study area without unnecessary repetition. The western one-third of the continent is excluded in this study because of the complex nature of the topography, which

Table I. Mean 1500 LST temperatures (°C) associated with diverse air mass types at Birmingham, AL, and Kapuskasing, ON, for the snow cover season

Air mass	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Birmingham, AL						
DP	11.7	6.0	4.0	6.5	11.4	17.4
DT	22.2	18.1	18.8	21.7	24.7	28.0
DM	19.6	14.5	13.4	15.4	19.1	24.1
MP	9.3	6.2	4.3	5.1	8.2	13.0
MM	16.5	13.4	11.6	13.3	15.5	19.2
MT	23.1	20.4	18.7	20.9	23.3	26.3
Tr	14.2	10.3	7.6	10.3	16.1	19.9
Kapuskasing, ON						
DP	−7.3	−16.9	−19.0	−14.4	−6.4	2.5
DT	11.2	—	—	6.4	9.1	19.5
DM	5.2	0.7	−3.2	1.8	6.2	11.2
MP	−3.2	−8.6	−10.5	−9.6	−5.8	1.2
MM	2.9	−0.1	−1.7	0.0	3.1	6.6
MT	12.4	8.9	1.4	5.7	7.2	19.8
Tr	−2.4	−11.6	−13.2	−10.6	−4.3	4.2

may make identification of relationships problematic. Data from the period 1972 through 1998 were used in this study to match the period of record of the satellite-derived snow cover extent information.

Snow cover data were obtained from the National Centers for Environmental Prediction (NCEP), Climate Prediction Center. Visible satellite imagery is used to construct weekly charts of snow cover extent. The daily presence or absence of snow cover is determined for each cell of an 89×89 grid on a polar stereographic projection that covers the Northern Hemisphere (Dewey and Heim, 1982; Robinson *et al*., 1993). The change of size of the grid cells with latitude, resulting from the projection, is accounted for in all calculations. The daily snow cover information is aggregated to a weekly product that depicts the presence or absence of snow cover on the last day of the week that the Earth's surface was visible. The snow cover during the last week of the month for each of five extreme cases (large snow cover extent and small snow cover extent) is composited by identifying those grid boxes that are snow covered in at least four of the five extreme years. The grid cells that are snow covered during large extent extremes and not covered during small extent extremes are mapped to show the difference in snow extent between the extreme snow cover phases. Snow cover extent data are available starting in 1972 and were used through to 1998.

The National Oceanic and Atmospheric Administration Cooperative Institute for Research in Environmental Science (NOAA-CIRES) Climate Diagnostics Center in Boulder, CO, provided the 500 hPa geopotential height data from their Web site at http://www.cdc.noaa.gov/. The atmospheric data are taken from the NCEP re-analysis data set (Kalnay *et al*., 1996). Data are obtained for the years 1972 through 1998.

The association between North American snow cover extent and air mass frequency was evaluated in the following manner. We define the snow cover season as the period November through April (the time when ephemeral snow cover is present across the USA and southern Canada). The total North American snow cover extent for each month (November through April) is sorted for the period 1972 through 1998, and the five largest extent and smallest extent years are identified for each month (Table III). The five largest and smallest snow cover extent years, for each month, are used to create composites of air mass frequency at each station under these extreme continental snow cover conditions. In addition, these same years are used to construct composites of 500 hPa geopotential heights from the NCEP re-analysis data.

An additional difficulty in defining the impacts of snow cover on atmospheric variables is the synergistic relationships between snow cover, air mass frequency, and the atmospheric circulation (Leathers and Robinson, 1993). Simply stated, it is difficult to assess the impact of snow cover on air mass frequency when both may be a symptom of variations in the large-scale circulation of the atmosphere. Therefore, it is imperative

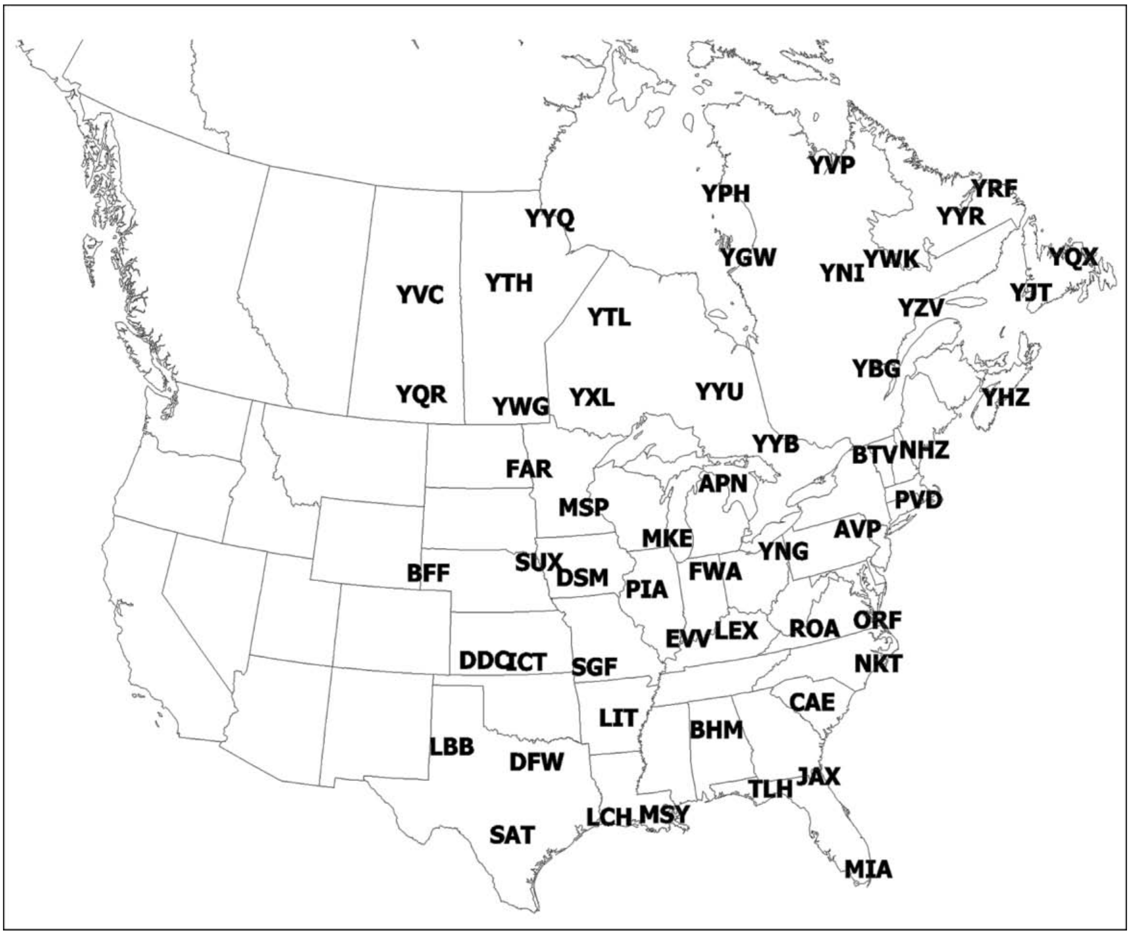


Figure 1. Distribution of air mass frequency stations. Three-letter codes are given in Table II

that circulation anomalies be considered when assessing the relationship between snow cover extent and air mass frequencies. To address this concern, 500 hPa geopotential height data are stratified according to North American snow cover extent extremes in order to assess the effect of circulation variations on air mass frequencies. Because a limited number of cases are being composited to obtain average high snow cover extent (HS) and low snow cover extent (LS) patterns, it is possible that a large circulation anomaly during a single year could dominate the composited pattern. This possibility was evaluated by inspecting 500 hPa maps for each month used in the compositing analyses. It was determined that no single month dominated any of the composited geopotential height patterns. Concern has been raised that atmospheric fields, especially those near the surface, in the NCEP re-analysis data may have been contaminated in their generation by erroneous snow cover information (Cullather *et al.*, 2000). However, only 500 hPa geopotential height fields are used in this study, a level that is above those affected by this problem (Namias, 1985). In all subsequent examples, difference maps of snow cover, air mass frequency and 500 hPa geopotential heights are based on HS minus LS.

3. RESULTS

3.1. November

The shading on the November air mass frequency difference maps (Figure 2) shows those grid cells covered by snow during the five HS months that were not covered during the five LS Novembers. During HS months,

Table II. Stations used in the air mass frequency analysis with location, elevation and three-letter identification code

City	State/Province	ID	Latitude	Longitude	Elevation (m)
Alpena	MI	APN	45.07	83.57	211
Wilkes Barre	PA	AVP	41.33	75.73	289
Birmingham	AL	BHM	33.57	86.75	192
Brownsville	TX	BRO	25.90	97.43	6
Burlington	VT	BTV	44.46	73.15	104
Columbia	SC	CAE	33.97	81.00	74
Dodge City	KS	DDC	37.77	99.97	790
Dallas/Ft Worth	TX	DFW	32.83	97.00	168
Des Moines	IL	DSM	41.53	93.65	294
Evansville	IN	EVV	38.05	87.53	118
Fargo	ND	FAR	46.91	96.80	274
Ft Wayne	IN	FWA	41.00	85.20	252
Wichita	KS	ICT	37.65	97.42	408
Jacksonville	FL	JAX	30.50	81.70	9
Lubbock	TX	LBB	33.65	101.81	988
Lake Charles	LA	LCH	30.11	93.21	10
Lexington	KY	LEX	38.03	84.60	301
Little Rock	AR	LIT	34.73	92.23	172
Miami	FL	MIA	25.80	80.27	4
Milwaukee	WI	MKE	42.95	87.90	211
Minn./St Paul	MN	MSP	44.88	93.22	252
New Orleans	LA	MSY	30.03	90.03	3
Brunswick	ME	NHZ	43.88	69.93	24
Cherry Point	NC	NKT	34.85	76.88	13
Norfolk	VA	ORF	36.90	76.20	9
Peoria	IL	PIA	40.67	89.68	202
Providence	RI	PVD	41.73	71.43	19
Roanoke	VA	ROA	37.32	79.97	358
San Antonio	TX	SAT	29.53	98.46	242
Springfield	MO	SGF	37.23	93.38	387
Sioux City	IA	SUX	42.40	96.38	336
Tallahassee	FL	TLH	30.38	84.37	21
Bagotville	QC	YBG	48.33	71.00	163
Halifax	NS	YHZ	44.88	61.50	141
Stephenville	NF	YJT	48.53	58.55	8
Youngstown	OH	YNG	41.27	80.67	365
Nitchequon	QC	YNI	53.20	70.90	536
Inukjuak	QC	YPH	58.47	78.08	25
Prince Rupert	BC	YPR	54.28	130.38	52
Regina	SK	YQR	50.43	104.66	573
Gander	NF	YQX	48.95	54.57	150
Cartwright	NF	YRF	53.70	57.03	13
Thompson	MB	YTH	55.80	97.86	212
Big Trout Lake	ON	YTL	53.83	89.86	220
La Ronge	SK	YVC	55.15	105.27	375
Kuujjuaq	QC	YVP	58.10	68.42	815
Winnipeg	MB	YWG	49.90	97.23	239
Wabush	NF	YWK	52.93	66.90	551
Sioux Lookout	ON	YXL	50.10	91.90	374
North Bay	ON	YYB	46.37	79.42	369
Churchill	MB	YYQ	58.75	94.07	35
Goose Bay	NF	YYR	45.88	82.57	193
Kapuskasing	ON	YYU	49.45	82.46	229
Sept-Iles	QC	YZV	50.22	66.27	55

Table III. The five smallest snow cover extent years (LS) and five largest snow cover extent years (HS) identified for each month during the period 1972 through 1998 (numerical values in 10^6 km^2). Identifications based on total North American snow cover

LS	Extent	HS	Extent
November			
1977	10.3	1973	12.4
1979	9.4	1985	12.8
1987	9.5	1991	12.7
1990	10.1	1993	12.3
1998	10.2	1996	12.7
December			
1976	13.7	1978	15.4
1979	12.6	1983	15.8
1980	12.4	1985	15.8
1986	13.4	1989	15.3
1988	13.4	1992	15.6
January			
1981	13.8	1978	16.1
1986	15.0	1979	16.4
1989	14.5	1982	16.3
1990	14.6	1985	16.6
1992	14.6	1988	16.0
February			
1977	13.8	1978	16.8
1981	13.6	1979	16.6
1991	13.9	1980	15.9
1992	13.6	1982	15.8
1995	14.1	1993	15.5
March			
1973	12.6	1974	14.1
1981	12.5	1975	14.7
1986	13.0	1978	15.1
1988	12.4	1979	14.6
1992	12.5	1998	14.2
April			
1984	10.5	1975	13.0
1987	9.8	1979	13.1
1988	11.4	1982	12.7
1993	10.2	1995	12.4
1998	10.2	1997	12.5

snow is found throughout a large portion of the northern plains extending to the south through Montana, South Dakota, Minnesota, and northern Wisconsin. A more complete snow pack is also present in the Rocky Mountains from British Columbia, south through New Mexico. Table IV shows the difference in air mass frequency (days/month) between the HS and LS months averaged across all 54 stations. During November, the frequency of DM, DP, and MP air masses are most highly associated with snow cover extremes (Table IV). During HS months the frequency of DM air masses is decreased by 3 to 5 days/month throughout a large portion of eastern North America (Figure 2(a)) compared with LS. Most of the decrease in the frequency of DM air masses is accounted for by increases in the frequency of DP air masses across the same general regions (Figure 2(b)). Figure 2(c) indicates that MP air masses also increase in frequency during HS months compared with LS Novembers, especially across the southern tier and Maritime Provinces of Canada (3 to 7 days increase per month) and into the Midwest portion of the USA.

A map of 500 hPa geopotential height anomalies for HS Novembers shows an anomalous trough across the western USA, with large positive geopotential height departures over the Aleutian Islands and smaller positive departures over the southeastern USA (Figure 3(a)). This pattern is indicative of the negative phase of the Pacific–North American (PNA) teleconnection pattern (Leathers *et al*., 1991). In fact, an inspection of the PNA index values for the HS Novembers indicates that 4 in 5 years did have negative index values. This upper-level flow pattern brings anomalously cold air into the

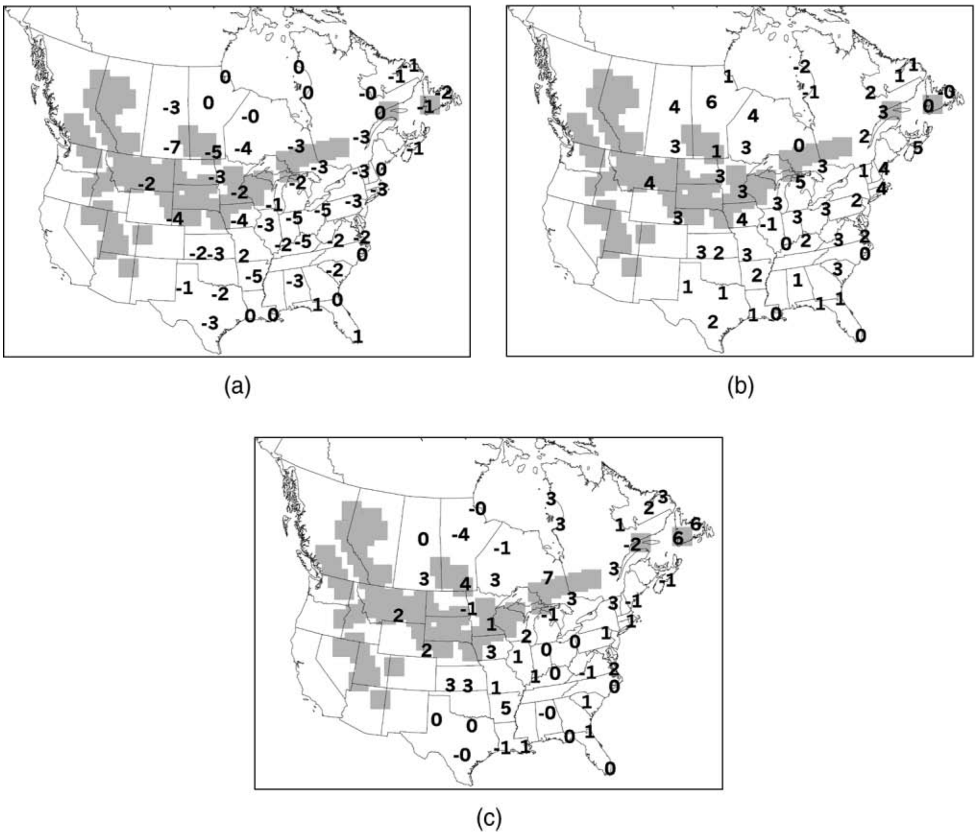
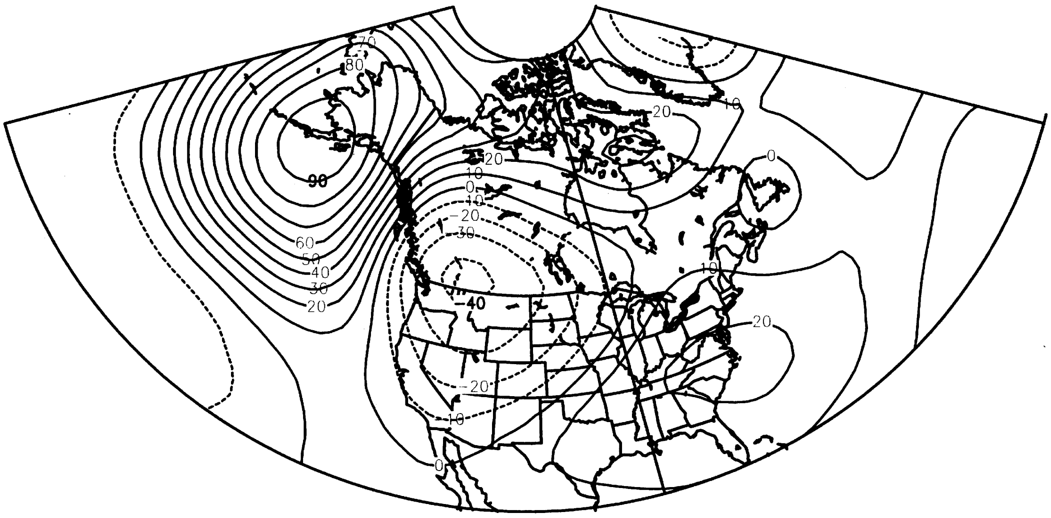


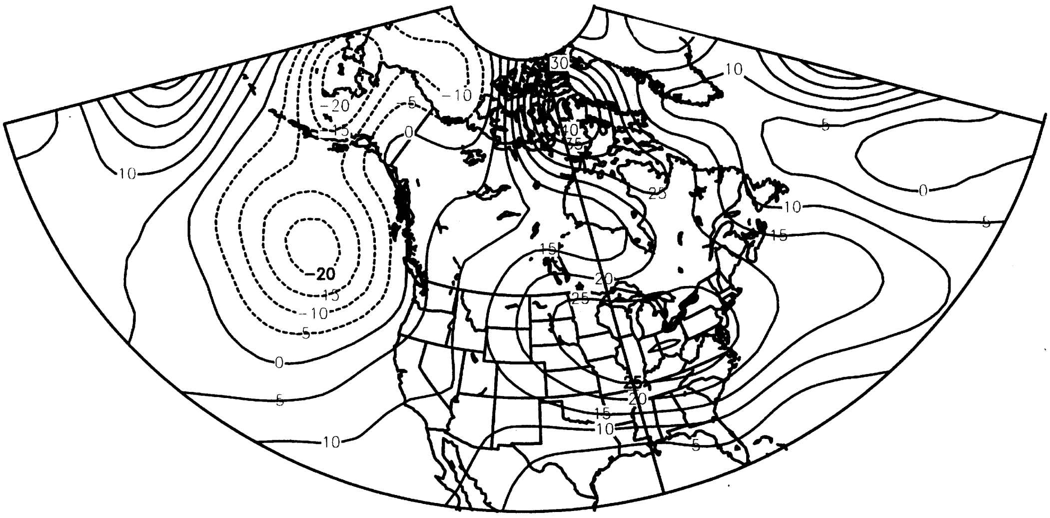
Figure 2. Difference in air mass frequency (HS − LS) for November: (a) DM; (b) DP; (c) MP. Shading represents those grid cells covered by snow during HS months and not covered during LS months

Table IV. Air mass frequency difference (HS − LS) averaged for all stations for each month and each air mass type

Month	DM	DP	DT	MM	MP	MT	Tr
November	−1.95	1.96	−0.63	−0.33	1.28	−0.19	0.06
December	−2.08	2.48	−0.33	−0.37	0.44	0.09	−0.44
January	−4.16	4.91	−0.88	−1.60	1.71	−0.57	0.55
February	−2.69	4.65	−0.91	−1.68	1.76	−0.79	−0.50
March	−2.39	2.25	−0.52	−0.52	0.97	0.01	0.89
April	−3.29	3.06	−1.45	−0.77	0.71	0.60	1.01



(a)



(b)

Figure 3. 500 hPa geopotential height anomaly maps (gpm) for (a) HS and (b) LS Novembers. Anomalies based on the period 1968 through 1996

western and central portions of North America (DP, MP), allowing for the initiation and maintenance of snow cover over this region. During the five LS months, the upper-level flow pattern is much different, with weak positive geopotential height anomalies covering much of eastern North America (Figure 3(b)). This anomalous ridging creates a more zonal flow pattern across North America, allowing for air masses from the Pacific to traverse the continent in an eastward progression, likely leading to an increase in DM air mass frequencies during LS months. The increased frequency of DM air mass days would be less likely to initiate or maintain a snow cover at this early time in the snow cover season.

Thus, during November there is a distinct association between snow cover extent and the frequency of several air mass types. However, it is clear that the air mass frequency changes and the snow cover variations are associated with anomalous upper-level flow patterns. Thus, the circulation and snow cover anomalies are likely working in concert to produce the resulting air mass frequency changes.

3.2. December

During HS Decembers, the snow pack is greatly expanded in the western USA and extends farther to the south through Nebraska, Iowa, the Ohio Valley region, and into the northeast across western Pennsylvania and New York, compared with LS months (Figure 4). Two air mass types, DM and DP, show an association with the snow cover differences during December, as does the transition 'air mass' situation. DM air mass frequencies are substantially decreased across the entire eastern portion of North America when comparing HS months with LS months (Table IV), with the largest differences found across the central plains, eastward to the mid-Atlantic (3 to 8 days/month; Figure 4(a)). Note that this is along the same axis as the anomalies in snow cover. The decrease in DM frequency is accounted for by increases in DP air masses when comparing HS with LS years (Table IV). Increases in DP frequency are greatest over the central USA and Canada, especially the Great Plains of both countries (3 to 9 days/month; Figure 4(b)). Transition days also vary along with the snow cover extremes. The number of transition days are generally decreased during HS compared with LS months in the north and increased in the southern portions of the study region (Figure 4(c)).

During HS Decembers, the eastern portion of North America is covered by negative 500 hPa geopotential height anomalies, while a centre of positive anomalies is found just off the Pacific Coast (Figure 5(a)). The enhanced trough in the eastern portion of North America would favour the movement of DP air masses across the region and lead to a greater likelihood of snowfall and snow cover. This type of meridional situation would decrease the likelihood of the movement of DM air masses into the eastern portion of the continent. It would also explain the increase of Tr air mass days in the southern portion of the region and their decrease to the north. An anomalous trough across eastern North America would push the baroclinic zone, and hence the jet stream, to the south, increasing the likelihood of the movement of

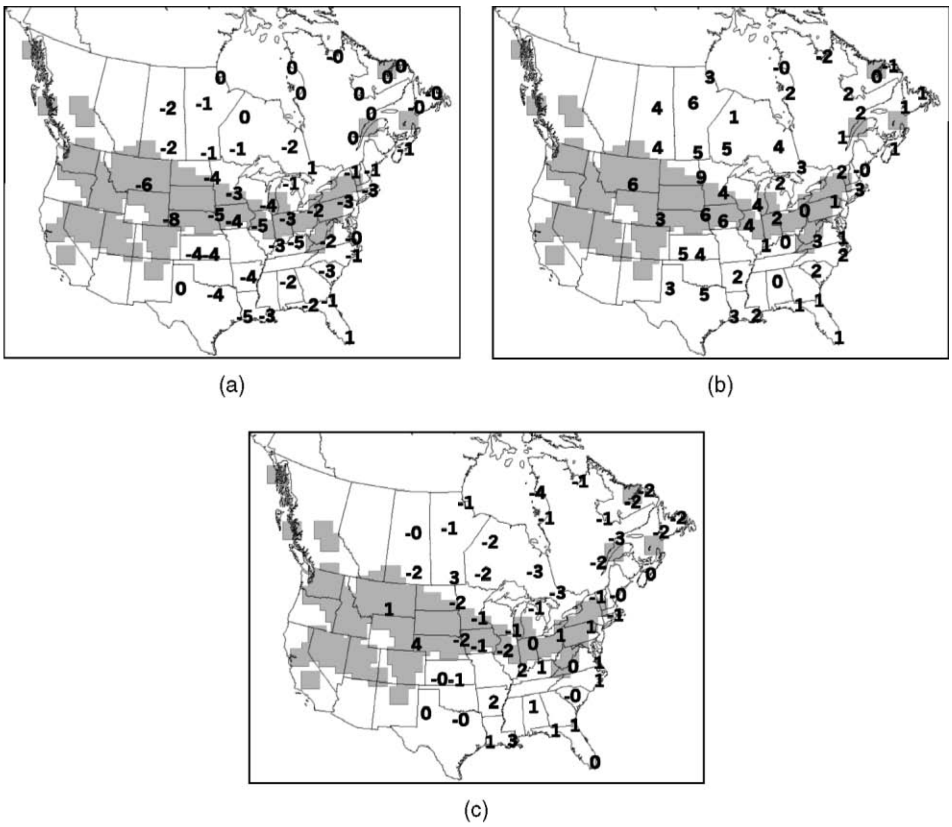
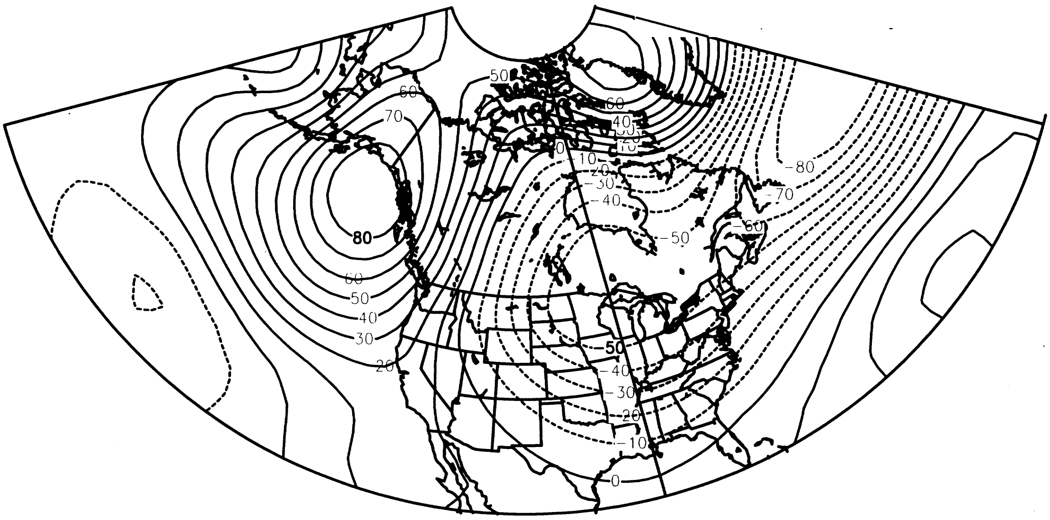
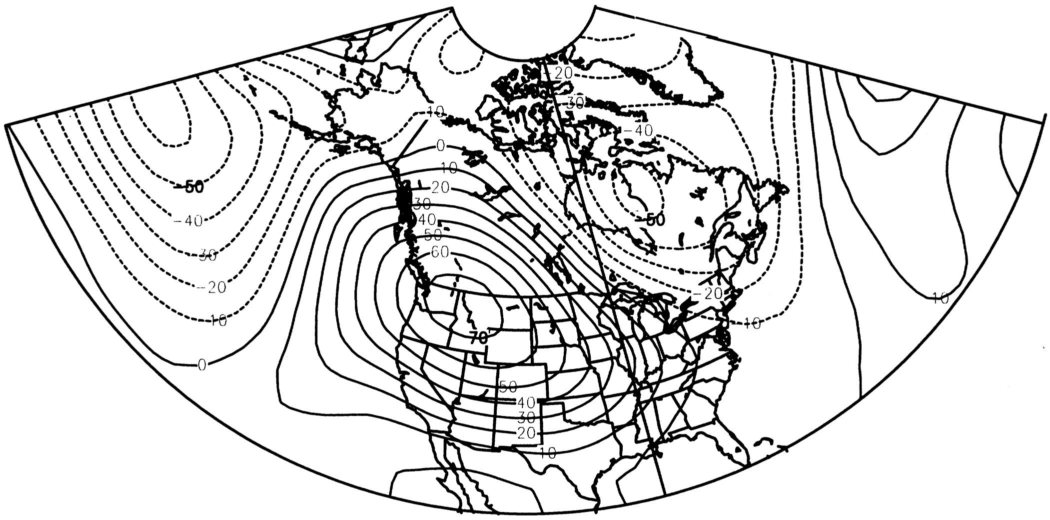


Figure 4. Difference in air mass frequency (HS − LS) for December: (a) DM; (b) DP; (c) Tr. Shading represents those grid cells covered by snow during HS months and not covered during LS months



(a)



(b)

Figure 5. 500 hPa geopotential height anomaly maps (gpm) for (a) HS and (b) LS Decembers. Anomalies based on the period 1968 through 1996

storms through the region and their accompanying frontal passages (recorded as transition days). To the north of the jet stream, Tr frequencies would be reduced due to the lack of cyclone activity. During LS years, the western portion of North America is dominated by anomalous ridging (positive 500 hPa geopotential height anomalies; Figure 5(b)). This upper-level flow regime would lead to an increase in the frequency of DM air mass days at the expense of DP, especially across the western and central portions of the study region.

Similar to November, there is a definite association between snow cover extent and the frequency of air mass types across eastern North America during December. Although the areas with the largest air mass frequency differences are found generally coincident with the snow cover anomalies, the circulation variations during times of anomalous snow cover would themselves lead to the observed air mass frequency changes. Once again, it seems clear that atmospheric and land-surface forcings are working together to modify the air mass climatology of the region during December.

3.3. January

Large differences are found in the equatorward extent of the snow pack between snow cover extremes in January (Figure 6). During HS months, snow covers South Dakota, Nebraska, Iowa, Missouri, Indiana, and Ohio. These same areas are without a snow pack during LS Januarys. The extremes in snow cover extent are associated with large differences in air mass frequencies during this month (Table IV). In fact, all seven air mass types evidence spatially coherent frequency changes. Two air masses are particularly affected. The frequency of DM air masses decreases by between 8 and 12 days/month across the central plains of the USA during HS compared with LS months (Figure 6(a)). The frequency of DP air masses increases dramatically when comparing HS with LS Januarys (Figure 6(b)), up to 13 days/month across the northern Great Plains of the USA. It seems evident that, during Januarys with extensive snow cover, DP air is more common across the entire eastern portion of the continent, even as far south as the Gulf Coast and northern Florida (Figure 6(b)). During LS months, the DP air is generally replaced by DM air at most stations. During HS months the southern portion of the study region has substantial increases in the frequency of MP air (up to 7 days/month), while much of Canada shows decreased frequencies (up to 6 days/month; Figure 6(c)). Nearly every station has decreased frequencies of MM air masses during HS Januarys when compared with LS months (Figure 6(d)). The number of DT days decreases across the central and southern plains and the southeast when comparing HS with LS months (Figure 6(e)), and MT days are also less numerous during extensive snow cover months compared with LS Januarys (Figure 6(f)). During HS years, the number of Tr days increases across the southern portions of eastern North America, and stations across Canada show decreases in Tr frequencies (Figure 6(g)).

During HS Januarys negative 500 hPa geopotential height anomalies cover nearly all of eastern North America (Figure 7(a)), whereas during LS months the same area is covered by positive anomalies (Figure 7(b)). During HS years, the anomalous trough across eastern North America favours the movement of DP-type air masses into the region at the expense of DM. As cold air moves far to the south in this situation it reaches the southern portion of eastern North America as relatively cold, MP air, instead of warmer MM. Both DT and MT air masses are diminished during HS years because of the movement of cold air far to the south in association with the southward movement of the jet stream. It is likely that a southward extension of the snow pack is associated with a displacement of the baroclinic zone to the south, resulting in increased storm formation across the southern tier and a decreased number of storms to the north, manifesting itself as changes in Tr frequencies.

Clearly, the same problem presents itself here as in November and December. It is unclear whether the changes in air mass frequency are a result of snow cover anomalies or a symptom, along with snow cover, of large-scale circulation variations. However, it is important to point out that the presence of snow cover would enhance the air mass frequency anomalies that were already present as a result of circulation variations.

3.4. February

The difference in snow pack extent between HS and LS Februarys is smaller than during previous months (Figure 8). Areas covered during HS compared with LS years include Montana, North and South Dakota, Iowa, Indiana, Ohio, and western Pennsylvania. The extremes in snow cover extent are associated with large changes in air mass frequencies across eastern North America, with six of the seven air mass types showing substantial changes. DM air masses are significantly reduced across the entire region during HS months (Table IV; Figure 8(a)). The largest decrease in DM air mass frequency is found from the central Great Plains, eastward through the central Appalachians (up to 11 days/month; Figure 8(a)). The decrease in DM air masses is associated with a sharp increase in DP air mass types over the same general region of up to 10 days/month (Figure 8(b)). As in January, this increase in DP frequency extends southward away from the ephemeral snow cover region. DT air mass types decrease during HS compared with LS months across the southern one-half of the region, especially over the southern Great Plains states (Figure 8(c)). HS Februarys bring large decreases in MM air mass frequencies when compared with LS months (Figure 8(d)). This decrease is especially large across the northern tier of the USA and the southern tier of Canada. The frequency of MP air masses decreases across Canada and increases across the USA during HS Februarys

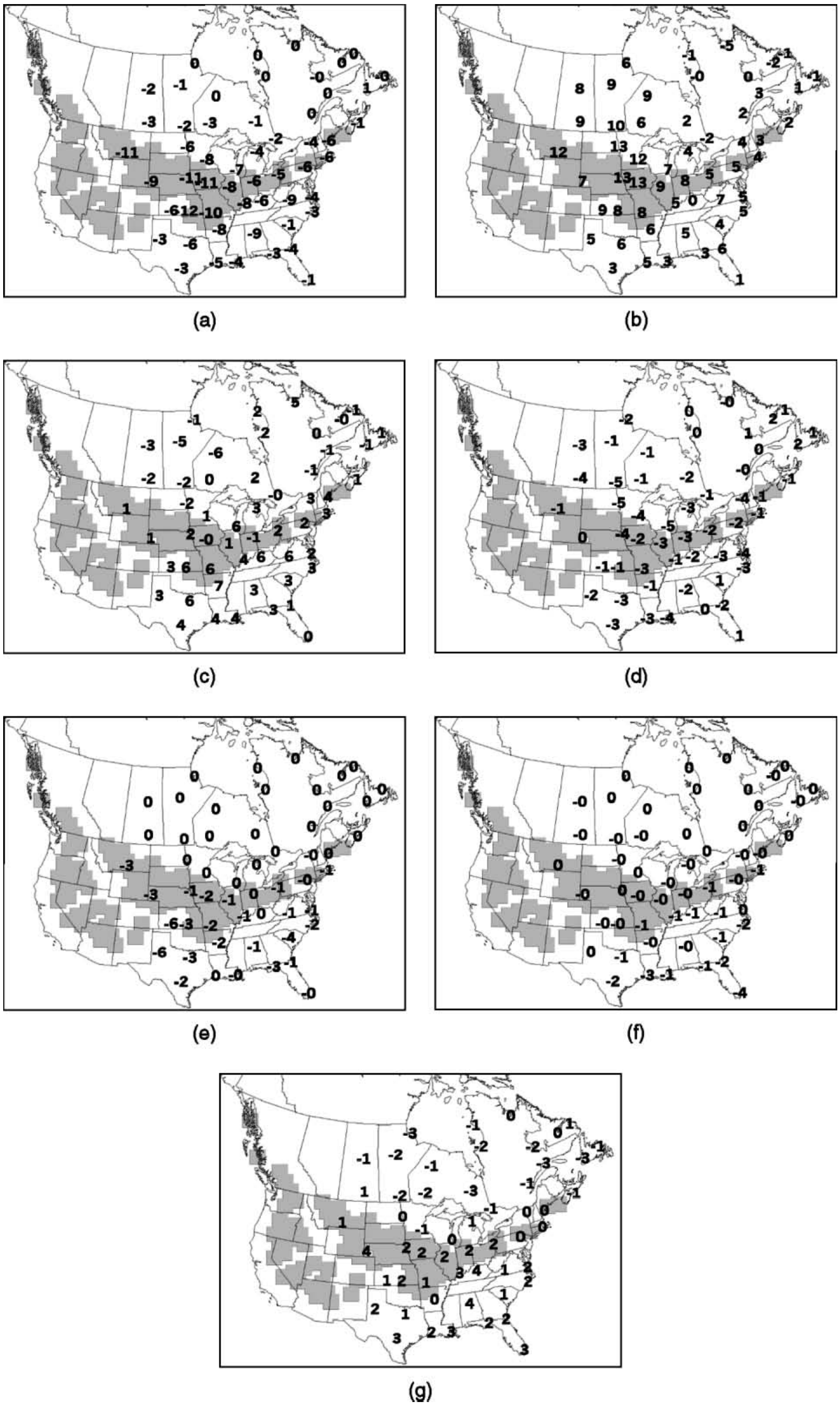
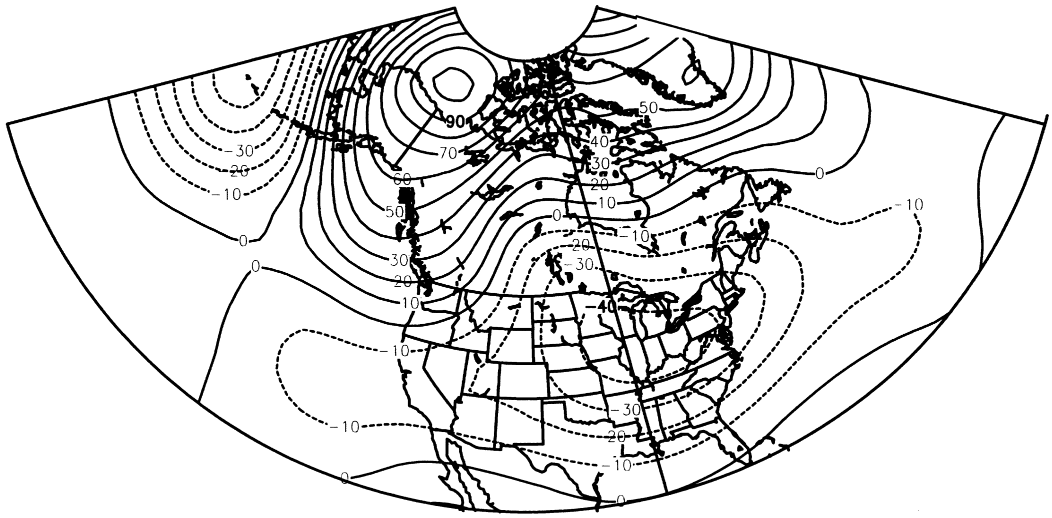
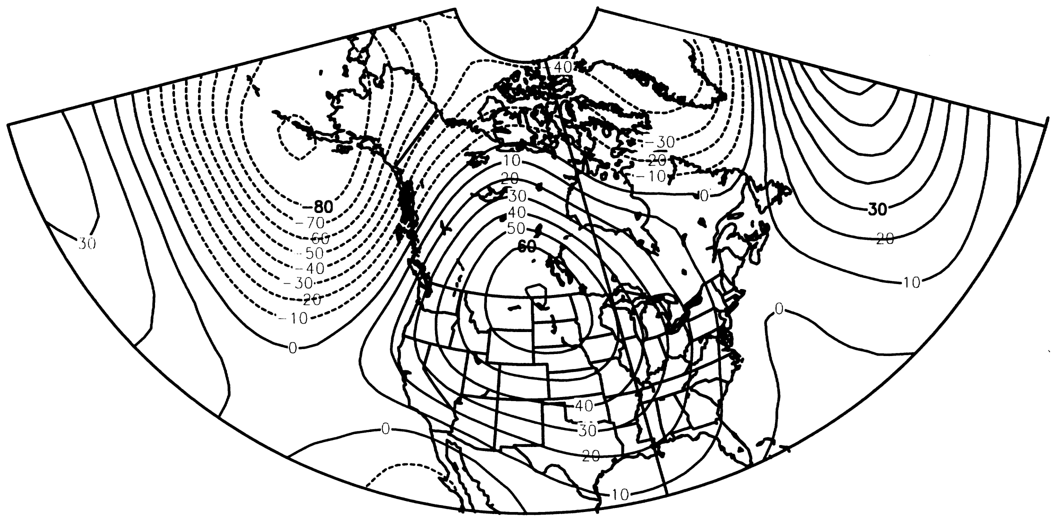


Figure 6. Difference in air mass frequency (HS − LS) for January: (a) DM; (b) DP; (c) MP; (d) MM; (e) DT; (f) MT; (g) Tr. Shading represents those grid cells covered by snow during HS months and not covered during LS months



(a)



(b)

Figure 7. 500 hPa geopotential height anomaly maps (gpm) for (a) HS and (b) LS Januarys. Anomalies based on the period 1968 through 1996

compared with LS (Figure 8(e)). Some increases in MP frequencies are very large, as large as 9 days/month in the southern Great Plains region of the USA. There is a decrease of MT air mass frequency across the southern portion of the USA when comparing HS and LS Februarys, with changes as large as 5 days/month along the Gulf Coast region (Figure 8(f)).

During HS Februarys the 500 hPa circulation is dominated by anomalous troughing over the eastern Pacific Ocean and the North Atlantic (Figure 9(a)), whereas LS months are characterized by a strong ridge over western North America (Figure 9(b)). Interestingly, there are no large differences in the 500 hPa geopotential heights over eastern North America when comparing HS and LS months. Therefore, unlike the previous months, there is no apparent atmospheric circulation anomaly that easily explains the variations in air mass frequencies across the region. Land surface conditions associated with the presence or absence of snow cover are likely to be primarily responsible for the air mass frequency variations. In particular, during HS months

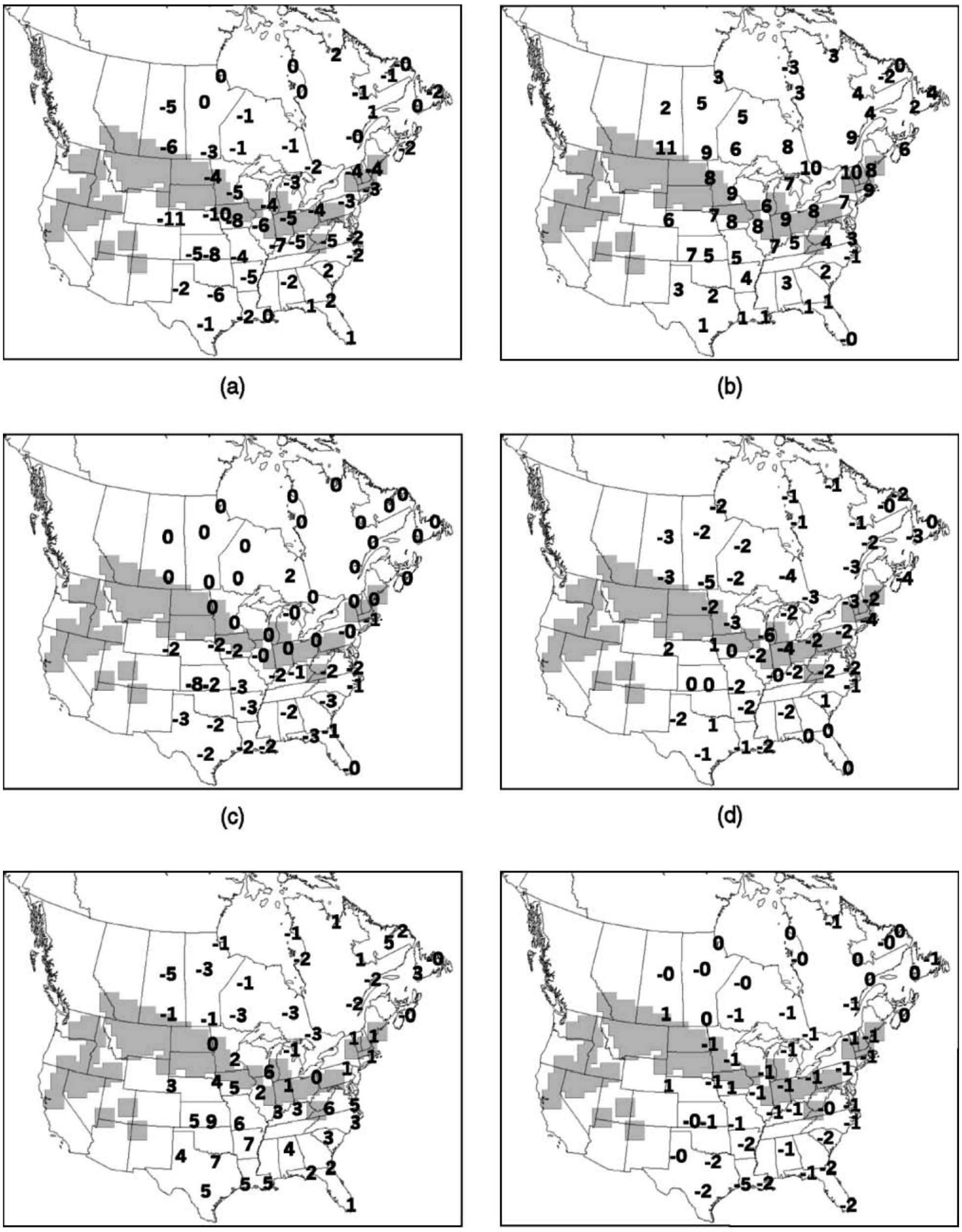


Figure 8. Difference in air mass frequency (HS – LS) for February: (a) DM; (b) DP; (c) DT; (d) MM; (e) MP; (f) MT. Shading represents those grid cells covered by snow during HS months and not covered during LS months

it is likely that the characteristics of the snow pack, such as its high albedo and its effect upon sensible and latent heat fluxes (Ellis and Leathers 1998a,b, 1999), lead to significant modification of the air mass climatology of the region.

3.5. March

Differences in snow cover extent between HS and LS conditions during March are found mainly across the Rocky Mountains and High Plains regions of the USA and Canada and in a narrow band from Saskatchewan

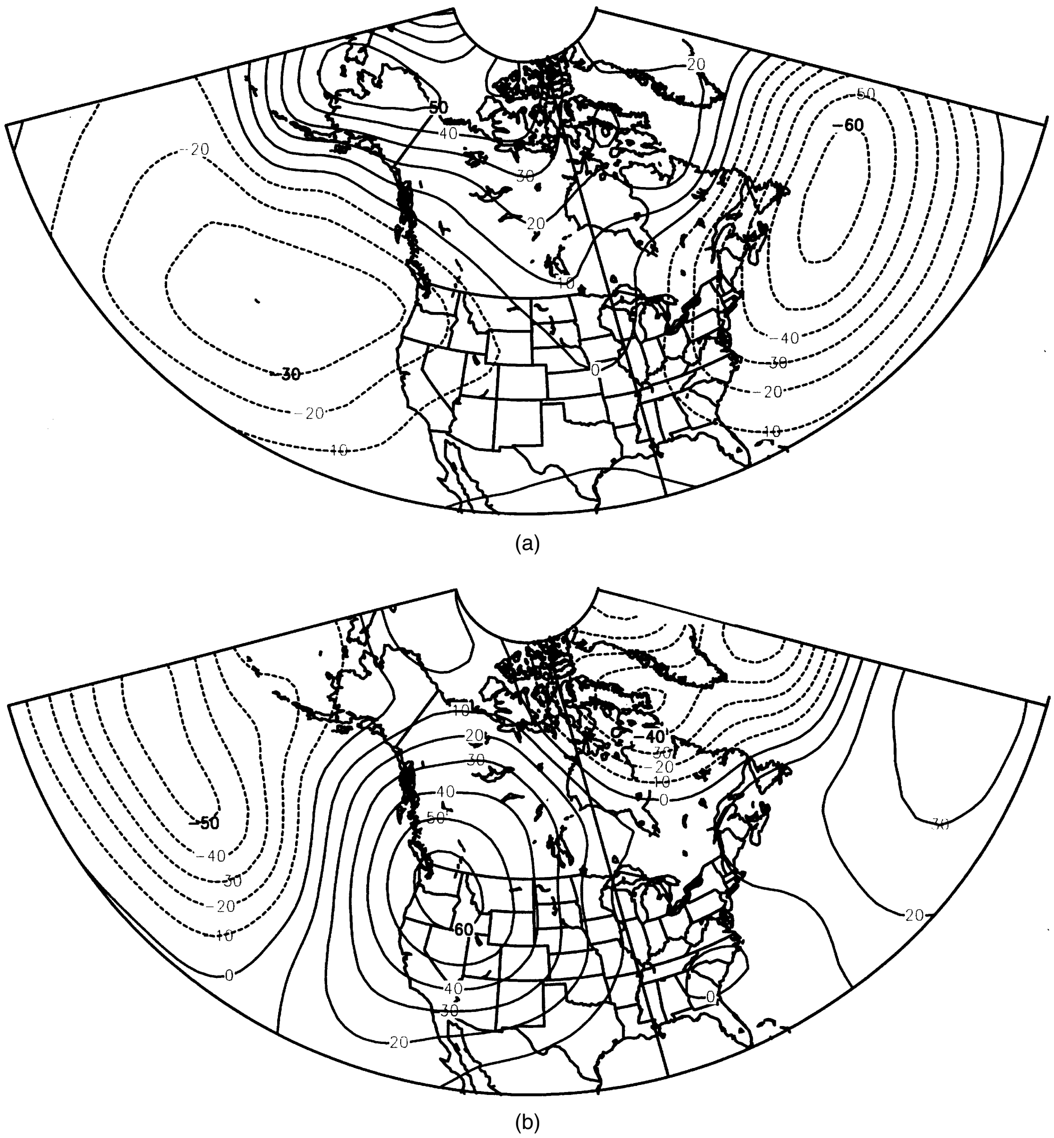


Figure 9. 500 hPa geopotential height anomaly maps (gpm) for (a) HS and (b) LS Februarys. Anomalies based on the period 1968 through 1996

and North Dakota, eastward to Maine (Figure 10). These snow cover extent differences are associated with appreciable variations in air mass frequencies for five of the seven air mass types. During HS months, days with DM air mass types are greatly reduced, especially across the Great Plains regions of the USA and Canada (Figure 10(a)). DM days are generally replaced with DP air mass types during HS when compared with LS March conditions (Figure 10(b)). Similar to February, DT air mass frequency is depressed throughout the southern portion of eastern North America, while MM air mass types are less frequent, especially in the Great Plains region (Figure 10(c) and (d)). During HS months, MP air mass types exhibit a much higher frequency throughout the central USA, while decreasing throughout much of eastern Canada (Figure 10(e)).

The 500 hPa circulation anomalies are quite weak during HS months except in extreme northeastern Canada (Figure 11(a)), whereas during LS months there is moderately strong ridging found across central Canada and an intense trough is located over the Aleutian Islands (Figure 11(b)). As with February, there is little change

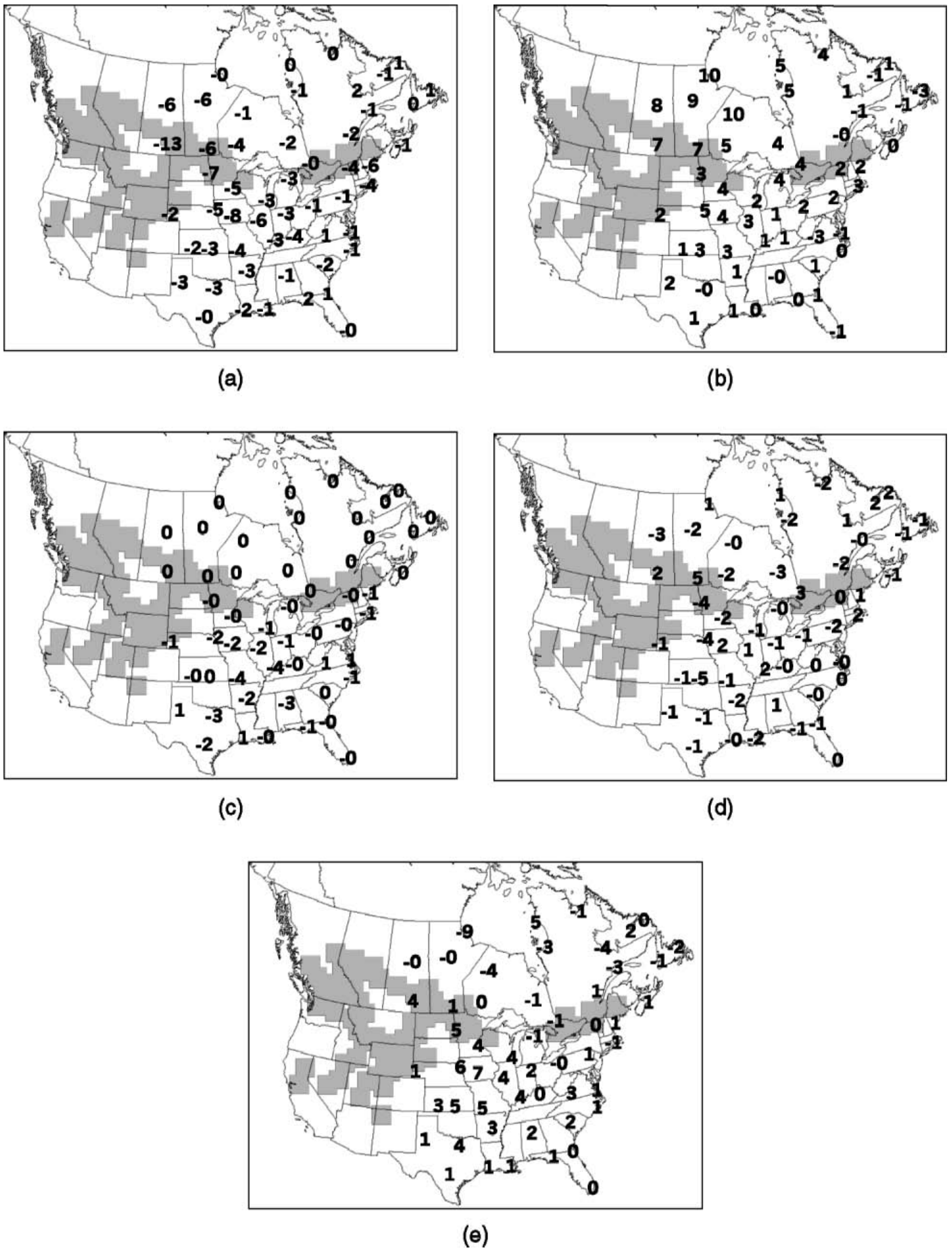
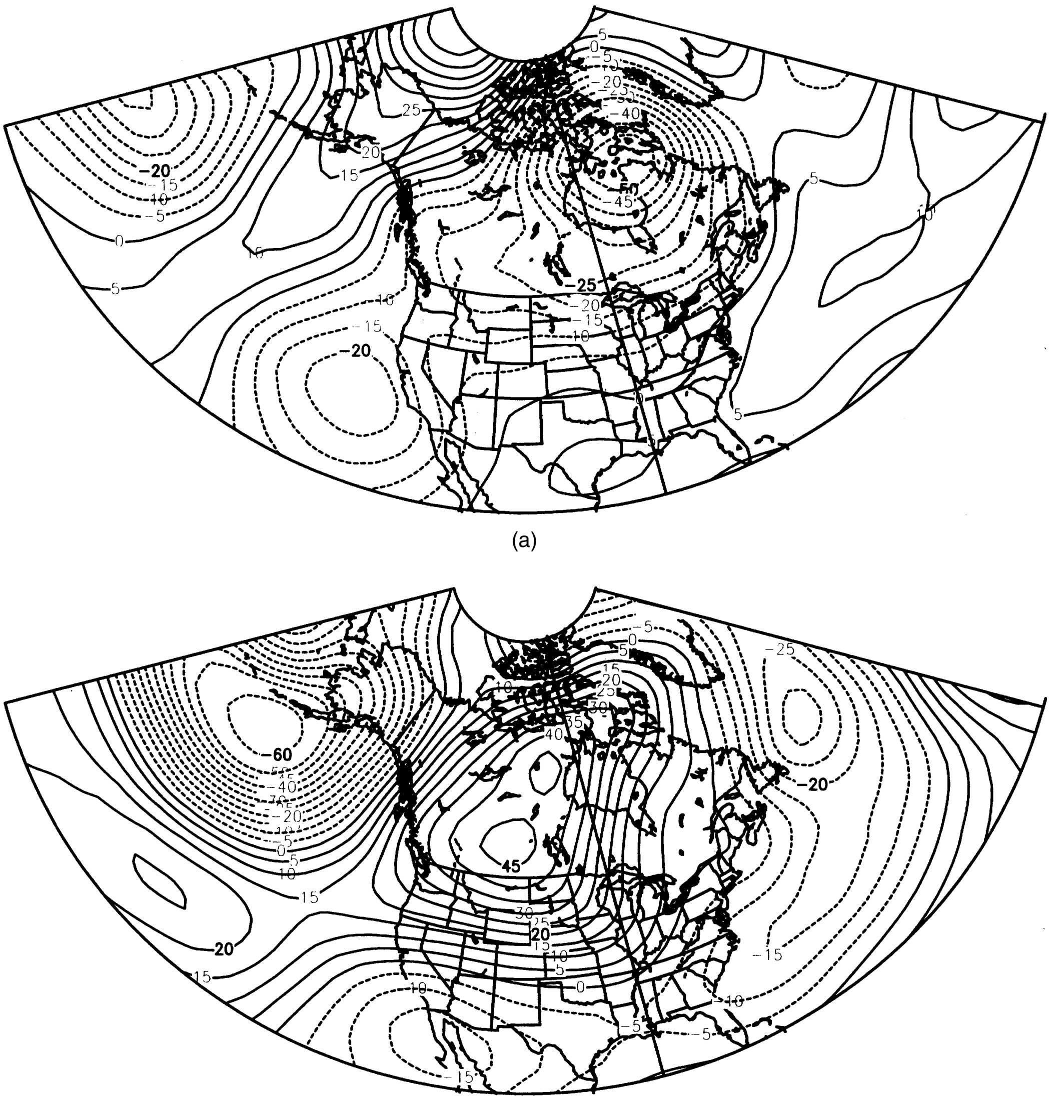


Figure 10. Difference in air mass frequency (HS − LS) for March: (a) DM; (b) DP; (c) DT; (d) MM; (e) MP. Shading represents those grid cells covered by snow during HS months and not covered during LS months

in 500 hPa geopotential heights over the region of eastern North America where large changes in air mass frequency are occurring. During LS months, the rather strong ridge over central Canada likely leads to both a decreased snow pack in the area and inhibits the southward progression of cold air mass types. These two factors working in concert adequately explain the increase in warm air mass types, especially DM and MM, during these months. Atmospheric conditions during HS months do not explain the great increase in cold air mass types that are prevalent during these situations. Instead, an expanded snow pack may cause a decrease in modification processes as air masses move south out of Canada, resulting in colder air mass types across much of the southern portions of the region.



(a)

(b)

Figure 11. 500 hPa geopotential height anomaly maps (gpm) for (a) HS and (b) LS Marches. Anomalies based on the period 1968 through 1996

3.6. *April*

Eastern Canada evidences the greatest change in snow cover extent when comparing HS and LS conditions during April (Figure 12). During HS months, snow cover is found throughout most of Ontario and much of the southern portion of Quebec, areas that are not snow covered in LS Aprils. These snow cover variations are associated with large frequency changes in all seven air mass types defined in this study. DM air masses are much less frequent across the northern tier of the USA and the southern portion of Canada during HS when compared with LS Aprils (Figure 12(a)), whereas DP air masses increase in frequency across the same region (Figure 12(b)). During HS months, DT frequency is strongly depressed throughout the Great Plains of eastern North America (Figure 12(c)), whereas MM air masses are depressed, especially across eastern Canada (Figure 12(d)). MP air mass types show an interesting change when comparing HS and LS Aprils. In general, MP frequencies during HS months are lower across most of the USA and higher from the northern

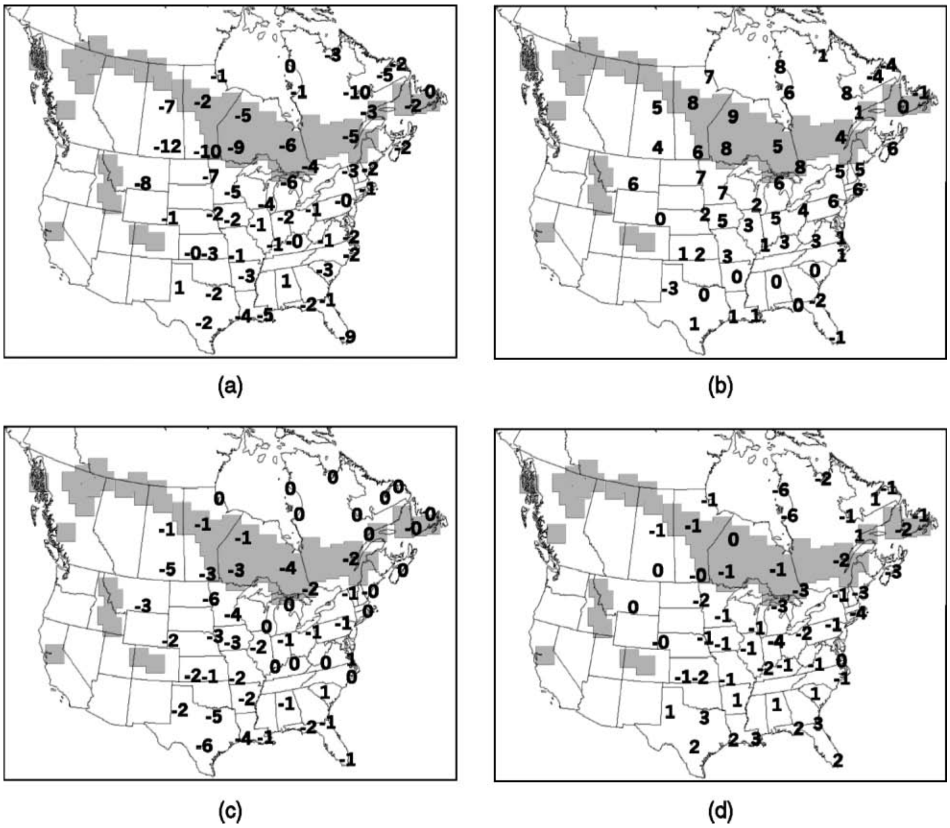


Figure 12. Difference in air mass frequency (HS – LS) for Aprils: (a) DM; (b) DP; (c) DT; (d) MM; (e) MP; (f) MT; (g) Tr. Shading represents those grid cells covered by snow during HS months and not covered during LS months

Great Plains of the USA across a large portion of southern Canada (Figure 12(e)). For stations surrounding Hudson Bay, MP frequencies are lower during HS months, possibly as a result of continued ice cover on the bay. Interestingly, MT air masses are greater during HS months across the southern one-half of eastern North America (Figure 12(f)), whereas Tr air mass days generally increase throughout the eastern portion of the continent (Figure 12(g)).

A broad area of below-normal 500 hPa geopotential heights is found across the western two-thirds of North America during HS Aprils extending eastward to another centre of below-normal geopotential heights over the Atlantic Ocean (Figure 13(a)). However, none of these geopotential height anomalies, are particularly strong. The LS months are very different, with a height anomaly dipole present over eastern North America (lower heights to the south and higher heights to the north), and a broad trough centred over the eastern Pacific Ocean (Figure 13(b)). During HS months, the rather weak atmospheric forcing does not seem to be sufficient to explain the very large changes in the air mass climatology of eastern North America. Once again, it is likely that snow-covered surfaces are responsible for diminishing air mass modification processes, allowing cold air mass types to move farther south than normal. During LS Aprils, the 500 hPa ridging found over northeastern North America leads to lessened snow cover in this area and a greater likelihood of warmer air mass types. Thus, during this month, air mass frequencies are once again responding to both atmospheric circulation anomalies and land-surface (snow cover) conditions.

4. SUMMARY AND CONCLUSIONS

This research represents an initial attempt at quantifying the effects of snow cover on air mass frequencies across a large portion of North America. The major hypothesis of this study is that large-scale snow cover

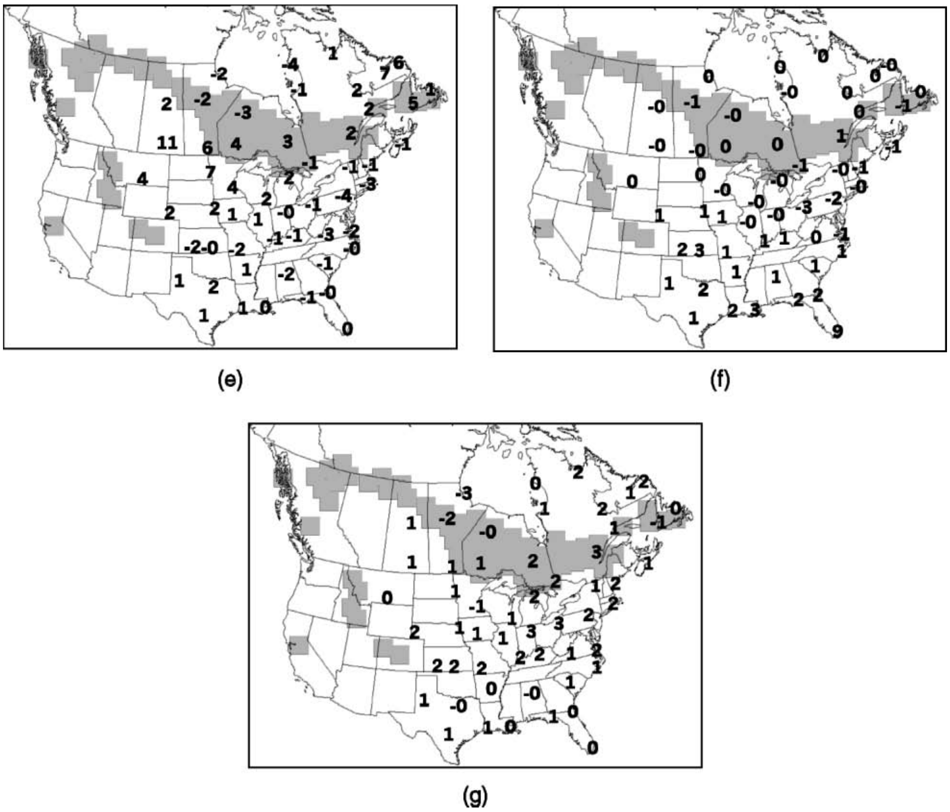


Figure 12. (*Continued*)

anomalies should influence air mass frequencies because of the their important effects on the land-surface radiation budget and on sensible and latent heat fluxes (Ellis and Leathers 1998a,b, 1999). Satellite-derived Northern Hemisphere snow cover data were used in conjunction with a new air mass classification routine developed by Kalkstein *et al*. (1998) and Sheridan (2000, 2002) to ascertain the nature of snow cover–air mass relationships. The influence of snow cover on air mass frequencies was investigated for eastern North America during the snow cover season, defined here as the period November through April. The 500 hPa circulation features were also investigated to better understand their role in snow cover/air mass frequency variations. The results of this 27 year study (1972–98) can be summarized as follows.

(1) Major snow cover anomalies are associated with changes in the air mass climatology of eastern North America for all months from November through April.
(2) Strong circulation anomalies are often associated with the snow cover anomalies and the air mass frequency changes, making it difficult to judge the relative importance of the snow cover to the observed variations in air mass frequency.
(3) There is a seasonality in the magnitude of the changes in air mass frequency during times of extreme snow cover. Generally, the largest changes in air mass frequencies are found during the months of December, January, and February, with smaller changes earlier and later in the annual cycle.
(4) During the months of November, December, January, and April, circulation patterns are present that would lead to the observed snow cover anomalies and associated air mass frequency changes. Thus, we hypothesize that snow cover anomalies (resulting from the strong circulation anomalies) help to enhance changes in the air mass climatology of the region. However, during the months of February and March there are no strong circulation anomalies apparent, suggesting that during these months snow cover may play a dominant role in air mass frequency variations.

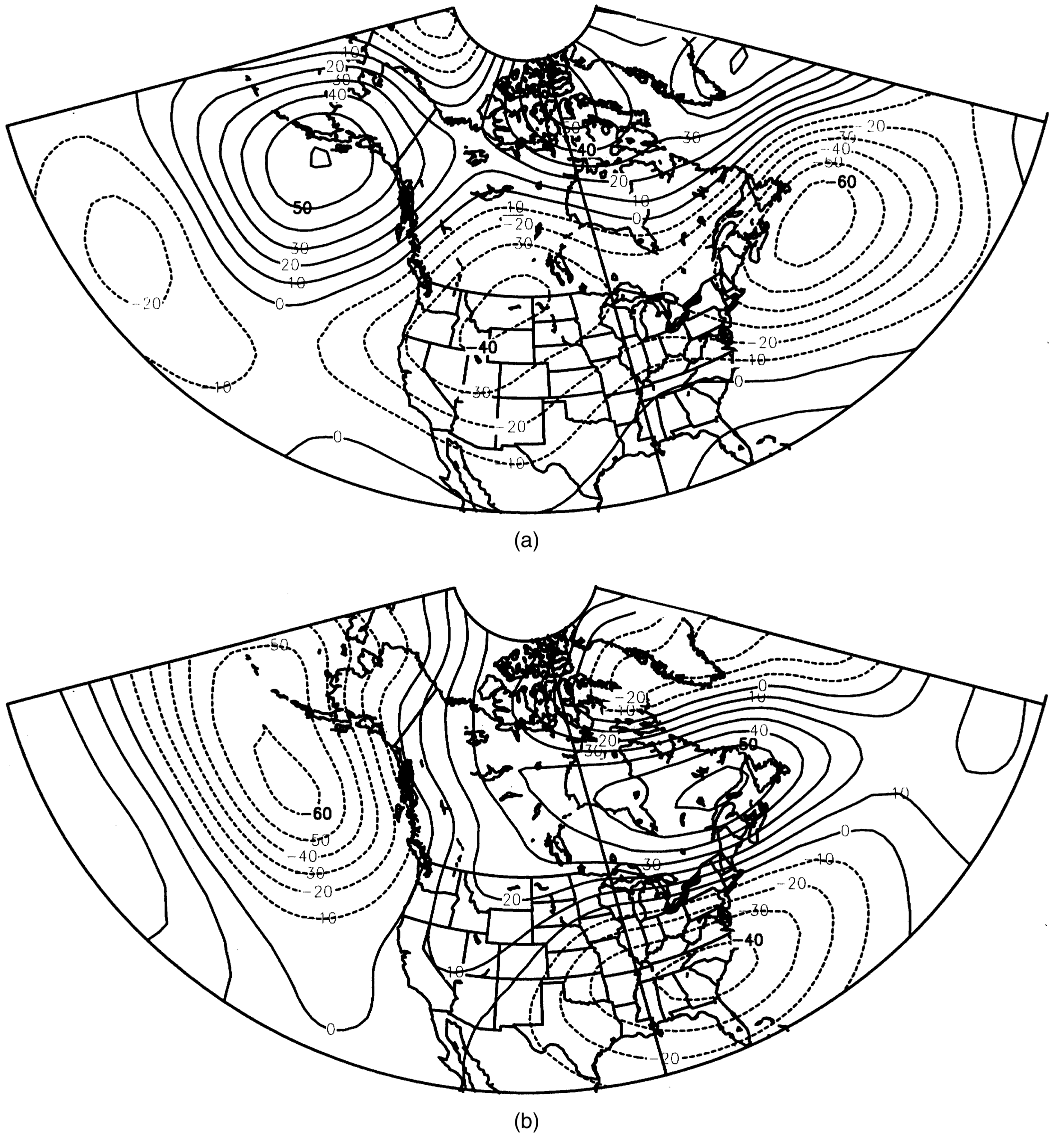


Figure 13. 500 hPa geopotential height anomaly maps for (a) HS and (b) LS Aprils. Anomalies based on the period 1968 through 1996

This research clearly indicates a strong relationship between the frequency of various air mass types and continental-scale snow cover anomalies. However, the most important finding of this study is the nature of that relationship. During the early (November, December, January) and late (April) portions of the snow cover season, large-scale circulation variations seem to be the driving force in establishing both the snow cover anomalies and the resulting changes in air mass frequency. The interaction between the circulation and snow cover anomalies is synergistic. The circulation variations are responsible for 'laying down' the snow cover, which then helps to perpetuate the circulation patterns and enhance their effects on the air mass climatology of the region.

During the months of February and March, there is no indication of persistent, strong circulation variations associated with the snow cover and air mass frequency anomalies. Thus, it is possible that pre-existing snow cover conditions are a major factor in determining both February and March snow cover and air mass frequency anomalies, at least in the absence of other strong forcing mechanisms (i.e. central Pacific sea-surface temperature anomalies). This result confirms and expands the findings of Leathers and Robinson (1993), who found that temperature anomalies across the eastern portion of the USA were more closely aligned with snow cover anomalies than with circulation variations during the month of February.

Future research into linkages between snow cover conditions and air mass characteristics should concentrate on the seasonality of the relationships. Recent findings indicating a decrease in snow cover extent during the spring months across the Northern Hemisphere and an associated increase in temperature (Groisman *et al*., 1993, 1994) that may be tied to the disposition of snow cover earlier in the annual cycle.

ACKNOWLEDGEMENTS

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