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A Case Study of the Synoptic Patterns Influencing Midwinter Snowmelt Across the Northern Great Plains

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ABSTRACT

The ability to forecast meltwater quantities is dependent upon a knowledge of the factors influencing the snowmelt process. This paper employs a hybrid modeling and synoptic climatological approach to investigate the relationship between synoptic weather patterns, surface energy fluxes, and midwinter snowmelt in the northern Great Plains. The first objective of this study is to identify distinct synoptic patterns that are associated with days where significant snow cover ablation occurred. The second objective is to evaluate the relationships among synoptic scale weather patterns, snow-surface energy transfers, and snowmelt. A case study of 21 February 1975 is used to illustrate these relationships.

Three major synoptic types, characterized by the presence of a midlatitude cyclone, are associated with large midwinter snowmelt episodes in the northern Great Plains. The case study illustrates how variations in temperature, humidity, cloud cover, and wind speeds associated with such cyclonic storms can play a major role in affecting snow-surface/atmosphere energy exchanges.

Key words: snowmelt, synoptic typing, modeling, Great Plains.

INTRODUCTION

Snow cover is present over extensive regions of the Northern Hemisphere during winter and early spring months. On average, the extent of winter snow cover peaks at forty-six million square kilometers and covers forty-six percent of the Northern Hemisphere land surface (Robinson et al., 1993). This large volume of snow influences continental scale energy and water budgets, and can substantially affect human activities. Worldwide, melting snow provides at least one-third of all water utilized for irrigation (Steppuhn, 1981). In the semi-arid Great Plains of North America, snow provides twenty to twenty-five percent of the total annual precipitation and is an especially important source of water for crop growth (Steppuhn, 1981). Rapid ablation, however, can have detrimental affects. During the late winter and early spring, it is often associated with large flood events which can threaten human life and cause significant damage to crops and other property (Steppuhn, 1981). An example of such a disaster occurred in 1997 with the severe spring flood event in the Red River Valley of Minnesota and North Dakota.

Given the importance of snow as a resource and potential hazard, much effort has gone into understanding the snowmelt process and into forecasting the timing and quantity of snow cover ablation. Studies have been conducted at a variety of levels from the microscale to the synoptic scale. Microscale studies such as those by Gold and Williams (1961), Price and Dunne (1976), Mckay and Thurtell (1978), Granger and Male (1978), Kuusisto (1986), Hong et al. (1992), and Harding et al. (1995) have focused on single locations or point sites for their respective analyses. Harding et al. (1995), however, looked at the interaction of meteorological variables, surface cover, and snow-surface energy fluxes at several sites along a transect in Greenland. They noted differences in energy exchanges in response to variations in snow cover, soil moisture, and surface roughness.

Others have looked more directly at the influence of large scale meteorological patterns. Treidl (1970) followed the passage of a warm air mass over a snow covered surface and observed its influence on

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turbulent exchange processes. He observed that as the warm, moist air mass passed over the snow cover, it underwent rapid cooling and transferred heat towards the surface in the form of both sensible and latent heat fluxes. Particularly during periods of strong winds, sensible heat fluxes from an air mass can be more important than radiative fluxes in the melt process (Grundstein, 1996; Grundstein and Leathers, 1997; Leathers et al., 1998). Several studies have examined the variation of snow-surface energy exchanges among different synoptic types. Authors such as Moore and Owens (1984), Hay and Fitzharris (1988), McGregor and Gellatly (1996), and Cline (1997) have conducted such studies in diverse areas including a New Zealand Alpine basin, the French Pyrenees, and the U.S. Rocky Mountains. Generally, most studies found that during periods of low wind speeds and low gradients of temperature and humidity, ablation was dominated by net radiation. Turbulent fluxes became more important during periods when warm, moist air was advected into the study region.

In this study, a hybrid modeling and synoptic climatological approach is employed to study midwinter snowmelt in the northern Great Plains of the United States. The first part of this study identifies distinct synoptic weather patterns that are associated with periods of significant midwinter ablation. The second part of this project uses a detailed case study to illustrate the relationships among synoptic weather patterns, snowmelt, and the snow-surface energy budget. Unlike previous synoptic scale studies which rely on single index sites for energy flux information, this study utilizes a physically based snow cover model to generate snow-surface energy fluxes for sites throughout the study region.

This paper is organized into four major sections. The first section describes the snowpack model and the meteorological data utilized in the study. The following two sections describe the methodology and results for the synoptic typing and the case study respectively. The last section integrates the first two parts of the paper and provides both a summary and concluding comments.

DATA & MODEL VALIDATION

A snowpack model (SNTHERM) was used in place of measured data to obtain snow-surface energy fluxes as well as changes in the snowpack depth due to melt. SNTHERM is a one-dimensional mass and energy balance model which was designed for use with seasonal snow covers and can handle winter meteorological conditions such as snowfall, rain, freeze-thaw cycles, and the transition between bare and snow-covered ground (Jordan, 1991). Snow and soil layers are divided into a finite number of control volumes or nodes, each of which is subject to the governing equations of heat and mass balance . New layers can be added if snow accumulates, or they can be combined as layers decrease in thickness due to melt. The surface energy balance is based on meteorologically determined fluxes of mass and energy, and includes the turbulent fluxes of sensible and latent heat, short and longwave radiation, ground heat flux, and convected heat due to snow or rainfall. The model has been successfully used in climate oriented research projects by Rowe et al. (1995), Cline (1997), and Leathers et al. (1998).

To generate surface fluxes and snowpack melt characteristics, the model must be initialized with a beginning snow depth and supplied with inputs of meteorological variables including temperature, relative humidity, wind speed, cloud cover, and precipitation. Hourly meteorological data from first order National Weather Service (NWS) stations were obtained from the NCDC surface airways CD-ROM data base. Nineteen stations, with data from 1966 to 1990, were utilized in this study (Figure 1). Some years within the data set contain only three-hourly observations. These data were interpolated to an hourly resolution using an akima cubic spline interpolation routine. Missing cloud height data were estimated using a convective cloud base scheme where the height was computed by multiplying the dew-point depression by a constant value. Initial snow depths were obtained from the Historical Daily Climate Data Set which contains long-term digitized records of daily snow cover, snowfall, precipitation, and maximum and minimum temperatures from cooperative observing stations (Robinson, 1989; Hughes and Robinson, 1996). Data from the nineteen snow cover stations which most closely matched neighboring NWS stations were utilized.

Using the snow cover and meteorological data at each of the nineteen Northern Great Plains stations, the computer model was run for Februaries between 1966 and 1990. Hourly model output of radiative and turbulent fluxes along with the daily change in snow depth were produced . Decreases in snow depth were used as surrogate values for snowmelt. Throughout this paper, these terms are used interchangeably but it must be noted that metamorphic changes in the snowpack or compaction due to overburden can also contribute to variations in snow depth. The accuracy of the modeled radiative fluxes was evaluated by comparing modeled and measured values from a site in Minneapolis, Minnesota. The measured data include average daily

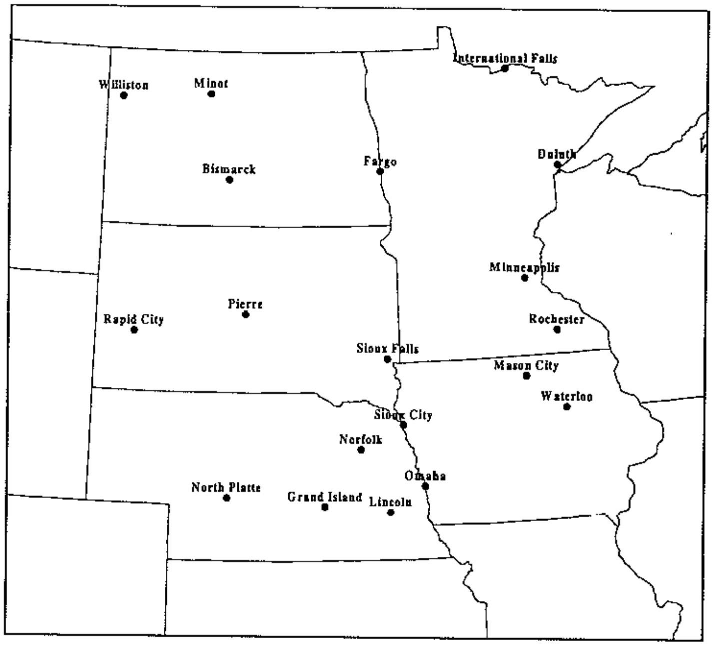

Figure 1. National Weather Service stations.

Table 1. Model evaluation statistics for snow depth (m) and radiative fluxes (Wm^{-2}): root mean square error (RMSE), mean absolute error (MAE), Pearson's correlation coefficient (R), index of agreement (D), number of sample days (N).

	Site	RMSE	MAE	R	D	N
Snow Depth	Grand Island, NE	0.04	0.02	0.88	0.93	504
	International Falls, MN	0.08	0.06	0.94	0.95	616
	Minneapolis, MN	0.07	0.05	0.95	0.96	532
	Minot, ND	0.07	0.05	0.87	0.91	616
	Rapid City, SD	0.04	0.02	0.73	0.85	420
	Sioux Falls, SD	0.05	0.04	0.92	0.92	420
Net Longwave	Minneapolis, MN	11.16	8.61	0.89	0.93	28
Incoming Solar	Minneapolis, MN	20.62	16.42	0.87	0.90	28

values for incoming solar radiation and net longwave radiation for February 1982. Model evaluation statistics indicate that SNTHERM provides accurate estimates of radiative fluxes (Table 1). The snow depth values were validated by comparing modeled snow depths from sites throughout the region with daily data from nearby cooperative observing stations. As with the radiative fluxes, model evaluation statistics indicate a close agreement between the measured and modeled values (Table 1).

The data used in the synoptic scale weather analysis were obtained from two sources. Sea-level pressures used in producing composite synoptic maps were obtained from the National Meteorological Center (NMC) grid point data set. Sea-level pressure, temperature, dew-point temperature, as well as 500-mb height data used in the case study were taken from the National Climate Data Center (NCDC) Radiosonde Data of North America data set.

SYNOPTIC PATTERNS ASSOCIATED WITH MIDWINTER SNOWMELT

Methodology

An "environment to circulation" approach, where circulation patterns are selected based on specific surface conditions, was used in determining the meteorological patterns to be studied. The synoptic patterns evaluated in this study were limited to days that had decreases in snow depth of greater than 2.54 cm (1 inch). This threshold was selected because it is indicative of a significant snowmelt episode and because it represents snow depth changes that can be measured at cooperative snow observing stations. Sioux Falls, South Dakota was chosen as a reference site for determining melt days because of its large number of years of complete data and its central location within the Great Plains study region. Twenty-one days over the 1966 to 1990 period fit the melt criteria and were used in the study.

An unrotated principal components analysis (PCA) was used to identify the major modes of surface pressure variation among the melt days (SPSS, 1986). The NMC data set contains 404 surface pressure grid points across the general area of the conterminous United States. A 404 (grid point) by 21 (day) matrix was used as an input into the PCA and seven components, explaining 85% of the surface pressure variance, were retained from the analysis. Days with similar component scores were subsequently clustered into distinct synoptic groups using Ward's minimum variance clustering method (SPSS, 1986). A three cluster solution was deemed appropriate from an inspection of the cluster analysis results. For each synoptic type identified by the cluster analysis, surface pressure composite maps were generated.

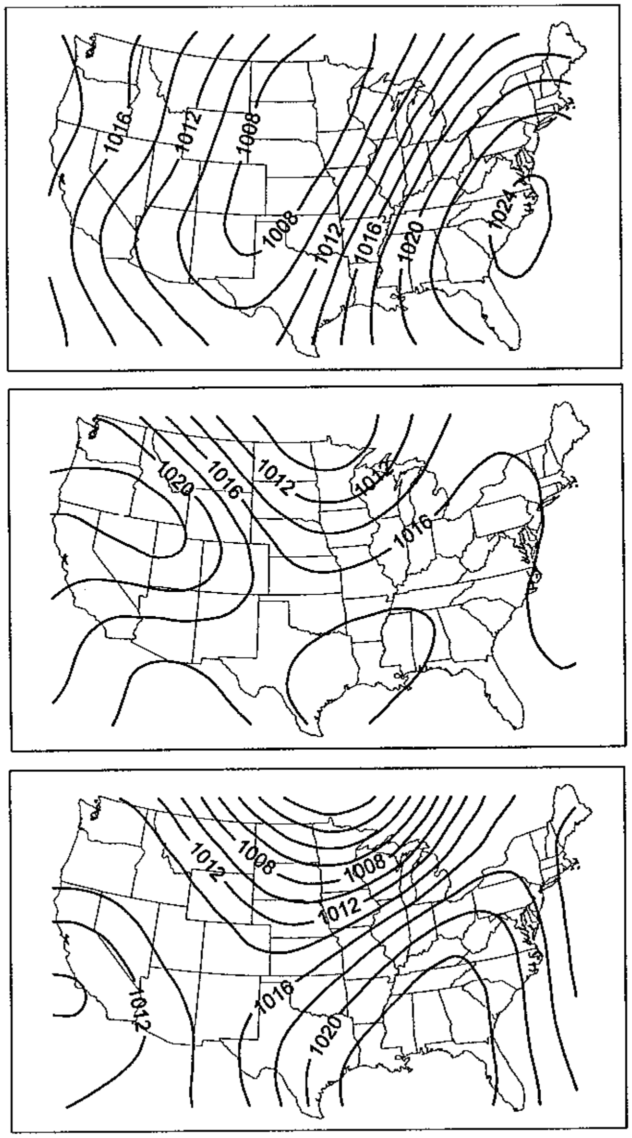

Figure 2. Synoptic weather types: a) type 1, b) type 2, c) type 3.

Results

Days with common synoptic patterns as derived from the PCA and cluster analyses were grouped together as one of three snowmelt synoptic types. The composite maps reveal distinct pressure patterns for each cluster (Figures 2a-c). Synoptic type 1 is characterized by a low pressure center over the study region and an area of high pressure over the southeastern United States (Figure 2a). The tight pressure gradient combined with strong southerly flow at the surface lead to high overall wind speeds but moderate temperature and humidity values. Synoptic type 2 has a low pressure center further north than in synoptic type 1, a high pressure area across the Western states, and a weak area of high pressure over the Gulf states (Figure 2b). Temperatures and humidities are similar to synoptic type 1 events but because of the weaker pressure gradient about the low pressure center, overall wind speeds are somewhat lower. In synoptic type 3, a high pressure area is present over the southeast and low pressure centers are situated to the north of the study region and over the pacific southwest (Figure 2c). This synoptic type has the lowest overall wind speeds of the three synoptic types but the highest overall temperature and humidity values.

Each synoptic type is associated with cyclonic activity and notable snowmelt across the study region. Despite such similarities, clear differences in meteorological parameters such as temperature, humidity, and wind speed among the different synoptic types are evident. The next question, then, is how these synoptically induced meteorological differences are linked to variations in energy transfers and snowmelt. For instance, synoptic type 1 events have high wind speeds that may aid turbulent energy exchanges but moderate temperatures. Conversely, synoptic type 3 events have lower wind speeds but higher temperatures. The following section will present a case study of a synoptic type 1 event that will be used to illustrate the relationship between the synoptic scale forcing mechanisms and the snow-surface/atmosphere energy budget.

CASE STUDY: 21 February 1975

Methodology

A case study of a single day with a significant snowmelt episode is used to depict the interactions among snowmelt, snow-surface energy fluxes, and synoptic scale weather systems. February 21, 1975 was selected for study because a large proportion of stations at that time were subject to snow depth decreases of over 2.54 cm (1 inch) and because it presents an excellent example of a synoptic type 1 event. Snow depth and snow depth change across the region were obtained from model output at each of the nineteen stations. The synoptic meteorological setting was established using surface pressure, temperature, dew-point temperature, and 500-mb heights from the NCDC Radiosonde Data set. Finally, "snapshots" at 1200 CST of regional meteorological characteristics from NWS stations and modeled surface fluxes were developed. The snow-surface energy fluxes were then compared and analyzed with regard to the prevailing synoptic pattern and its associated meteorological characteristics.

Results

February 21, 1975 presents an interesting case study of how synoptic weather conditions interact with surface conditions to influence snow-surface energy transfers and snowmelt. This day was characterized by an extensive areal snow cover and experienced a notable regional decrease in snow depth over the course of the day (Figures 3a and 3b). The prevailing surface pressure pattern is similar to synoptic type 1 where a strong low pressure center is located over the U.S.-Canadian border and a high pressure region is present over the southeastern United States (Figure 4a). A strong high pressure region is also located over the Pacific Northwest.

This pressure pattern greatly influences the surface meteorological conditions across the study region. The low pressure center combines with the high pressure region over the southeast to drive strong southerly flow at the surface which brings in warm, moist air from the Gulf of Mexico. These advections of temperature and moisture are clearly depicted in the 600 CST temperature and dew point maps as ridges in the isotherms (Figures 4b and 4c). The high pressure region over the Pacific Northwest contributes to a northwesterly circulation with brings in adiabatically warmed and dried air off the Rocky Mountains. The ascending branch of an upper level trough is located over the region and meridional flow is indicated at the 500-mb level (Figure 4d).

A regional view shows that a high percentage of cloud cover is present at 1200 CST over most of the

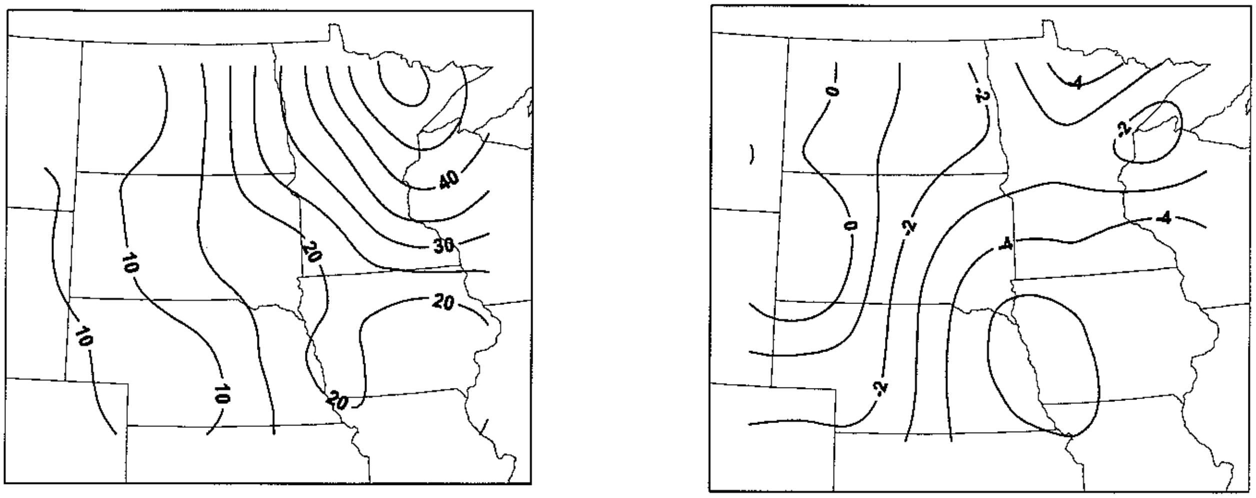

Figure 3. Snow depth (cm): a) snow depth on 21 February 1975 at 1200 CST, b) daily snow depth decrease on 21 February 1975.

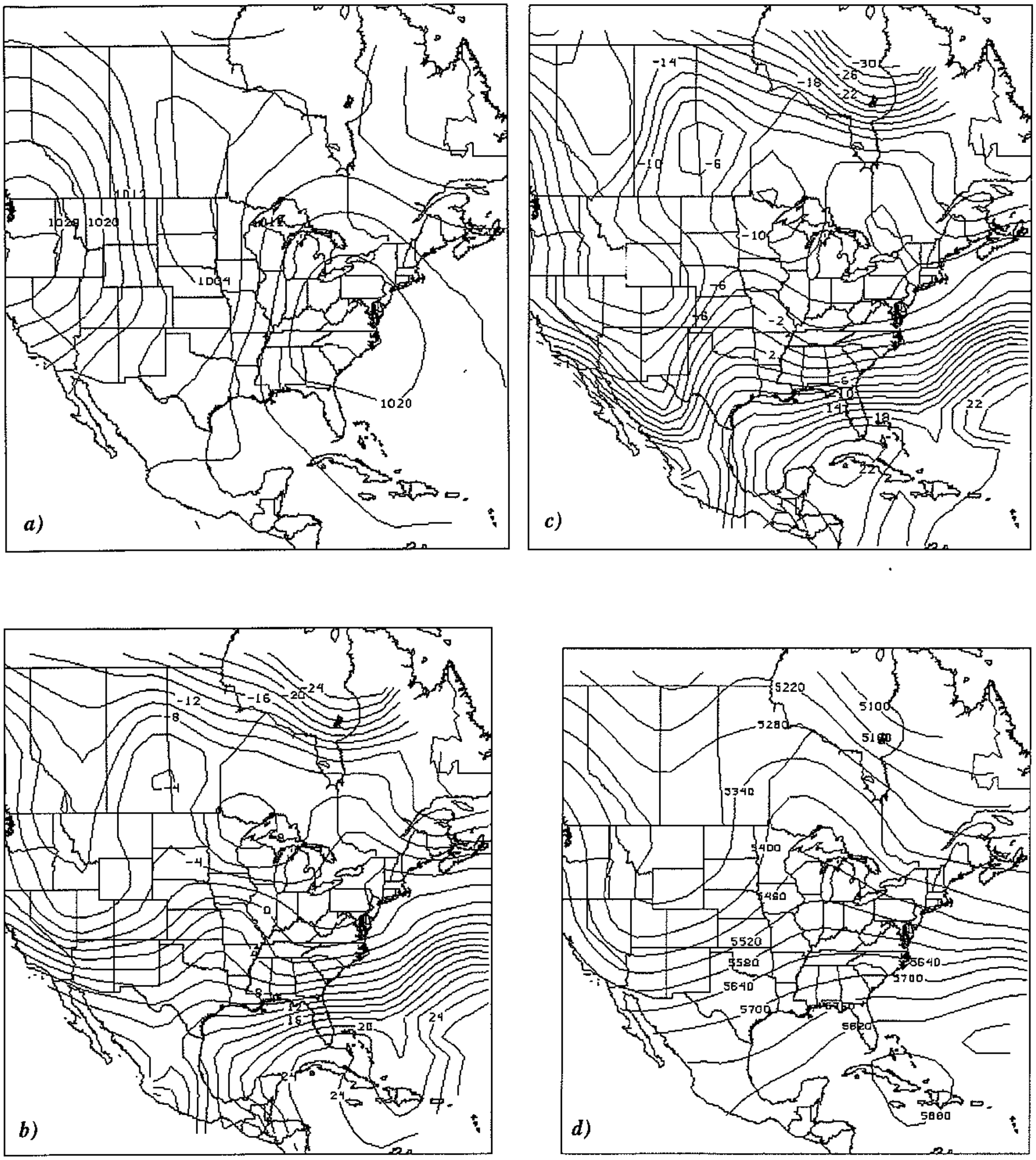

Figure 4. Synoptic meteorological variables on 21 February 1975 at 1200 CST: a) surface pressure (mb), b) temperature (°C), c) dew-point temperature (°C), and d) 500-mb heights.

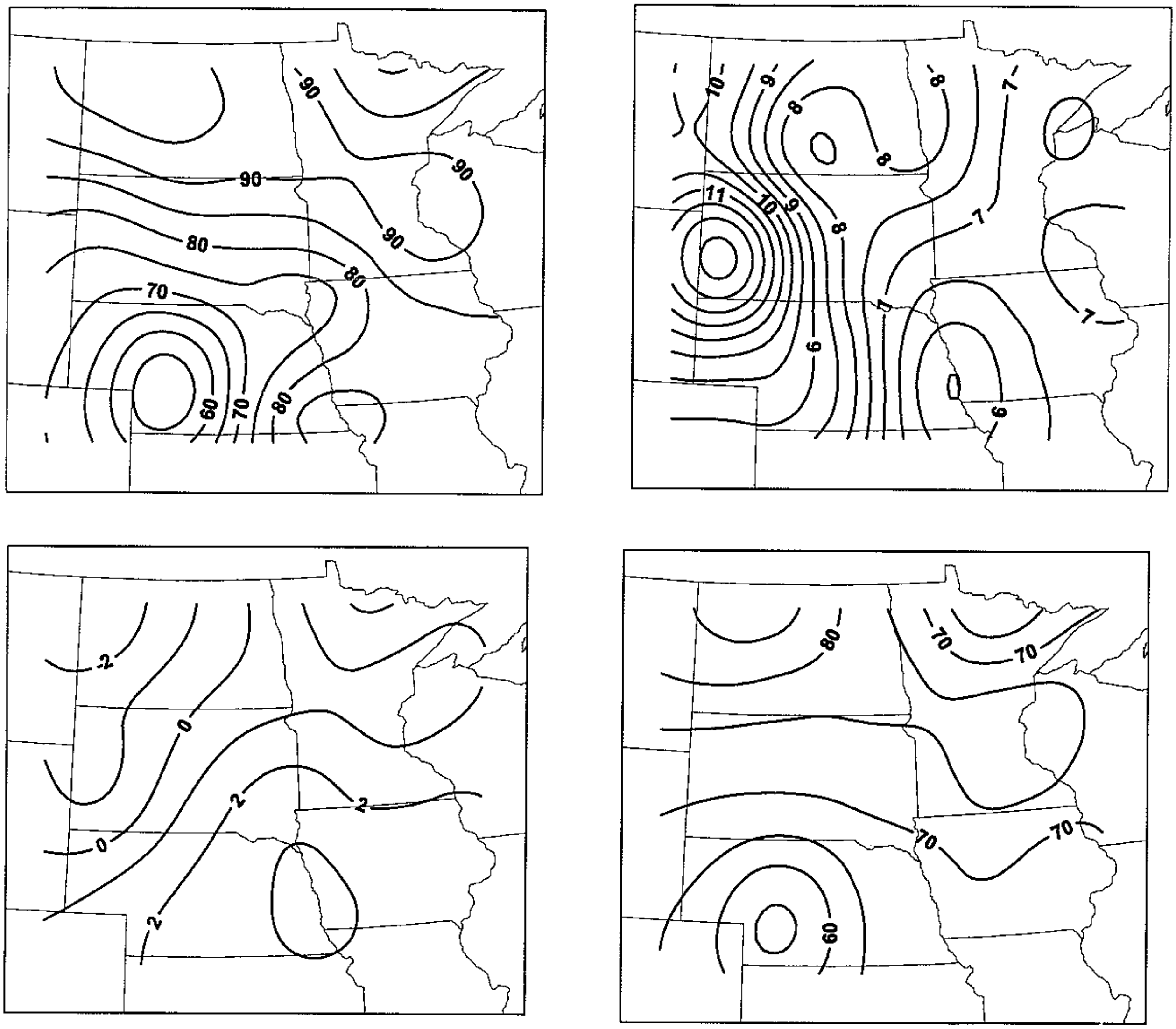

Figure 5. Regional Meteorological Variables on 21 February 1975 at 1200 CST: a) cloud cover (%), b) wind speed (ms^{-1}), c) temperature (^{0}C), and d) relative humidity (%).

area (Figure 5a). The greatest cloud cover is in the northwest quadrant near the center of the low pressure and the least cloud cover is in the southwest quadrant. High wind speeds are prevalent across the region in response to the strong pressure gradients. Peak wind speeds at 1200 CST, however, are found in the western portion of the study area and are associated with the passage of the cold front (Figure 5b). The regional temperature map clearly delineates both the cold front which is moving southeastward across the Dakotas and the warm front which is pushing northeastward across Nebraska and Iowa (Figure 5c). Below freezing temperatures are present behind the cold front while slightly above freezing temperatures are found in the warm sector. The relative humidity map shows that the lowest values are centered over North Platte and International Falls while somewhat higher relative humidities are located over the northwestern portion of North Dakota (Figure 5d).

A "snapshot" of the surface energy fluxes at 1200 CST reveals a close relationship with the prevailing surface meteorological conditions. Cloud cover plays a key role in influencing both net solar and net longwave radiative exchanges. Net solar radiation values are generally small across the region due to the high albedo values of the clouds and snow cover (Figure 6a). The greatest net solar radiative fluxes, however, occur in regions such as the southwest quadrant where the cloud coverage is least extensive. Throughout the study area, net longwave radiation values are negative and directed away from the

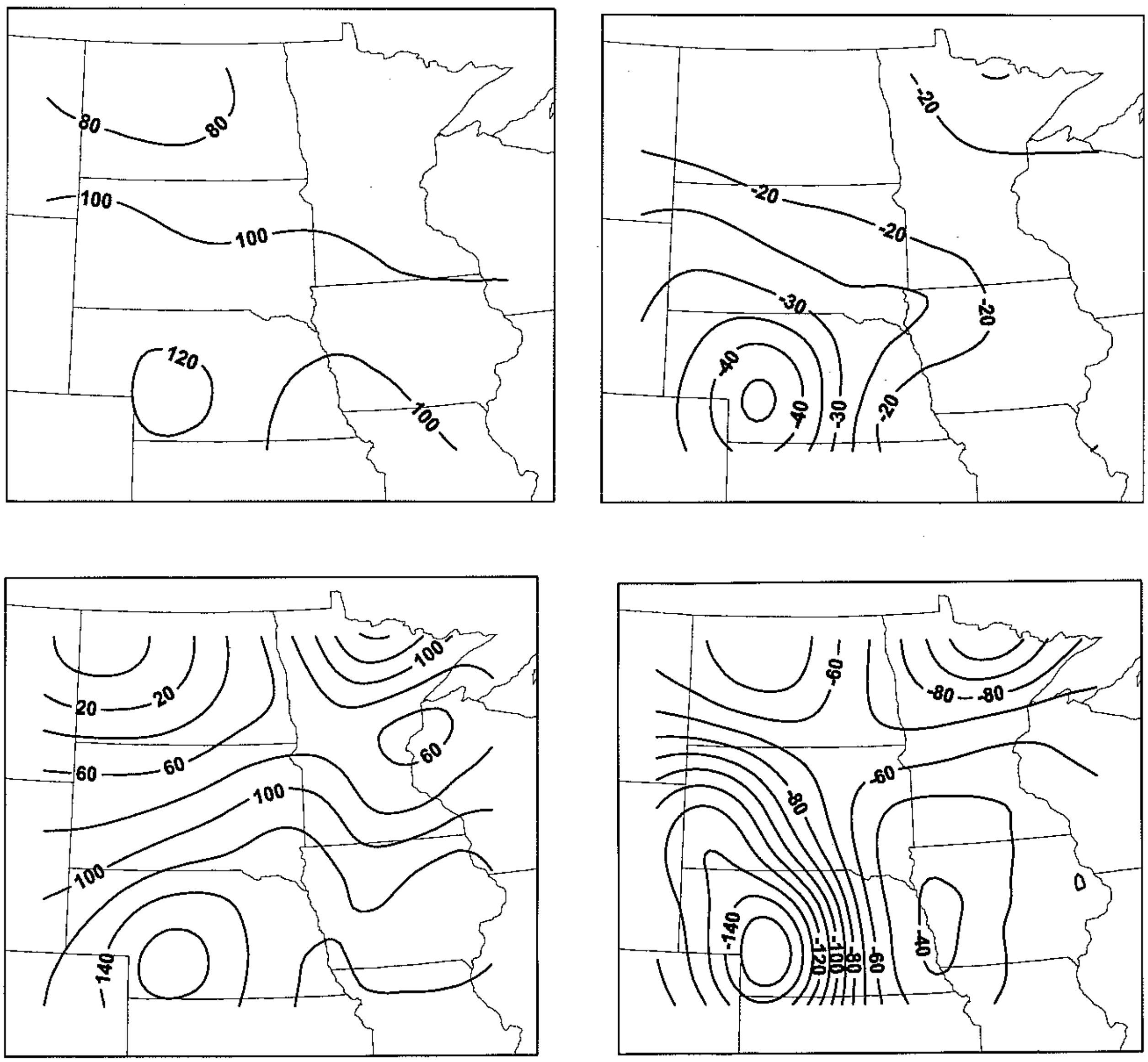

Figure 6. Regional snow-surface energy fluxes (Wm^{-2}) on 21 February 1975 at 1200 CST: a) net solar radiation, b) net longwave radiation, c) sensible heat, and d) latent heat.

surface (Figure 6b). These values are generally small due to the high percentage of cloud cover which reduces losses of outgoing longwave radiation. The greatest net losses of longwave radiation are in the southwest quadrant where the cloud cover is most sparse.

Fluxes of sensible heat and latent heat are most influenced by surface meteorological conditions such as air temperatures, humidity gradients, and wind speeds. Over the whole region, the flux of sensible heat is directed downward from the atmosphere to the snowpack (Figure 6c). The greatest transfers of sensible heat occur in the southwest quadrant where high wind speeds combine with above freezing temperatures (Figures 5b and 5c). Moderate wind speeds and below freezing temperatures in the northwest corner of the study region contribute to small transfers of sensible heat.

During periods of snowmelt, evaporation of meltwater and/or sublimation contribute to an outward directed flux of latent heat (Figure 6d). Variations in humidity gradients and wind speeds influence the magnitude of the energy loss. Peak transfers of latent heat occur in the southwest quadrant and over northern Minnesota. In these areas, lower relative humidities are combined with high wind speeds to assist the evaporation/sublimation process (Figures 5b and 5d).

The smallest latent heat fluxes are found in areas with smaller humidity gradients and/or lower wind speeds. For instance, the smallest transfers of latent heat are found over eastern Nebraska where the slowest wind speeds are present. Areas in the northwest quadrant of the study region also have smaller exchanges of latent heat. At these locations, the smaller values are associated with the higher relative humidities which suppress evaporation/sublimation by reducing the snow-surface to atmosphere humidity gradient. Interestingly, since evaporation and sublimation are energy consuming processes, they tend to cool the snowpack and may reduce the amount of ablation that would otherwise have occurred.

SUMMARY & CONCLUSIONS

The transfer of energy from synoptic scale circulation patterns to the surface provides an important source of energy for snow cover ablation. Despite its importance in the snowmelt process, little research on this topic has been conducted. Most previous snowmelt research has been empirical in nature and has focused on the microclimatic relationships between snowmelt and the surface energy budget. Others have examined the relationship between snow cover ablation and the surface-energy budget on a larger scale, but in most cases have used only a single index site to study the transfer of energy. This paper examines the transfer of energy from the synoptic scale to the snow cover over a larger spatial scale by using modeled energy fluxes in lieu of difficult to obtain measured values.

Large midwinter melt episodes in the northern Great Plains can be explained by three major synoptic types. All three are characterized by a low pressure center located over or near the study area and the advection of relatively warm air into the region. A case study of a synoptic type 1 event provides an example of the interrelationships among snowmelt, snow-surface energy transfers, and synoptic weather conditions. The passage of a midlatitude cyclone with its constituent low pressure center and frontal zones is associated with changes in cloud cover, wind speed, temperature, and humidity across the region. Spatial differences in these meteorological variables have a distinct influence on snow-surface energy transfers across the region. Variations in cloud cover over the study area greatly influenced both longwave and shortwave radiative fluxes. Those areas with more cloud cover, for instance, had reduced insolation values but also smaller losses of outgoing longwave radiation. Interactions between wind speed and temperature or humidity were especially important in determining the magnitude of latent and sensible heat fluxes. Areas with both high wind speeds and temperatures had larger transfers of sensible heat towards the snowpack. Similarly, portions of the study region with the highest wind speeds and humidity gradients had the largest exchanges of latent heat.

The relationship between synoptic forcing and snowmelt was only studied in detail for a single day. A more extensive study by Grundstein and Leathers (Submitted) documents several examples of how synoptic forcing influences snow-surface energy exchanges. Future research will attempt to establish more general relationships between synoptic scale meteorological variables, snow-surface energy fluxes, and snowmelt. For instance, composite maps could be constructed for each of the above variables and studied for relationships between particular synoptic types and certain patterns of energy transfers. Establishing such relationships could be very useful in snowmelt forecasting because the more readily available meteorological data could be used to make inferences about the pattern of energy transfers and therefore the pattern of snow cover ablation.

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