A MODEL BASED ANALYSIS OF THE SYNOPTIC AND MESOSCALE PROCESSES ASSOCIATED WITH SUBSIDENCE INTO WESTERN GREAT LAKES WILDFIRE ENVIRONMENTS

By

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ABSTRACT

Meteorological assessment of dangerous wildfire environments has traditionally involved the identification of specific synoptic weather patterns empirically determined to be associated with wildfire development and spread. Specifically, in the Great Lakes region, high wildfire danger is often witnessed in association with 500 hPa ridges and surface high pressure systems. Such synoptic scale flow is regularly associated with large scale subsidence, adiabatic warming, drying of mid-tropospheric air from mid-levels as well as surface anticyclogenesis. In this thesis the notion that the 3-D circulations associated with surface anticyclogenesis can play important roles in promoting wildfire development and spread is advanced through observations and interrogation of the output from numerical model simulations of four large fires in the western Great Lakes region. This 3-D flow begins downstream of upper level ridge axes and provides: 1) large scale subsidence and drying that leads to the development of reservoirs of dry air just above the Planetary Boundary Layer (PBL), 2) the associated clockwise circulations that provide the means to advect the subsided air toward the fire environment. In addition, specific meso and microscale boundary layer processes must operate in order that mixing of the reservoir of dry air to the surface can lower the near surface relative humidity.

The Mack Lake Fire, Ham Lake Fire, Black River Falls Fire, and Pinery Fire all had synoptic evolutions that differed from those identified in prior studies which also identified large scale subsidence as a key physical process involved in the development of the wildfire environment. The results of this research suggest that identification of 3-D circulations associated with surface anticyclogenesis can help in predicting future high wildfire danger and the development of large fires in the western Great Lakes region. Based upon the results of this research further case studies are suggested to confirm the results and to create a climatology of how often these basic circulatory elements of mid-latitude anticyclogenesis are associated with western Great Lakes fire environments.

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Chapter 1. Introduction

Wildfires are costly and dangerous phenomena that can damage not only valuable wilderness areas but also residential dwellings and larger communities. Because of the threat they pose to society, considerable intellectual effort has been expended concerning theories of fire suppression and on understanding the variety of physical factors and environmental scenarios that conspire to produce the wildfire environments. An overview of the recent developments regarding fire suppression in the United States can be found in Omi (2005). Other resources are Chandler (1983), Donoghue (1984), Pyne (1984), and the Review and Update of the 1995 Federal Wildland Fire Management Policy (2001).

The concept of fire danger is directly tied to the problem of diagnosing the physical factors leading to wildfires. One of the most accepted definitions of fire danger was formulated by Deeming et al. (1972) - “The resultant descriptor of the combination of both constant and variable factors which affect the initiation, spread and difficulty of control of wildfires on an area.” Among the “variable factors” are fuels, weather, topography and risk. The most variable of these several factors is the weather. This thesis will examine the manner in which synoptic and mesoscale aspects of the weather influence the pre-fire environment in ways that are conducive for the development and maintenance of significant wildfires.

a. Background

The studies by Byram (1954), Schroeder et al. (1964) and Hull et al. (1966) are among the seminal studies in fire weather. Byram (1954) examined the connection between different weather factors and explosive wildfire growth; what he termed “blowup” fires. He concluded that dry fuels, atmospheric instability, high wind speed at low levels, and decreasing winds with height were the significant weather factors.[1] Another study of consequence with respect to fire weather was a brief paper by Shafer (1957) detailing a correlation between wildfires and the jet stream location. This study was one of the first to tie synoptic-scale atmospheric phenomena to the occurrence of wildfires, though it failed to explain the physical connection between jet stream location and the development of atmospheric conditions conducive to the initiation and maintenance of significant wildfires.

Schroeder et al. (1964) and Hull et al. (1966) instead focused their research on patterns of 500 hPa height and sea level pressure fields associated with high fire danger days in certain regions and how often these specific types of 500 hPa height and sea level pressure patterns occurred. They found that in different regions of the United States, fire danger was associated with different synoptic weather patterns. For the “Lake States Region” - comprised of northeastern Minnesota, Wisconsin, Michigan, and northern portions of Illinois, Indiana and Ohio- four out of five types of surface high pressure systems were identified as related to the days of high fire danger (Fig. 1.1). The first weather type was the Hudson Bay high type which moved southeastward into the region with high fire danger on the south or northwest side of the high. The second type was the Northwest Canadian high which moved in a similar direction to the Hudson Bay high but originated in Northwest Canada and the high fire danger occurred either on the eastern side to the rear of the surface cold front, the southern side, or the northwestern side of the high. The other two types were referred to as

[1] In the same study Byram makes a contradictory statement that lower wind speeds at low levels may also to lead to dangerous fire environments.

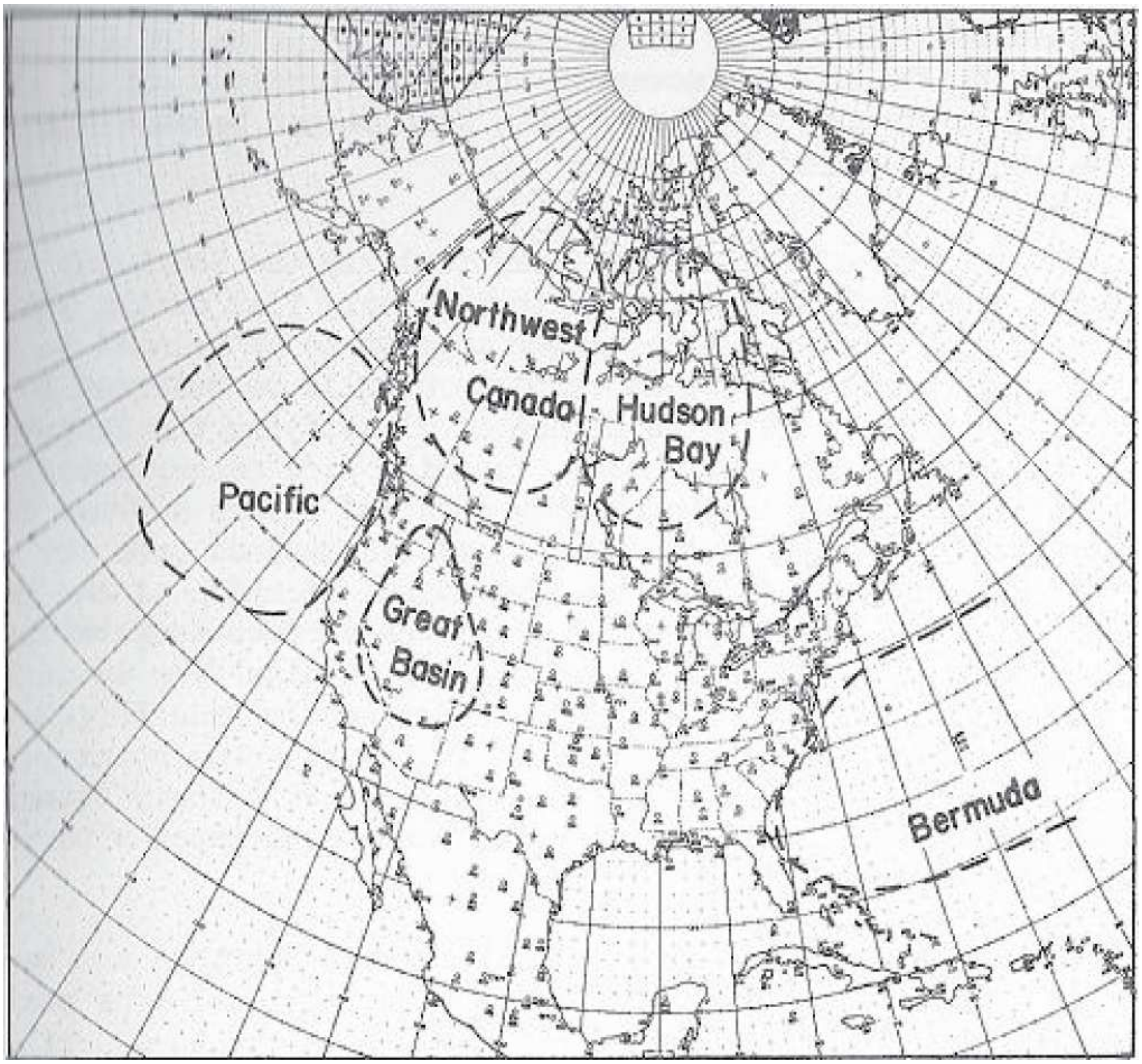

Figure 1.1. The places of origin for the five types of surface high pressure systems related to high fire danger in different regions of the United States. From Schroeder et al. (1964).

the Pacific high and Bermuda high. High fire danger occurred on the north and east sides of the Pacific high. High fire danger in the Bermuda high occurred in the pre-frontal warm sector or in an area of an enhanced pressure gradient as a surface pressure trough passed to the north in Canada. All of these types were associated with northwesterly flow aloft (i.e. at 500 hPa) over the Great Lakes at some point in the days both before and after the fire began. One of the problems with these two studies is that there is no explanation of the origin of the specific type of surface high pressure system leading to high fire danger in the region.

Building upon this work were the studies by Brotak and Reifsnyder (1977), Nimchuk (1983) and Heilman (1995) which examined the synoptic patterns associated with case studies of actual wildfires as opposed to simply identifying high fire danger days. Brotak and Reifsnyder (1977) examined major fires (>5000 acres) in eleven out of the thirty-seven states east of the Rocky Mountains. They examined the synoptic surface features that occurred within 24 hours of any part of the fire duration. This meant that one fire could be associated with more than one type, especially if the fire was of long duration. They found that relatively rare synoptic conditions attended the vast majority of the fires (e.g. such conditions appeared only about 6 percent of the time in two years they looked at). This suggested to them that forecasting these rare atmospheric conditions would significantly aid in preparing for large fires. Though they considered a non-representative sample, they found that half the fires they investigated occurred following the passage of a dry cold front, while 25 percent occurred *prior* to a cold frontal passage, 12 percent occurred in the warm sector of a surface low pressure system, 5 percent in the warm sector of a surface high pressure system far from any surface fronts or low pressure areas and 5 percent in a category of “other” not associated with the other four types. The study also noted that most of the fires occurred in the southeast portion of small amplitude but intense 500 hPa troughs simultaneously associated with strong, dry winds at 850 hPa.

A similar emphasis on synoptic weather types characterized the study by Nimchuk (1983) who determined that the breakdown of a series of 500 hPa ridges during the late summer of 1981 led to dangerous wildfires in Alberta on the eastern side of the Rocky Mountains. His analysis focused on the conditions characteristic of the lower to middle troposphere under an upper ridge: surface high pressure with warm temperatures, low relative humidity, little precipitation, light winds, and strong static stability. He showed that, although the breakdown of the upper ridge and subsequent progression of an upper trough often relaxed the fire danger, the period preceding the passage of the surface low pressure system can be a period of increased fire danger characterized by stronger winds, higher temperatures, continued low relative humidities and fuels dried by the conditions associated with the antecedent upper ridge. Heilman (1995) continued the trend of trying to associate certain circulation patterns with the occurrence of large wildland fires (>1000 acres) by looking at Empirical Orthogonal Functions of 500 hPa geopotential height anomalies[2] at 1200 UTC on the day of a fire. In addition, Heilman (1995) looked at the associated temperature (at 850 hPa) and relative humidity (surface to 700 hPa) anomalies present at 0000 UTC on the day of the wildland fires in the specific regions. Unlike the study of Schroeder et al. (1964), Heilman (1995) split the U.S. into only six regions and grouped northeast Minnesota into the North-central region while placing Wisconsin and Michigan in the Northeast region. For Wisconsin and Michigan he found two 500 hPa patterns to be

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[2] The anomalies were calculated by subtracting the monthly mean from the daily 500hPa geopotential height at 1200 UTC.

significant. One was a prominent trough over the eastern United States which brought cool dry air to parts of the Northeast and the other was a strong ridge over the eastern United States bringing warm, sometimes drier, air to the region. For the North-central region, which included northeast Minnesota, he found that one of three 500 hPa patterns; 1) a strong ridge over the central Plains of the U.S., 2) a strong ridge over the eastern U.S. bringing southwesterly flow to the northern Great Plains or 3) a strong ridge over the western U.S. bringing northwesterly flow to the northern Great Plains dominated. The first two patterns brought higher temperatures and lower relative humidities to much of the region, while the last circulation pattern brought somewhat cooler and drier air. Some of the problems with this study include that the different circulation patterns sometimes brought conflicting conditions to different parts of the identified regions and that the anomalies of the height field were determined at 1200 UTC, while the temperature and humidity anomalies were determined at 0000 UTC. Unfortunately, the location of the fires within the synoptic patterns was difficult to assess and more importantly, the connection between the fires and physical processes associated with the synoptic weather patterns was not identified.

Since the early 1990’s with the advent of more sophisticated computational, remote sensing, and modeling tools, there has been an expansion in fire weather research. As a result of this increased research activity, new conceptual models and updated meteorological composites have been produced to complement prior understanding attained through identification of synoptic weather types. Potter (1996) compared surface air temperature, humidity, and wind speed, lower atmospheric stability, and near surface wind shear[3] on fire

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[3] These variables have been suggested to influence the wildfire environment as discussed in the studies of Byram (1954), Brotak and Reifsnyder (1977), Deeming et al. (1977) and Haines (1988).

days versus non-fire days from upper air stations (none in the Great Lakes region). He found that surface temperature, dewpoint depression and relative humidity were the only variables that significantly differed between fire and non-fire days and even this was not the case at all stations. Some of the lack of coherence in his study may have arisen from the fact that his observations were sometimes as much as 500 km away from the fire location and thus may not have been a representative sample.

More recent studies, have identified specific meteorological processes or structures with a direct influence on the given wildfire environment. For instance, Charney et al. (2003) examined the influence of a low level jet affecting the Mack Lake fire environment. Though they did not examine the life cycle of the low level jet in their study, they correctly appealed to output from a numerical model as a means to that end. An example of a conceptual model in the tradition of Schroeder et al. (1964), Hull et al. (1966) and Brotak and Reifsnyder (1977) was recently offered by Lindley et al. (2007). They used high resolution model data to create a composite of the average meteorological conditions affecting wildfires that occurred in the dry winter of 2005/2006 in the Southern Plains of the U.S. They found that the fires were related to the passage of mid-latititude cyclone and associated wind maxima, intense low level cyclogenesis to the north of the fires, and deep mixing in the planetary boundary layer which conspired to render the surface air warm and dry in the region of interest. The composite by Lindley et al. (2007) connected a specific atmospheric situation to the production of warm and dry air in the region of interest, but like many previous studies they failed to specifically detail the processes through which this connection was achieved.

Another recent study by Zimet et al. (2007) examined the role of upper level fronts and frontogenesis to the production of dry air in the vicinity of the Mack Lake fire (1980).

Finally, two more recent studies by Kaplan et al. (2008) and Huang et al. (2009) followed the example set by Zimet et al. (2007) by attempting to attribute specific dynamical processes to the development of individual fire environments. Kaplan et al. (2008) discerned a process operating in a New Jersey wildfire environment where an initial drying following a surface cold front eventually combined with very dry air descending under the right exit region of the polar jet streak. Huang et al. (2009) discerned a similar but more complicated three stage process involving the coupling of an exit region of an upper level polar jet streak and high pressure ridge after the passage of a dry cold front. Once the front passed, the synoptic scale subsidence strengthened and surged toward the surface where it coupled with meso-beta subsidence in the lee of the Sierra Nevada Mountains to help produce the very warm and dry air in the region of very large southern California wildfires of 2003.

b. Thesis objective

Most of the previous studies have identified certain synoptic patterns that are related to fire danger or fire development, without identifying the physical connections between these patterns and their associated dynamical processes in producing atmospheric conditions that are conducive for the initiation and spread of large fires. A common theme in the various studies just described is that an upper ridge (near 500 hPa) and surface anticyclone affect Great Lakes fire areas in the days leading up to the fire events. This thesis will show that upper ridges and surface high pressure systems are components of a 3-D circulation system that simultaneously desiccates the air via synoptic scale subsidence and horizontally advects dry air from remote source regions that is then mixed into the wildfire environment. The subsidence ingredient is somewhat similar to that identified previously in the studies by Zimet et al. (2007), Kaplan et al. (2008), and Huang et al. (2009). The difference is that the subsidence is not always the result of frontal or post-frontal circulations. This thesis will also show that in order for the synoptic scale dry air reservoir, produced by the subsidence, to be of any consequence in the wildfire environment, smaller scale mixing processes, forced by diabatic heating or turbulence, must be involved. Through the consideration of several different wildfire cases in the western Great Lakes, the 3-D circulation system just described will be shown to be influential in creating dangerous wildfire environments.

The thesis is organized as follows; Chapter 2 will provide an overview of the data and methodology used for analysis in the case studies. This will include any definitions necessary and an overview of the numerical model used. Chapter 3 will introduce each case study separately. For each case study there will be a description of the fire behavior, an overview of the general atmospheric and vegetation conditions preceding the fire and a synoptic description of the conditions antecedent to and during the fire. Then output from numerical model simulations will be analyzed to show: 1) how the reservoir of mid-level dry air was produced by synoptic scale processes, and 2) which processes were involved in mixing that air down to the surface near the wildfire. Finally, at the end of each case a summary of the important findings along with discussion of the results in the light of previous studies will be offered. Chapter 4 will provide a broad summary of the case studies and will include some thoughts for future directions in fire weather research.

Ch 2. Data and methodology

This study will particularly focus on historic wildfires that have affected the western Great Lakes region of the United States, specifically the states of Minnesota, Wisconsin, and Michigan. As indentified previously by Davis (1959), Schroeder et al. (1964), Chandler et al. (1983), Pyne (1984) and Heilman (1995) the forested regions of northern Minnesota, Wisconsin, and Michigan (both upper and lower) exhibit similar climatic, topographical, and terrestrial features. Similar features lead to similar wildfire behavior, size, and other characteristics. This is supported by the current divisions of different U.S. fire suppression organizations [i.e. Eastern Area Coordination Center (EACC) , The Great Lakes Forest Fire Compact (GLFFC), U.S. Forest Service- Eastern Region (USFS)], all of which group northern Minnesota, Wisconsin, and Michigan in the same region.

All of the fires examined here are wildfires that burned in forested regions with similar fuels (types of trees, plants, and vegetation). A wildfire is defined by the National Wildfire Coordinating Group (NWCG) as:

> "An unplanned, unwanted wildland fire including unauthorized human-caused fires, escaped wildland fire use events, escaped prescribed fire projects, and all other wildland fires where the objective is to put the fire out." (Interagency Strategy for the Implementation of Federal Wildland Fire Management Policy, p. 19)

In a similar fashion the NWCG defines a wildland fire as:

> "Any non-structure fire that occurs in the wildland." (Interagency Strategy for the Implementation of Federal Wildland Fire Management Policy, p. 19)

Even though wildland fires are defined to be non-structure fires, the amount of land consumed when structures burn, and the associated costs, are grouped into the wildfire category for recording purposes by the National Interagency Fire Center (NIFC) and the National Interagency Coordination Center (NICC). As a result we will use the term "wildfire" to describe the fires examined in this thesis, even though all the fires at one time or another affected some type of existing structure. Any reference to statistics will, therefore, reference only wildfires. The other types of wildland fires; prescribed fire and wildland fire use (i.e. when naturally ignited fires are not suppressed and used for a benefit), are ignored. Finally, while the ignition factors[4] for the wildfire are important, the degree of subsequent wildfire growth, and therefore of overall fire danger, is most substantially tied to the antecedent and current meteorological conditions.

This thesis will investigate the detailed synoptic and mesoscale structures and processes characterizing previously identified "fire weather patterns" (Schroeder et al. 1964, Hull et al. 1966, Brotak and Reifsnyder 1977) that are thought to be conducive to dangerous fire environments in the western Great Lakes region. The central goal is to elucidate specific processes involved in rendering these patterns dangerous as in the studies of Charney et al. (2003), Zimet et al. (2007) and Kaplan et al. (2008). This goal will be pursued through the detailed interrogation of three recent fires that have occurred in this area along with a similar fire from 1980. Four other recent fires since 1999 were studied, but are not detailed in depth in this thesis. Two of the fires not examined in depth had similar evolutions to at least one of the four fires that were interrogated, while the other two did not fit the hypothesis and/or had

[4] In addition, most wildfires are caused by humans in the area examined with less then 3 % being caused by lightning (NIFC, statistics going back to 2001)

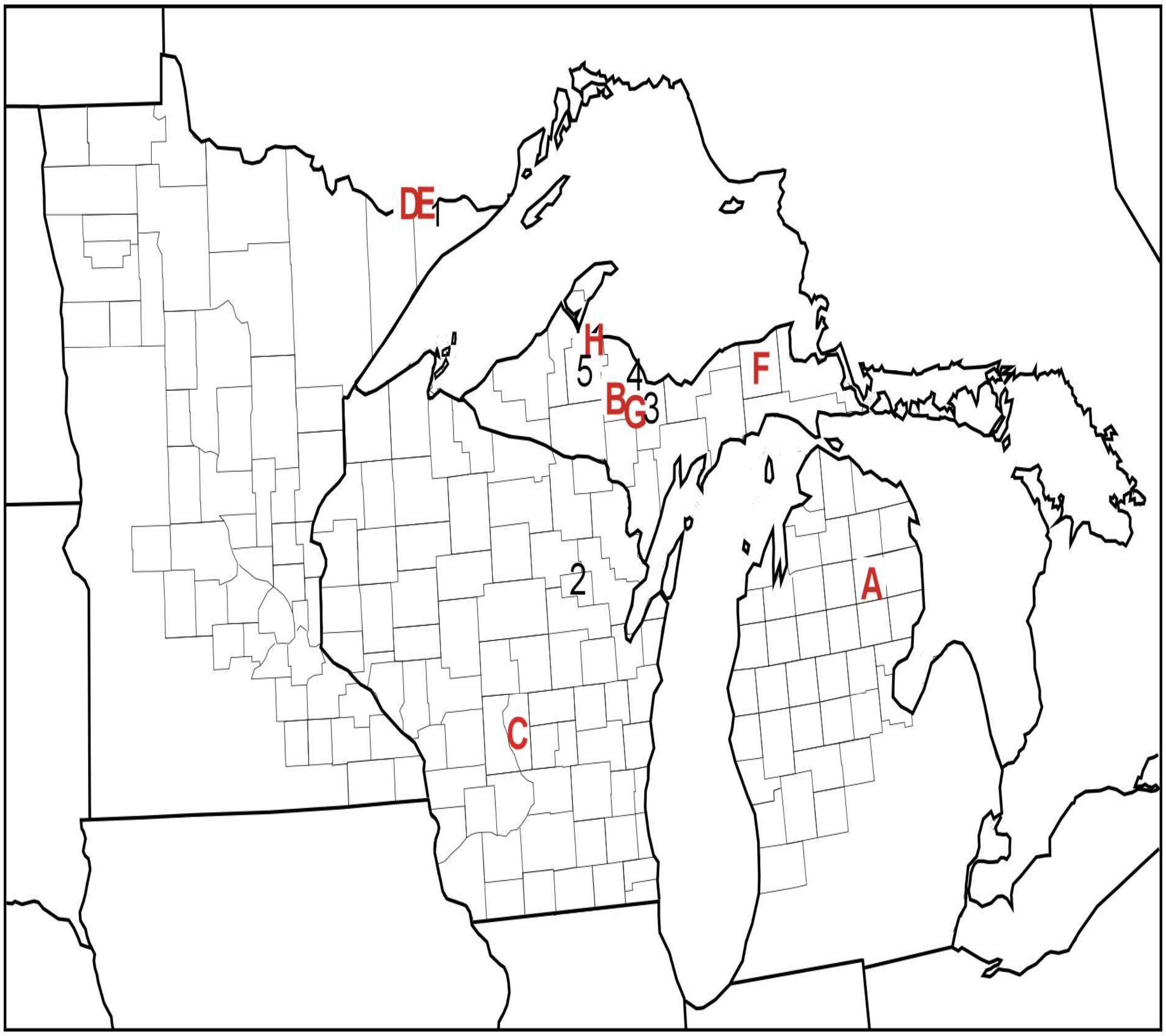

Figure 2.1. Locations of fires in red lettering. Letter A is the Mack Lake Fire, 5 May 1980. Letter B is the Tower Lake Fire, 2 May 1999. Letter C is the Cottonville Fire, 5 May, 2005. Letter D is the Cavity Lake Fire, 14 July 2006. Letter E is the Ham Lake Fire, 5 May, 2007. Letter F is the Sleeper Lake Fire 2 August 2007. Letter G is the Black River Falls Fire, 20 May, 2009. Letter F is the Pinery Fire, 20 May 2009.
Locations of station observations received from MesoWest in black numbering. Number 1 is the Seagull Remote Automated Weather Station (RAWS) owned and maintained by the U.S. Forest Service. Number 2 is the Antigo RAWS (Bureau of Land Management). Number 3 is Marquette, Sawyer International Airport Automated Service Observation Station (ASOS) (National Weather Service). Number 4 and 5 are the Negaunee and L'Anse Cooperative Weather Observers (CWO).

incomplete information. The locations of all the fires are shown in Fig. 2.1. All eight of these fires were large fires, with the two smallest burning between 500-1000 acres each, two others burned between 2500 and 10,000 acres, and four burned well over 10,000 acres. Large fires are defined by the NICC as wildfires that consume a minimum of 100 acres in timber fuel types or 300 acres in grass and brush fuel types (National Mobilization Guide, p. 69). Most of the fires examined were the largest in many years in their respective states. Using data from NICC and NIFC the studied fires accounted for 118,966 acres of land with the fires from the beginning of 2005- 13 July 2009 affecting 91966 acres of land. Since acreage statistics by states were not available before 2002, any subsequent reference to percentages describes only those fires that occurred from the beginning of 2005- 13 Jul 2009. The 91966 acres, which is small compared to the tens of millions of acres burned in the entire United States during this period, accounts for 27 percent of the total acres burned in the states of Minnesota, Wisconsin, and Michigan during this period. So while the number of acres may not be a lot in terms of the entire United States (the fact that these three states are only 7 percent of total U.S. land must also be considered (U.S. Census Bureau)), the fires studied do constitute a large portion of the historical acreage burned in the area of the western Great Lakes and thus are a good representative sample for making conclusions on patterns and processes that affect large western Great Lakes wildfires.

Larger fires are examined for many reasons. They generally are responsible for more damage and affect a larger area. Thus, the associated meteorological processes are not constrained to only the smallest scales in order to have a substantial impact on the fire environment. Large fires can, in fact, create their own circulations, like horizontal roll vortices [Haines (1982)], once they become large enough. This study is not concerned with this micro-scale fire behavior, nor with the combustion processes involved in ignition. Instead, the discussion will center on the synoptic and mesoscale meteorological processes that actually shape the pre-fire environment in the days leading up to the fire and on the day of the fire.

The analysis of the different wildfires will proceed using a combination of observations and the output from a numerical weather prediction (NWP) model. Observations were gathered from a variety of sources to be referenced when appropriate. Many of the automated observations used in the analyses were obtained from MesoWest (distributed by the University of Utah), which is an online database and central source for many surface observation stations of diverse ownership across the United States. The names, locations, types, and owners of the stations used are shown in Fig. 2.1. Later when a station from MesoWest is used only the name will be used as a reference.

The output from a NWP model was used to supplement the sometimes coarse observations and allow for a finer resolution in time and space of the atmospheric structure. Version 2.2 of the WRF-ARW community model (Skamarock et al. 2005) was used to simulate the atmospheric conditions for all the cases studied. The WRF-ARW model runs had horizontal resolutions of around 40 km and twenty-eight vertical levels. The simulations performed for all the cases used six-hourly, 2.5° x 2.5°, gridded analysis from the NCEP/NCAR Reanalysis Project (Kistler, R. 2001) as boundary conditions.[5] The following

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[5] Higher resolution data then the NCAR/NCEP reanalysis data in time and space was available for the more recent cases but not the old ones. Thus this dataset was used for all the cases so that the use of different datasets could not be the cause of differences in model output. The NCEP/NCAR Reanalysis Project data for this study came from the Research Data Archive (RDA) which is maintained by the Computational and Information Systems Laboratory (CISL) at the National Center for Atmospheric Research (NCAR). NCAR is sponsored by the National Science Foundation (NSF).

approaches were used to represent physical processes in the WRF-ARW simulations: cloud microphysics was parameterized according to Ferrier (2002), longwave radiation parameterization was based on Mlawer et al. (1997), shortwave radiation was based on Dudhia (1989), and the YSU approach was used for the boundary layer parameterization Hong et al. (2006). The Noah land surface model (LSM) was used (Chen and Dudhia 2001) as well as the datasets of land surface characteristics accompanying this model. For all the simulations, the Kain-Fritsch (1990) cumulus parameterization was used. With the data and methodology sufficiently explained, the individual cases are analyzed to verify the previously stated hypothesis.

Chapter 3. Case studies

Four wildfires are analyzed in depth in the following sections. The fires being interrogated are the Mack Lake Fire, the Ham Lake Fire, the Black River Falls Fire, and the Pinery Fire. These fires were chosen due to the presence of a 500 hPa ridge and surface anticyclone in the region of the fires either on the day of or the days before the fires. As previously explained these two features are known to be associated with high fire danger days, large fires, and synoptic scale subsidence. Synoptic scale subsidence is an important part of the 3-D circulation that is hypothesized to affect western Great Lakes fire environments. Thus these cases were seen as good choices for interrogating the hypothesis of this thesis. The cases are grouped in order of historical occurrence. The Black River Falls and Pinery Fires are grouped into one case since they happened close to each other on the same day.

a. Mack Lake Fire, May 1980

1. Fire characteristics and observed atmospheric conditions

The Mack Lake Fire began as a prescribed fire on 5 May 1980 near Mio, Michigan in the Huron National Forest, which is located in the northeast portion of the lower peninsula of Michigan (location A, Fig. 2.1). According to Simard et al. (1983) the fire was set to remove logging debris in preparation for replanting Jack Pine in the area. The fire was ignited at

1430 UTC and by 1615 UTC the fire spotted across Michigan highway 33 and was a wildfire. The fire spread rapidly from there and advanced 12.1 kilometers in the first three and a half hours. By 2225 UTC the fire had taken one life, destroyed 44 homes and buildings and burned some 20,000 acres. By the time the fire stopped its rapid growth at 0400 UTC 6 May it had consumed close to 23,000 acres containing 270,000 tons of fuel and released three trillion BTU's, approximately equal to 9 times the energy of the atomic bomb dropped on Hiroshima, Japan (Simard et al. 1983). The fire was officially contained at 2200 UTC 6 May with no additional growth.

Simard et al. (1983) showed that the fire spread the fastest (in ft s^{-1}) from 1710 to 1725 UTC 5 May 1980 with the overall major run of the fire being 1630 to 2000 UTC. From 2000 UTC to 2200 UTC the fire still increased in size substantially, but the rate of spread slowed. They cited an increase in relative humidity coupled with the fact that the fire reached a region of hardwoods (even though the hardwoods had not yet fully leafed out) as reasons for the slowdown. The relative humidity and winds played an interesting role in fire spread. The relative humidity at 1300 UTC that morning was 80%, but by 1400 UTC had dropped significantly to 28% and continued dropping to a low of 21% at 1600 UTC. This 21% compares with an average 1 p.m. local standard time relative humidity in Houghton Lake (48 km to the southwest) of 50% for May (National Climatic Data Center (NCDC)). From there until the passage of a dry cold front at 1800 UTC the relative humidity was stable. After the passage of the front the temperature cooled dramatically for a mid-spring afternoon going from 27.8°C at the time of the frontal passage to 18.3°C at 2200 UTC. This led to a corresponding increase in relative humidity, which was mostly a result of this temperature drop and not a sharp increase in moisture. The relative humidity reached a high of 55% at

2200 UTC and stayed steady from there. The winds were relatively light in the 4.5 m s^{-1} range before the front passed. During and after the frontal passage the winds increased dramatically with sustained wind speeds above 6.7 m s^{-1} and gusts approaching 13.4 m s^{-1}. The winds relaxed at the 0200 UTC 6 May observation. Simard et al. (1983) cited the low relative humidity, high wind speeds, and dense jack pine forest as the reasons for the fast rate of spread of the Mack Lake Fire. The only non-weather factor cited was a dense jack pine forest, which was a known constant. The conclusions of Simard et al. (1983) along with the significant destruction caused by the Mack Lake Fire provide the motivation to examine the atmospheric conditions before and during the initial run of the fire to determine what produced the low relative humidity and high wind speeds in the fire vicinity.

2. Atmospheric conditions preceding fire

In the month of April 1980, 82.3 mm of rain were reported at Mio, well above the 53.1 mm 30-year average[6] for the month of April. The first four days of May 1980 were characterized by above normal temperatures, low relative humidity, and no precipitation as the Great Lakes were under the influence of a slow moving surface high pressure system. This likely led to more evaporation than normal, but the above average April rains combined with the preceding year having close to normal precipitation led Simard et al. (1983) to conclude that drought was not a factor in the Mack Lake Fire. The same surface anticyclone that influenced the Great Lakes during the first four days of May 1980 stretched over an extensive portion of the central United States and Canada at 1200 UTC 2 May, as shown in

[6] Data from the Michigan State Climatologist's Office, the years of 1971-2000 determined the average.

Fig. 3.1a. This large, relatively weak anticyclone was associated with a high amplitude upper-ridge centered over the Canadian province of Saskatchewan at 1200 UTC 2 May (Fig. 3.1b). This anomalous early spring ridge had persisted in some fashion over west-central Canada for the entire month of April leading to dry conditions and warm temperatures in the region (Alexander et al. 1983). According to Alexander et al. (1983) the ridge and surface high played an important role in creating very dry air in the vicinity of a large fire that began at 2038 UTC 2 May just three days before the Mack Lake Fire near Cold Lake, Alberta.

By 1200 UTC 3 May the surface anticyclone had moved further east (Fig. 3.2a). The surface high stretched from Hudson Bay, Ontario to Denver, Colorado and exerted an influence over all of the central United States and east-central Canada. This contributed to a temperature of 25.5°C and relative humidity of 22% being observed at Mio. At 500 hPa the upper-level ridge which forced the movement of the surface anticyclone also moved eastward and amplified further over eastern Manitoba (Fig. 3.2b). A slow moving upper trough, east of Hudson Bay, stalled the eastward movement of the ridge. By 1200 UTC 4 May a small area of low pressure, located southwest of Hudson Bay, had split from a large surface cyclone that had moved into northwestern Canada over the previous few days (Fig. 3.3a). Most of the United States including the Mack Lake area remained under the influence of the high pressure system centered over the Rocky Mountains. This led Mack Lake to experience its lowest midday relative humidity of the month at 19% and a high temperature of 26.7°C (well above average for that date) (Simard et al. 1983). The upper-air pattern became more zonal at 1200 UTC 4 May over the north-central U.S. (Fig. 3.3b). The ridge flattened due to the eastward progression of an upper level trough over central Canada. Eventually, by 1200 UTC 5 May, the day of the Mack Lake Fire, the surface cyclone moved over the upper Great

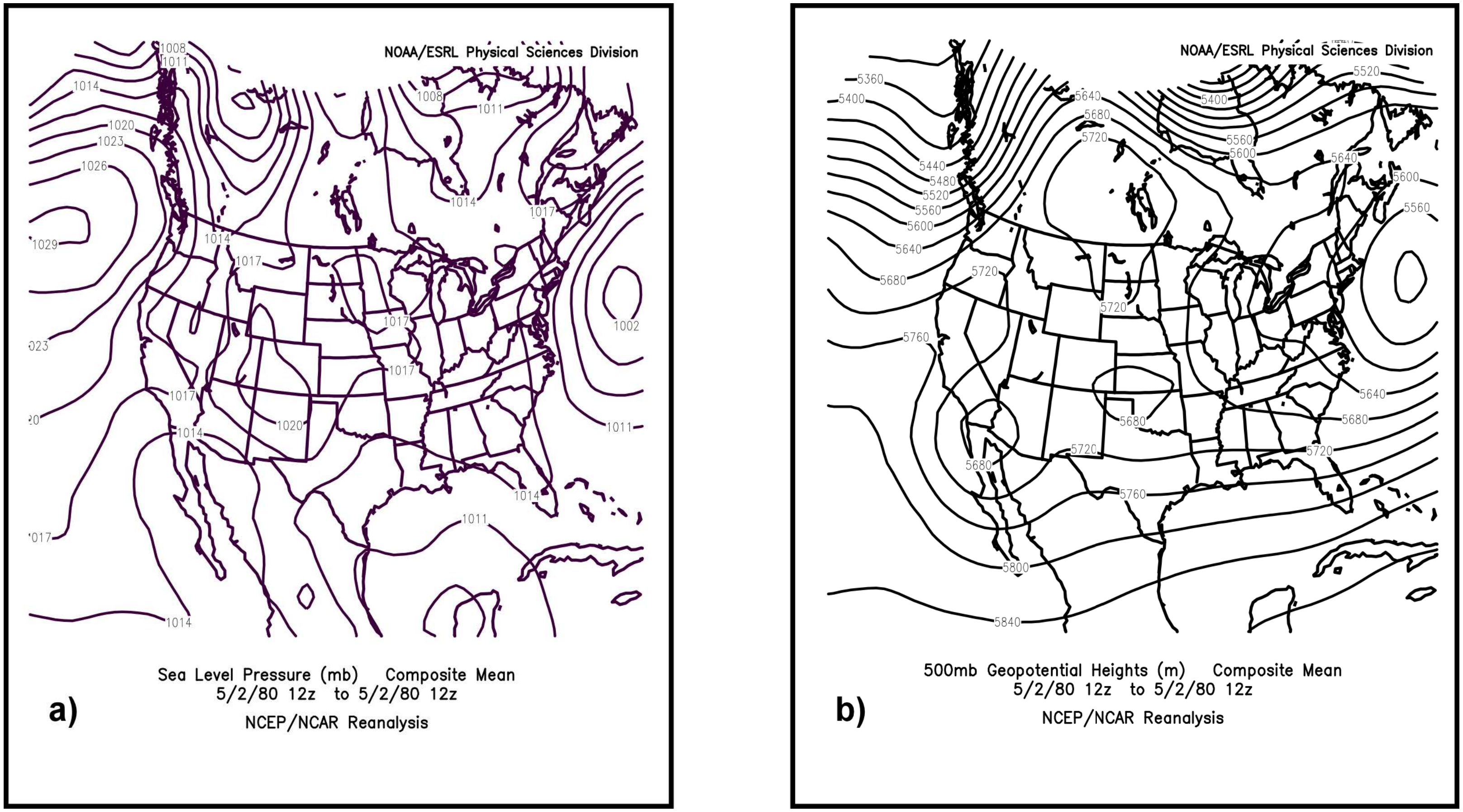

Figure 3.1. Maps showing locations of surface and upper-level features for 1200 UTC 2 May 1980. a) Mean sea level pressure contoured every 3 hPa from the NCEP/NCAR Reanalysis dataset. b) As for Fig. 3.1a except for 500 hPa geopotential heights contoured every 40 m. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

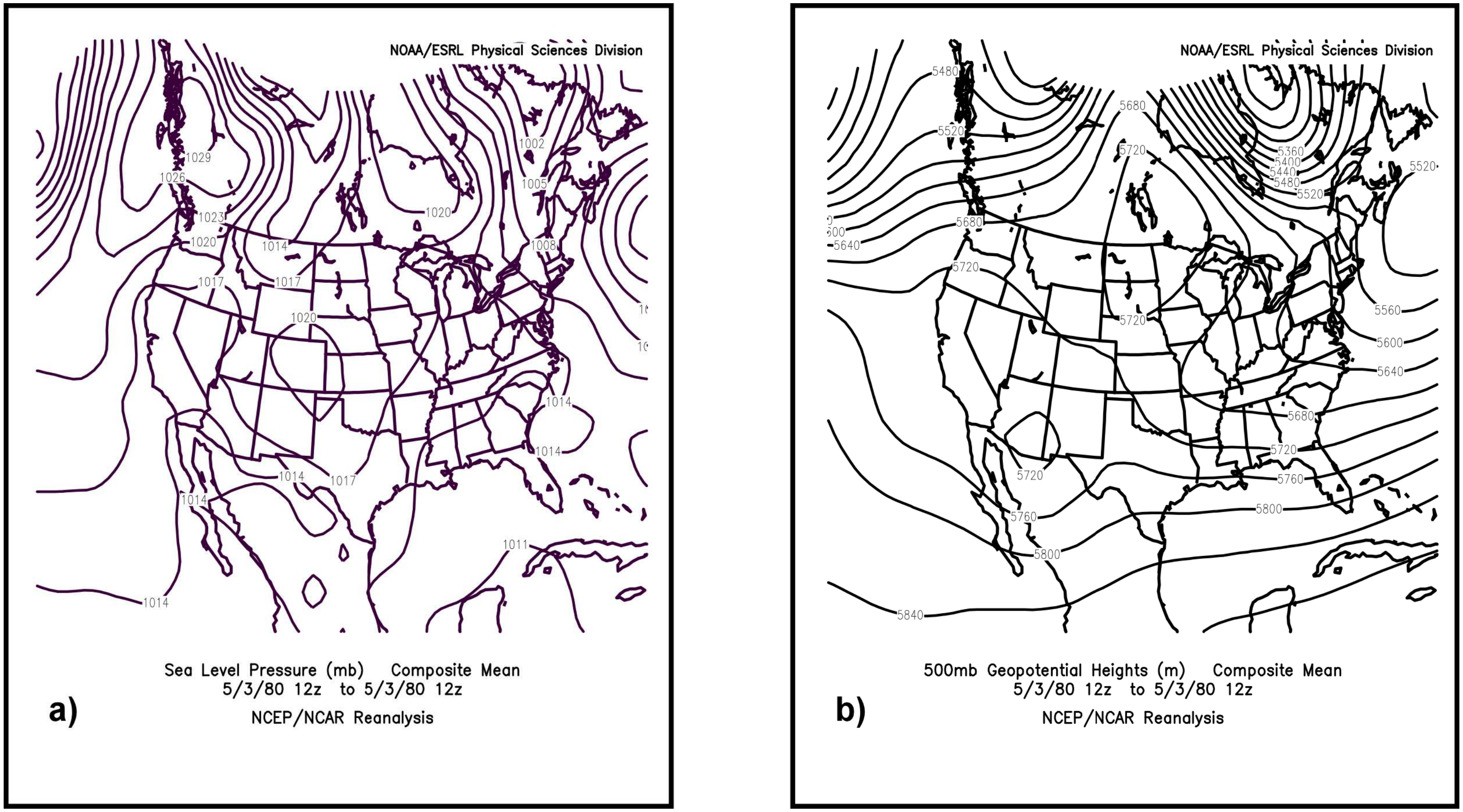

Figure 3.2. For Figure 3.1 but for 1200 UTC 3 May 1980. a) As for Fig 3.1a. b) As for Fig. 3.1b. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

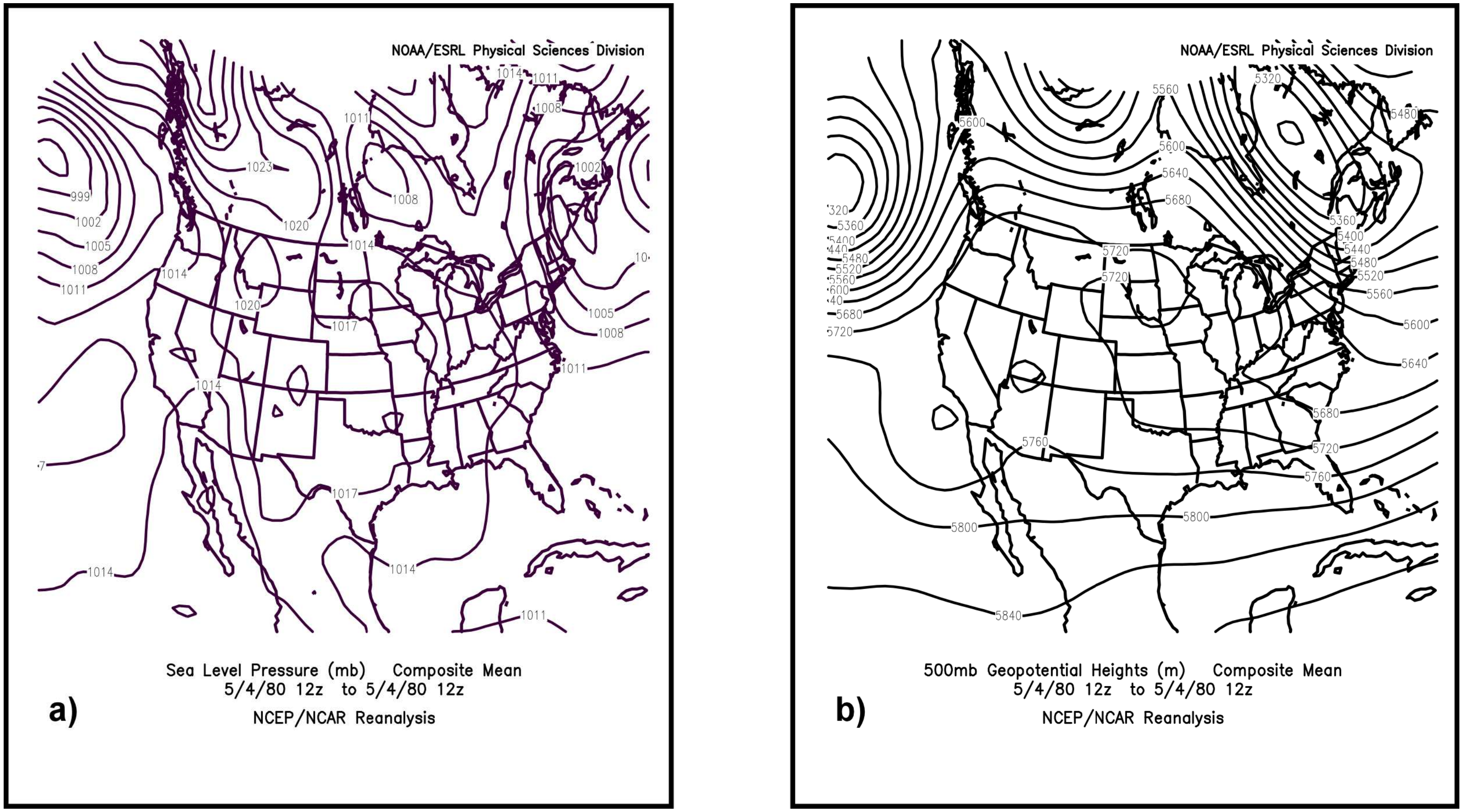

Figure 3.3. For Figure 3.1 but for 1200 UTC 4 May 1980. a) As for Fig 3.1a. b) As for Fig. 3.1b. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

Lakes and strengthened by 6 hPa (Fig. 3.4a). This ended the influence of the anticyclone on the Mack Lake area. The surface cyclone was ushered southeastward by the northwesterly flow aloft at 500 hPa on 1200 UTC 5 May (Fig. 3.4b). This northwesterly flow at 500 hPa was due to the redevelopment of a high amplitude ridge between 1200 UTC 4 May and 1200 UTC 5 May over the western United States and Canadian Rockies.

The pattern at 1200 UTC 5 May (Fig. 3.4) is only vaguely similar to previously identified patterns for large fires as found in Schroeder et al. (1964) and Heilman (1995). The Mack Lake Fire occurred in the pre-frontal region of a weak surface low embedded in northwesterly flow aloft. It is hard to determine what surface high pressure type Schroeder et al. (1964) would have classified as leading to the high fire danger experienced on 5 May 1980 as the region was dominated by the surface cyclone. The pattern at 1200 UTC 5 May is similar to the previously identified pattern by Brotak and Reifsnyder (1977) of a shortwave compact upper trough with an associated dry and windy cold front at 850 hPa. Two central questions remain, however: 1) from where did the dry air present on the day of the Mack Lake Fire originate and, 2) what processes involved in the observed patterns produced and transported the dry air? Was the dry air solely due to the circulation associated with an upper level front as shown in Zimet (2007) or did the antecedent 500 hPa ridge and surface anticyclone contribute to the production of the observed dry air at the time of the fire, through subsidence, that was advected and mixed into the Mack Lake region as hypothesized?

To further analyze the atmospheric conditions and connections between the upper level ridge and surface high with the Mack Lake Fire, output from the numerical model outlined earlier will be used. A 42 km horizontal resolution single domain of the WRF-ARW

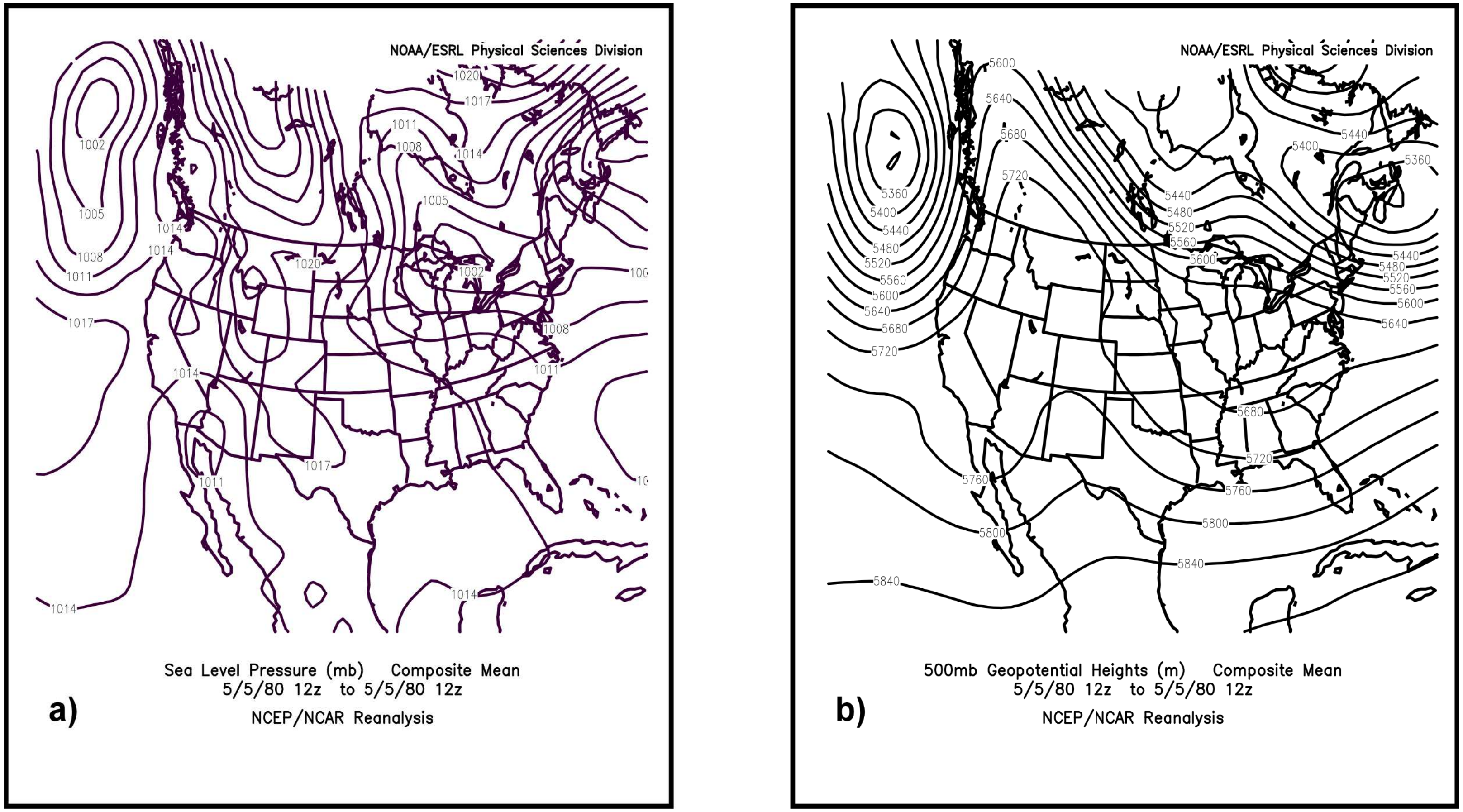

Figure 3.4. For Figure 3.1 but for 1200 UTC 5 May 1980. a) As for Fig 3.1a. b) As for Fig. 3.1b. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

model initialized at 1800 UTC 1 May 1980 and run for 114 hours centered over southern Manitoba is used for analysis of the large scale features (Fig. 3.5). While no formal statistical evaluation of the model performance will be provided here, a significant feature is used to informally evaluate the model accuracy. Figure 3.6a shows sea level pressure and the subjectively analyzed cold frontal position at 1800 UTC 5 May from the WRF-ARW model output (based on thermodynamic analyses), while Fig. 3.6b shows the surface cyclone and cold frontal analysis found in the official Mack Lake Fire report (Simard et al. 1983). The model is a little slow in bringing the surface trough and cold front through the Mio, MI area as compared to the position reported by the official Mack Lake fire report. Even with the slightly slow movement the model does represent the sea level pressure minimum, surface trough, and cold front in a similar fashion to observations. Thus the model is still deemed significantly realistic for the purposes of informing the diagnostic analyses.

3. Subsidence

The presence of dry air at the surface was found to be a consistent feature during the first five days of May 1980, as shown in Simard et al. (1983). In addition, a surface anticyclone and upper ridge dominated the central U.S. during the first four days of May before giving way to a surface cyclone and upper trough that moved southeastward from northwest Canada into the Great Lakes region on the 5 May 1980. Using the WRF-ARW model a more complete view of the atmospheric conditions in the Mack Lake region is obtained for 5 May 1980. To obtain a more complete picture a vertical cross section (along

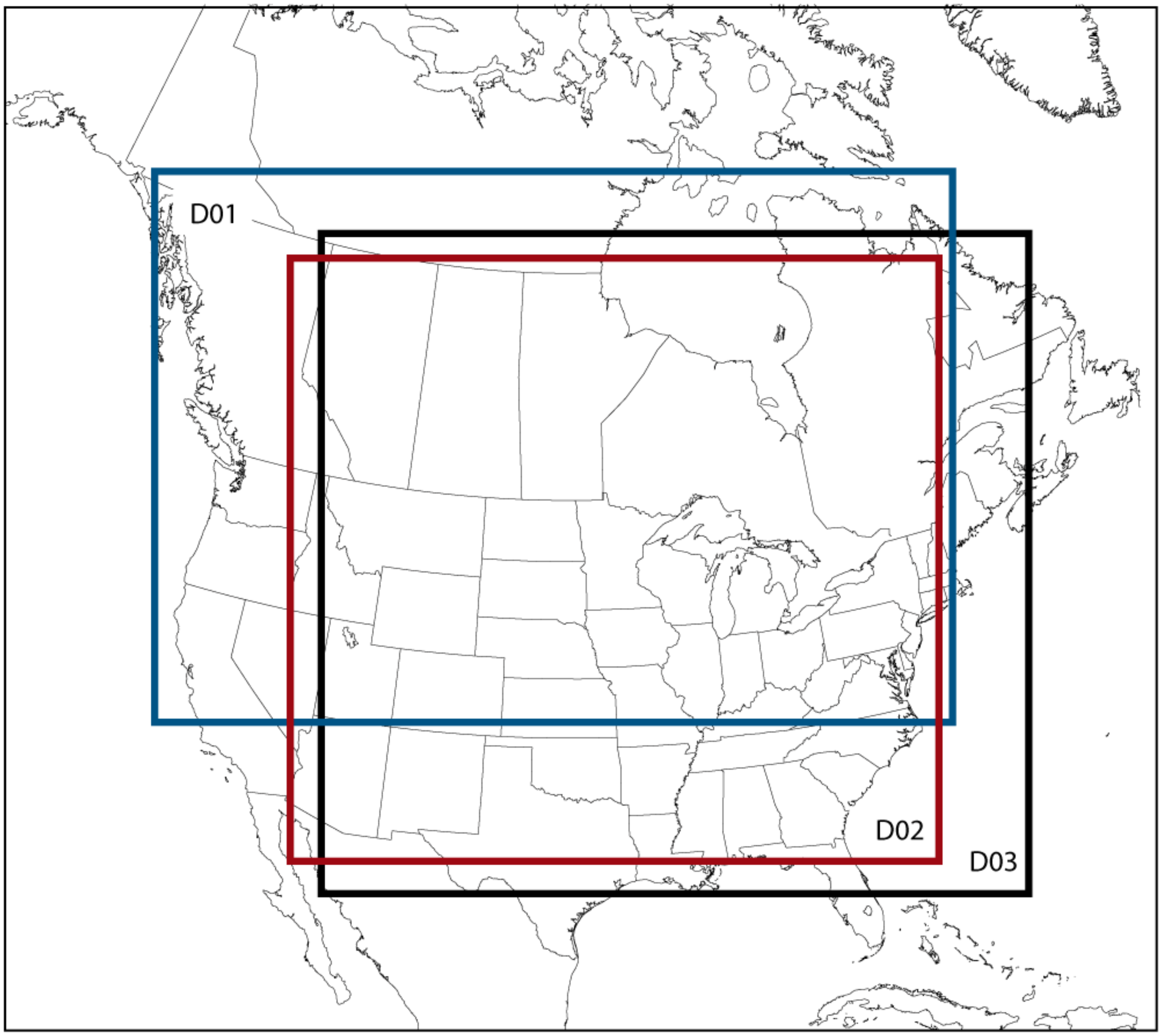

Figure 3.5. Domains of the WRF-ARW model run for each of the three case studies. D01, denoted by the bold blue line, was the domain for the Mack Lake Fire, which had a resolution of 42 km. D02, denoted by the bold red line, was the domain for the Ham Lake Fire, which had a resolution of 36 km. D03, denoted by the bold black line, was the domain for the Black River Falls and Pinery Fires, which had a resolution of 39 km.

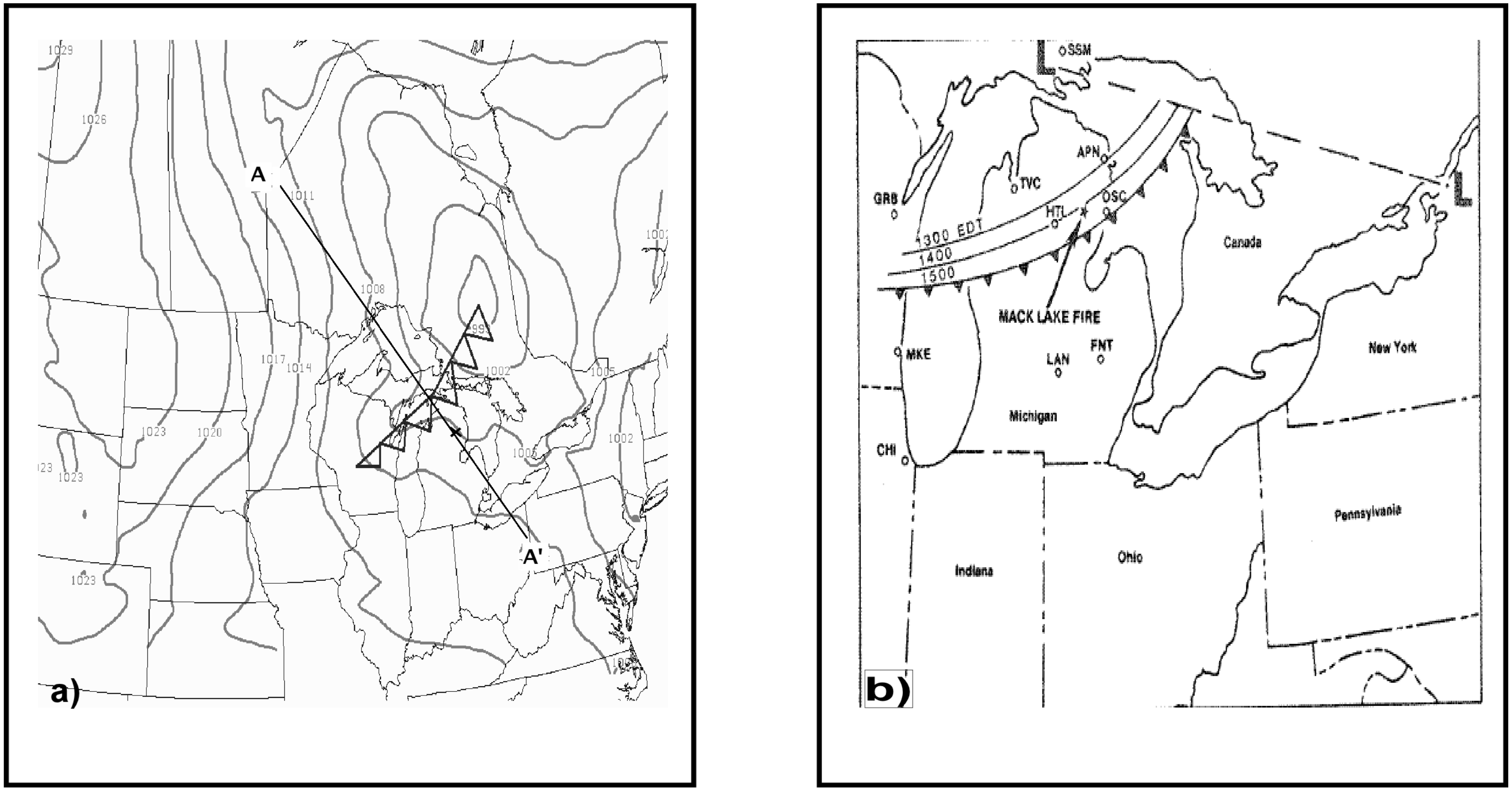

Figure 3.6. a) Mean sea level pressure contoured every 3 hPa at 1800 UTC 5 May 1980 from 96 hr WRF-ARW forecast. Frontal symbols indicate position of surface cold front while x marks the Mack Lake Fire location. Vertical cross section in Fig. 3.7 taken from A to A'. b) Location of the leading edge of the cold front on 5 May 1980 (Simard et al. 1983). The northernmost frontal location was analyzed at 1700 UTC, followed by 1800 UTC, and 1900 UTC.

the line A-A' in Fig. 3.6a) perpendicular to the surface front and in the same direction as the 500 hPa flow pattern is produced. At 0600 UTC the dry air is clearly evident above the fire environment from 850 hPa to 500 hPa (Fig. 3.7). The cold front was still off to the northwest at this time and this dry air was well out ahead of it.

So from where does the dry air in the lower troposphere (850 hPa to 700 hPa), present in the Mack Lake region on the day of the fire, originate? To ascertain the source of the air, backward parcel trajectories into the Mack Lake area were calculated using the WRF-ARW model output. Back trajectories were calculated for parcels moving into the region at 0600 UTC 5 May well ahead of the front. The trajectories show that the air parcels sank first over western Ontario and then subsided for a second time over extreme northern Minnesota (Fig. 3.8). The parcels began to sink for the first time, in southwestern Ontario, upstream from the fire location on the eastern side of the surface high located over southern Manitoba and Saskatchewan at 1800 UTC 2 May. Note that western Ontario is on the eastern side of the well defined 500 hPa ridge (Fig. 3.9). The eastern side of a 500 hPa ridge (its downstream side) is an area typically associated with convergence at upper levels, due to convergence of the ageostrophic wind and downward vertical motion in the column (Martin, 2006). In addition, Fig. 3.9 shows that northeast Ontario is a region of 500 hPa diffluence. As a result, there is convergence of the inertial advective component of the ageostrophic wind and additional downward vertical motion over southwestern Ontario (Martin, 2006). Thus the air subsided and adiabatically warmed as it sank in southwestern Ontario and the relative humidity decreased as a result. The large pool of dry air in the region of subsidence is shown with 600 hPa relative humidities less than 30% at 0000 UTC 3 May (Fig. 3.9). As the center of the high moved south and west and the upper ridge gained a more positive tilt on the 3rd

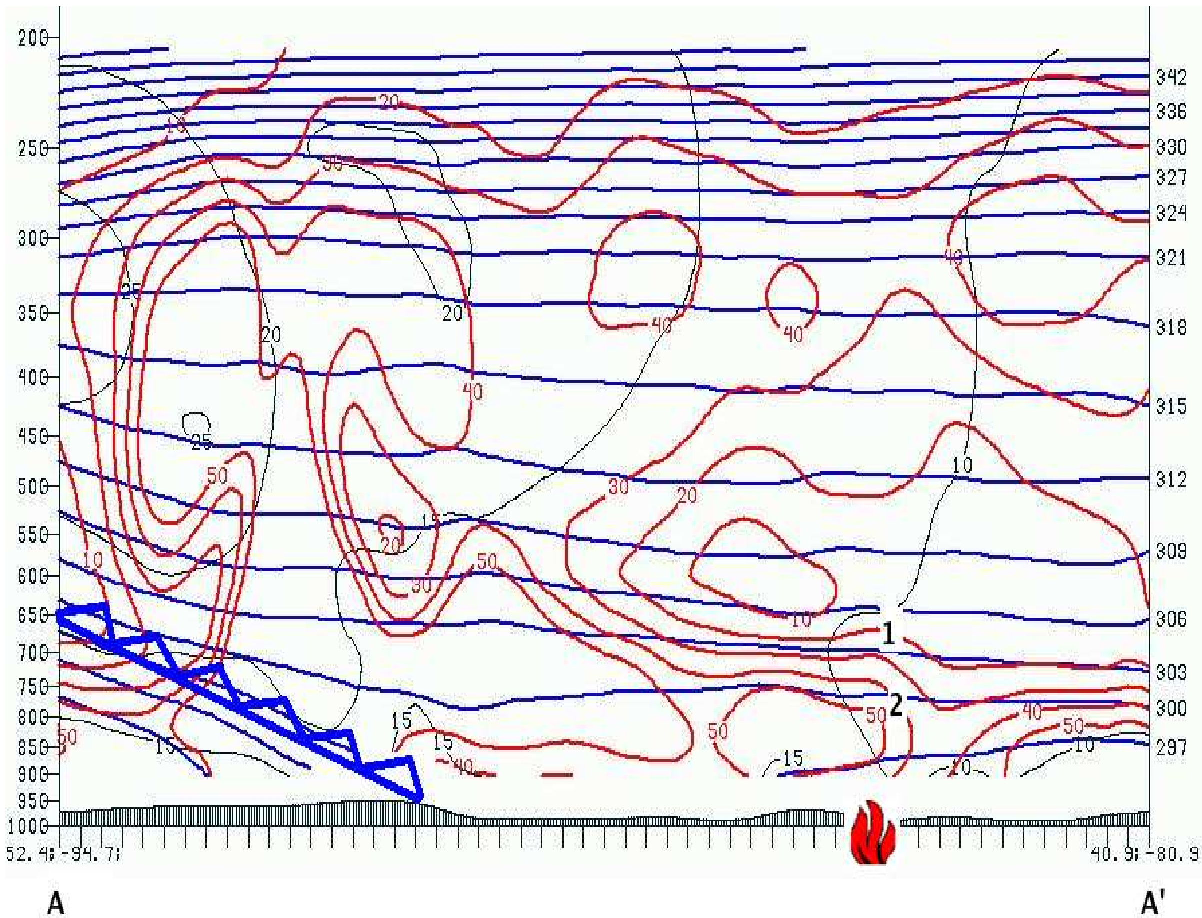

Figure 3.7. Vertical cross section along the line A-A' shown in Fig. 3.6a of potential temperature, relative humidity, and isotachs from the 84 hr forecast of the WRF-ARW valid at 0600 UTC 5 May 1980. Theta is labeled in K every 3 K with blue lines, RH is labeled every 10% with a maximum of 50% in red lines, and isotachs are labeled every 5 m s^{-1} in grey lines. The Mack Lake Fire location is denoted by the red fire icon. Additionally, the cold front location is marked by the blue triangles. Finally, the locations of the endpoints of the back trajectories are denoted by the numbers 1 and 2 above the fire location.

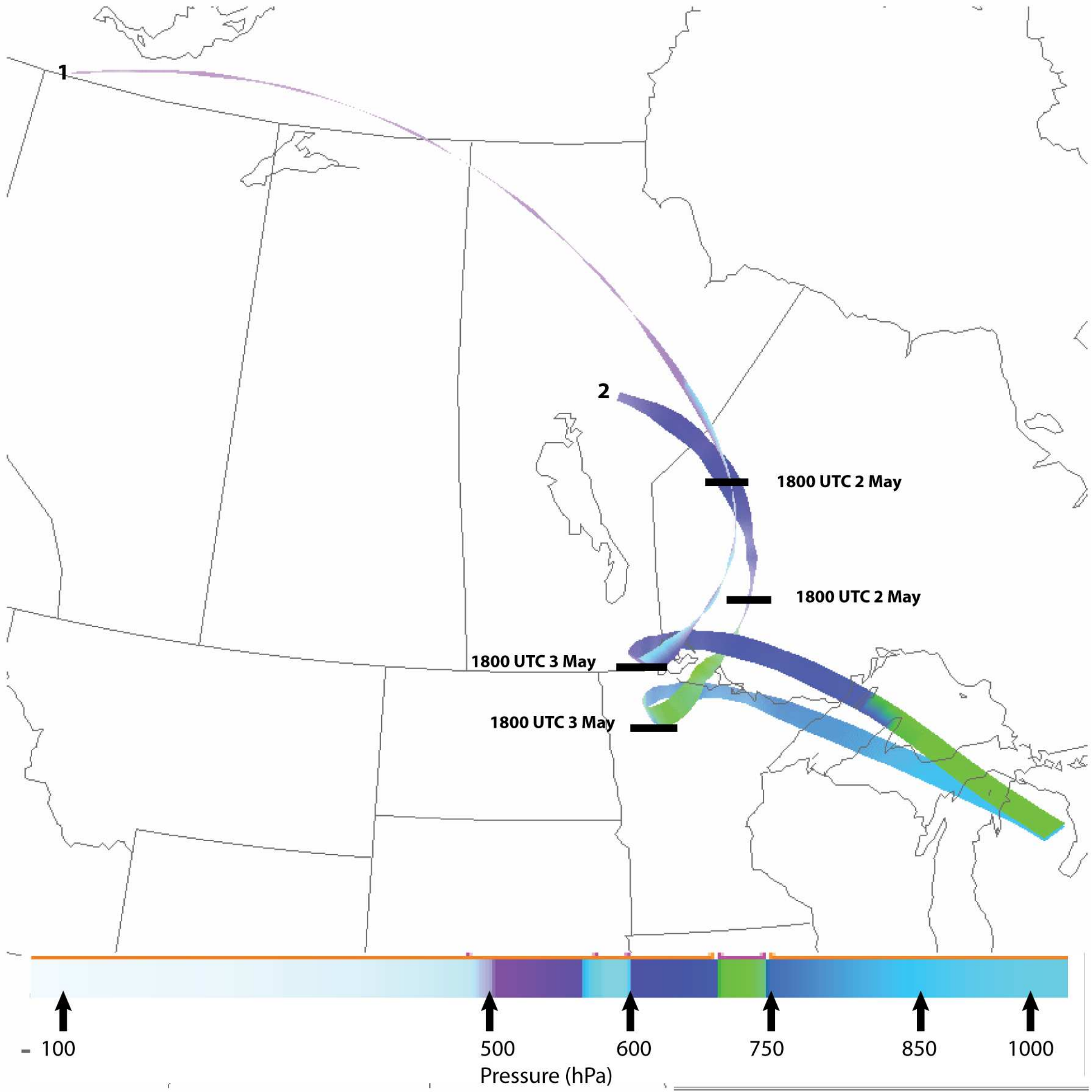

Figure 3.8. 84 hour backward trajectories ending at 0600 UTC 5 May 1980 at Mack Lake. The trajectories are shaded based on the pressure level at which they reside.

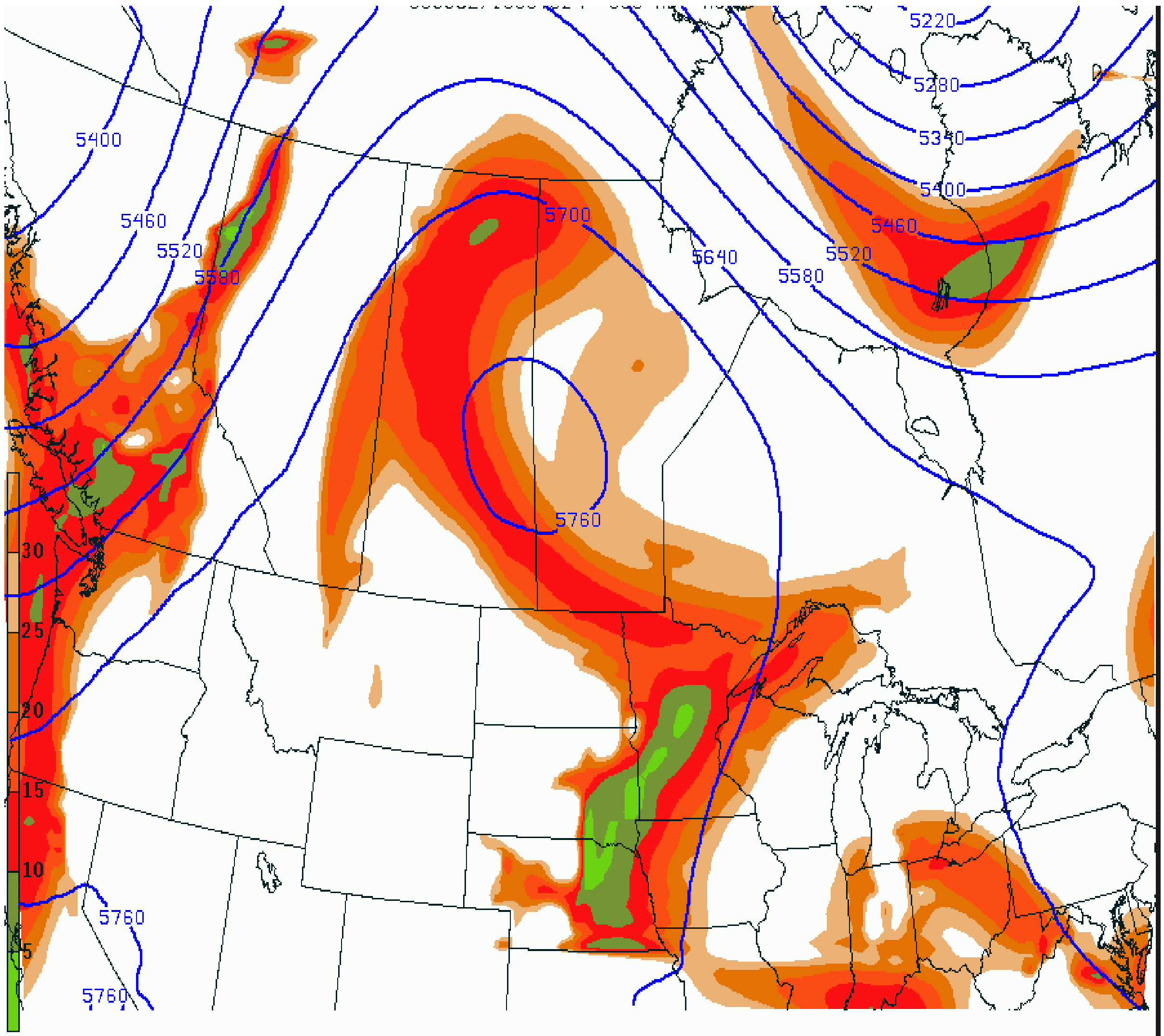

Figure 3.9. 500 hPa geopotential heights contoured with blue lines every 60 m at 1800 UTC 2 May 1980 from the 24 hr forecast of the WRF-ARW. 600 hPa relative humidity shaded every 5% (light green is 0% to 5%) with a maximum of 30% at 0000 UTC 3 May 1980 from the 30 hr forecast of the WRF-ARW.

the second sinking event began at 1800 UTC 3 May. This second sinking event again took place on the eastern side of the amplified upper ridge (Fig. 3.10). A positively tilted upper ridge generates even more Negative Vorticity Advection (NVA) on the eastern side of the ridge then a ridge with no tilt. The increased NVA at upper levels leads to increased synoptic scale descent as explained by the differential vorticity advection portion of the QG-omega equation (Martin, 2006). Again, a reservoir of relatively dry air in the region of subsidence is shown, but this time at 650 hPa at 0300 UTC 4 May, as the parcels sank further. The parcels then began to move eastward on the northeastern edge of the high as it weakened further and got caught up in the same 700 hPa flow that brought the weak surface cyclone from northern Canada toward Mack Lake on the 4th of May. This flow moved both the cyclone and the air out ahead of it toward Mack Lake. Thus the dry air in the lower troposphere (850 hPa to 700 hPa) previously seen in 0600 UTC 5 May vertical cross section was produced by synoptic scale subsidence on the eastern side of an upstream 500 hPa ridge in association with a potent 500 hPa jet maxima.

So how did the dry air present at 0600 UTC in the lower troposphere over Mack Lake reach the surface? At 1200 UTC 5 May a model sounding (not shown) at Mack Lake indicates the presence of a slight nocturnal inversion. The actual inversion is indicated to be much stronger by observations than the model simulates. The model simulates a temperature 3°C warmer than the 1200 UTC 5 May Mack Lake observation of 14°C. The fact that the model has a hard time representing the true surface conditions is likely due to factors such as its poor vertical resolution and the lack of high resolution surface data, shown to be important by Case et al. (2008). Regardless, the surface observations at 1300 UTC 5 May of 18.3°C and 80% relative humidity indicate the presence of a moist nighttime stable layer near the

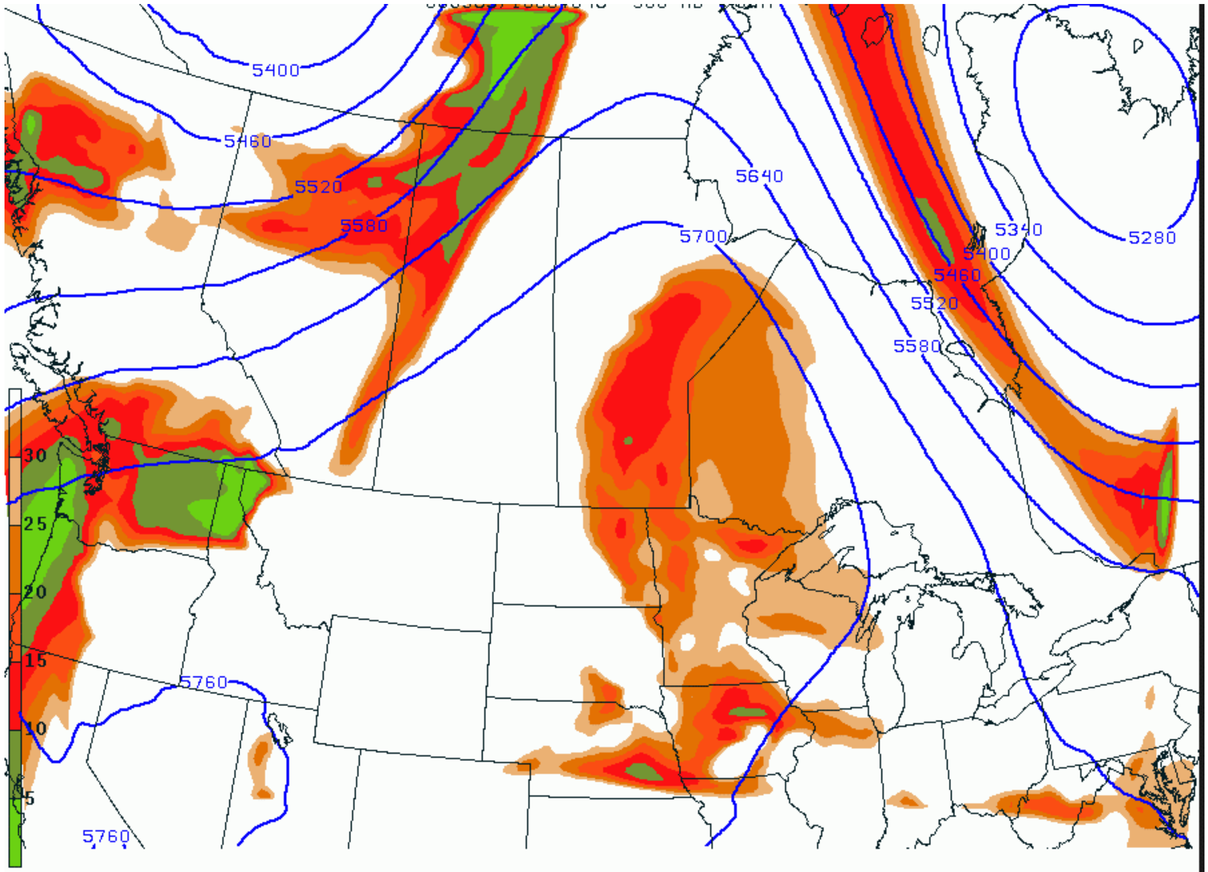

Figure 3.10. 500 hPa geopotential heights contoured with blue lines every 60 m at 1800 UTC 3 May 1980 from the 48 hr forecast of the WRF-ARW. 650 hPa relative humidity shaded every 5% with a maximum of 30% at 0300 UTC 4 May 1980 from the 57 hr forecast of the WRF-ARW.

surface. The moist nighttime stable layer was capped by a warmer and drier layer as shown in the 0600 UTC 5 May cross section. The presence of a nighttime stable layer capped by warmer and drier air is even further enhanced by the 1400 UTC surface observation, which included a temperature of 23.9°C and an observed relative humidity that plummeted to 28%. Thus once diurnal heating allowed the boundary layer to warm sufficiently the surface air began to rise and mix with the drier air from above. The observations indicate that the dewpoint dropped 7.3°C in one hour! This is four hours ahead of the surface cold front and thus represents robust evidence that the dry air was able to mix down to the surface as soon as the nighttime stable layer eroded and the mixed layer reached a significant enough depth.

4. Discussion

Considering all the information just detailed the decision to start a prescribed fire on the morning of 5 May 1980 is perplexing. The days before the fire were dry and had relatively high NFDRS burning index values (Simard et al. 1983). It is hard to say with the tools the fire managers had back in 1980 that they could have predicted the high fire danger rating to occur on the 5th, but when the relative humidity dropped from 80% at 1300 UTC 5 May to 28% at 1400 UTC just before the fire was started maybe they should have seen it as a warning for the high fire danger rating that May 5th would receive.[7] It has been clearly identified in the analysis that an upper 500 hPa ridge and jet were the two main factors in leading to synoptic scale subsidence upstream from the fire area in the days before the fire. This subsidence enhanced the dryness at mid-levels through adiabatic compression and warming, which led to air with very low relative humidities. This dry air was then transported to the Mack Lake region as the flow pattern shifted from strongly meridional to more zonal over the central U.S. in the day before the fire. Once transported to the fire region the dry air was mixed downwards towards the surface by diurnal surface heating on the morning of May 5th. This extreme dryness allowed for significant fire growth prior to the arrival of the cold front. The cold front and its connection to an upper level front as shown in

[7] The daily fire danger rating is not calculated until the 1pm local time observations are taken, consequently when fires are started in the morning this rating is often useless.

Zimet et al. (2007) maintained the dryness and increased the wind speeds just prior to the frontal passage through Mack Lake. Once the front passed Mack Lake surface relative humidities increased and the fire danger and fire growth abated. Thus the Mack Lake Fire combined the effects of large scale subsidence and the dry air it produced and advected, with an upper level dry cold front to allow a prescribed fire to turn into a deadly wildfire on 5 May 1980.

b. Ham Lake Fire, May 2007

1. Fire characteristics and observed atmospheric conditions

The Ham Lake Fire began on 5 May 2007 in a rural area of the Superior National Forest in Northeastern Minnesota (location E, Fig. 2.1). It was first reported to officials at 1640 UTC having consumed 20-30 acres, and is believed to have started at a campsite (K. Schierenbeck of the Gunflint District FMO Superior National Forest, personal communication January 7, 2009 and D. Miedtke of the Minnesota interagency Fire Center, personal communication, November 25, 2008). The previous night the relative humidity hovered around 45% and it remained at low levels during the day, bottoming out at 25% (data from the Seagull RAWS, Fig. 2.1). Both the daytime and nighttime relative humidity observations were well below average.[8] In less than two hours the fire grew to 480 acres in size and was 6.4 km long (Schierenbeck, personal communication). By 0600 UTC 6 May the

[8] The 6 a.m. and 12 p.m. average relative humidities respectively for the two closest climate observation stations of International Falls, MN and Duluth, MN are 77%/55% and 75%/58% (NCDC).

fire had burned 4000 acres. This was accompanied by no humidity recovery during the night and an actual drop to values around 20% in the early morning hours of May 6th (Seagull RAWS). The low relative humidities occurred even with relatively average daytime maximum temperatures and higher then normal nighttime minimum temperatures.[9] By 2100 UTC 6 May the fire was estimated to be 8000 acres in size and nearly double that by the morning of May 7th (Schierenbeck, personal communication). Sustained winds of 4.5 ms^{-1} to 6.7 ms^{-1}, gusting to 11.2 ms^{-1}, were observed during the first few days of the fire (Seagull RAWS). The fire consumed approximately 76000 acres by May 15th with 36500 of those acres being in the United States and the rest across the border in Canada (NICC- IC-209's). The Ham Lake Fire burned more acres than the large Cavity Lake Fire from the prior year making it one of the largest in recent memory in the region. The total cost for suppression of the Ham Lake Fire totaled $13 M, with $10 M worth of structures lost (Miedtke, personal communication). Suppression efforts succeeded in saving $35 M worth of structures and no fatalities occurred (Miedtke, personal communication).

Even though the Superior National Forest staffing levels were high and a large amount of equipment was used, the fire personnel were unable to put a stop to the fire. This was, in large part, a consequence of the existence of some of the most extreme burning conditions ever recorded for the Superior National Forest (Schierenbeck, personal communication). The extreme burning conditions coupled with the extensive destruction, provide the motivation to examine how the variable atmospheric conditions before and

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9 Compared to daily maximum and minimum normal temperatures for International Falls, MN and Duluth, MN (National Weather Service, Duluth, MN)

during the initial stages of the fire produced the low relative humidity and high wind speeds in the fire vicinity.

2. Atmospheric conditions preceding fire

The Ham Lake Fire burned in an area that had suffered a severe blowdown event (extensive amounts of trees blown over in one area), associated with an extreme derecho that went through the region on July 4th 1999. Thus, an abundance of dead fuels, which are easily burned, existed in the region before the Ham Lake Fire began. A number of large prescribed fires in the years since the 1999 blowdown failed to reduce the fuels sufficiently to prevent the Ham Lake Fire. The vegetation suppression left in the wake of the previously mentioned Cavity Lake Fire, which occurred in 2006, provided the only barrier to the Ham Lake Fire and served as its western boundary.

The Ham Lake Fire occurred following a winter with very little snow and an early spring with below average rainfall. Consequently, all of the fuels in the area were "cured" prior to spring green-up (Schierenbeck, personal communication). Data from the National Drought Mitigation Center's (NDMC) U.S. Drought Monitor further indicates that at the start of May 2007, the Ham Lake area was in extreme drought, one stage below the worst drought intensity. In addition, the Ham Lake area experienced its lowest 1000 hour fuel moisture[10] levels ever recorded from May 4th – May 23rd (Schierenbeck, personal communication). Finally, the combination of the drought conditions and ambient atmospheric conditions (to be

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[10] 1000 hour fuel moisture makes use of an appropriate version of the Fickian diffusion equation to represent the percentage water content of large, dead, woody fuels which tend to dry slowly. 1000 hour fuel moisture is a representation of the dryness of these fuels (Ottmar and Sandberg 1985).

described next) led to the assignment of very high to extreme categories for fire danger as given by the NFDRS on the day of and the day before the fire (Wildland Fire Assessment System, U.S. Forest Service).

The pre-fire atmospheric conditions began to take shape several days before the ignition of the fire. At 1200 UTC 1 May a slight 500 hPa ridge was present over the Rocky Mountains of the northern U.S. and southern Canada (Fig. 3.11a). At the same time a surface high pressure system developed over the central high plains of the U.S., downstream of the upper-level ridge axis (Fig. 3.11b). Both these features had progressed eastward from off of the eastern Pacific coast of the U.S. and Canada a few days earlier (not shown). By 1200 UTC 2 May the ridge had moved slightly east of the Rocky Mountains and amplified (Fig. 3.12a). The surface high also moved to the east and was centered over central Ontario (Fig. 3.12b). The upper ridge continued to move eastward, amplify, and acquire a negative tilt on the 3rd and 4th so that by 1200 UTC 4 May its axis was centered over the western Great Lakes and just east of the Chain of Lakes in central Canada (Fig. 3.13a). The surface high moved northeast and strengthened as well by 1200 UTC 4 May and became centered over Hudson

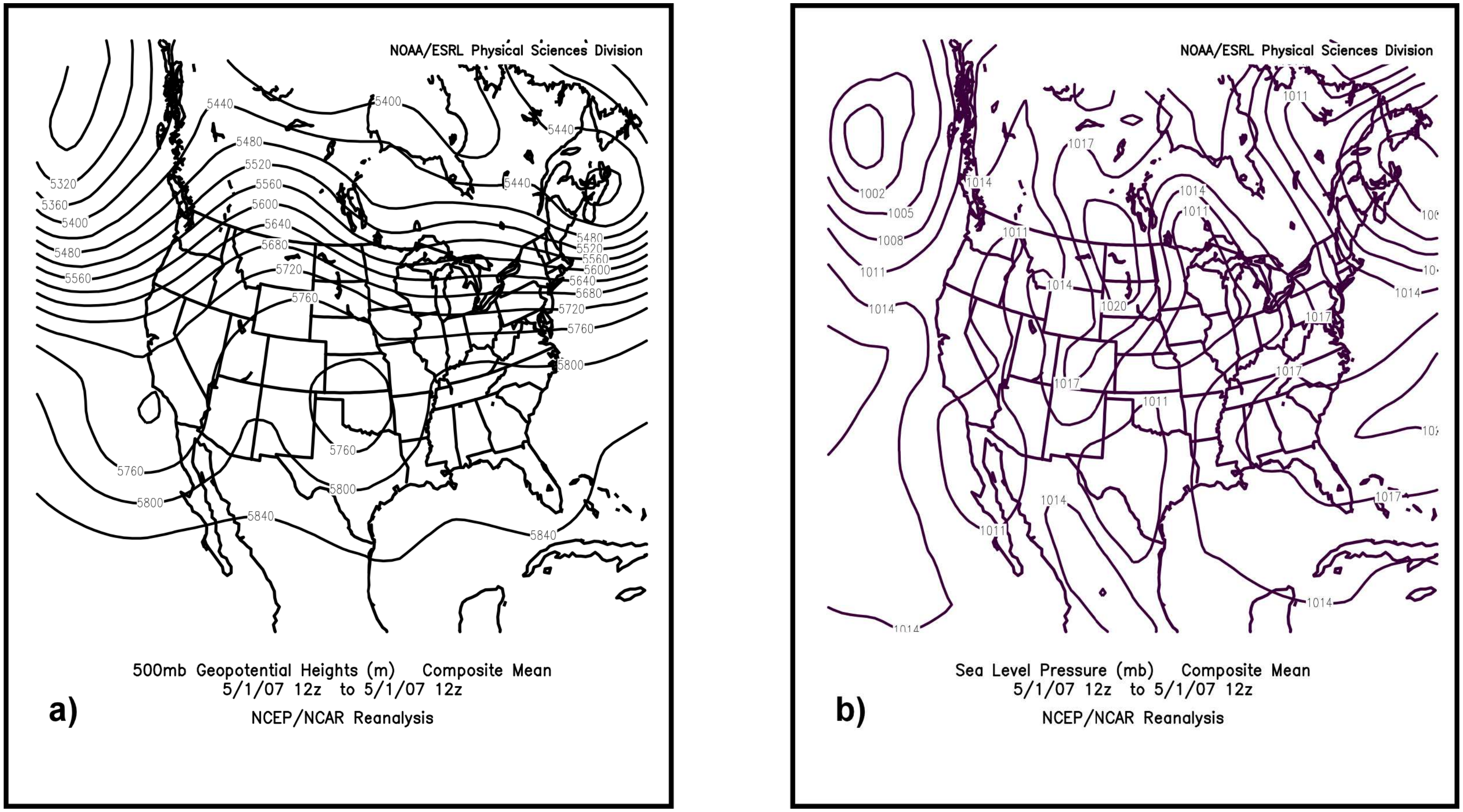

Figure 3.11. Maps showing locations of upper-level and surface features for 1200 UTC 1 May 2007. a) 500 hPa geopotential heights contoured every 40 m from the NCEP/NCAR Reanalysis dataset. b) As for Fig. 3.11a except for mean sea level pressure contoured every 3 hPa. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

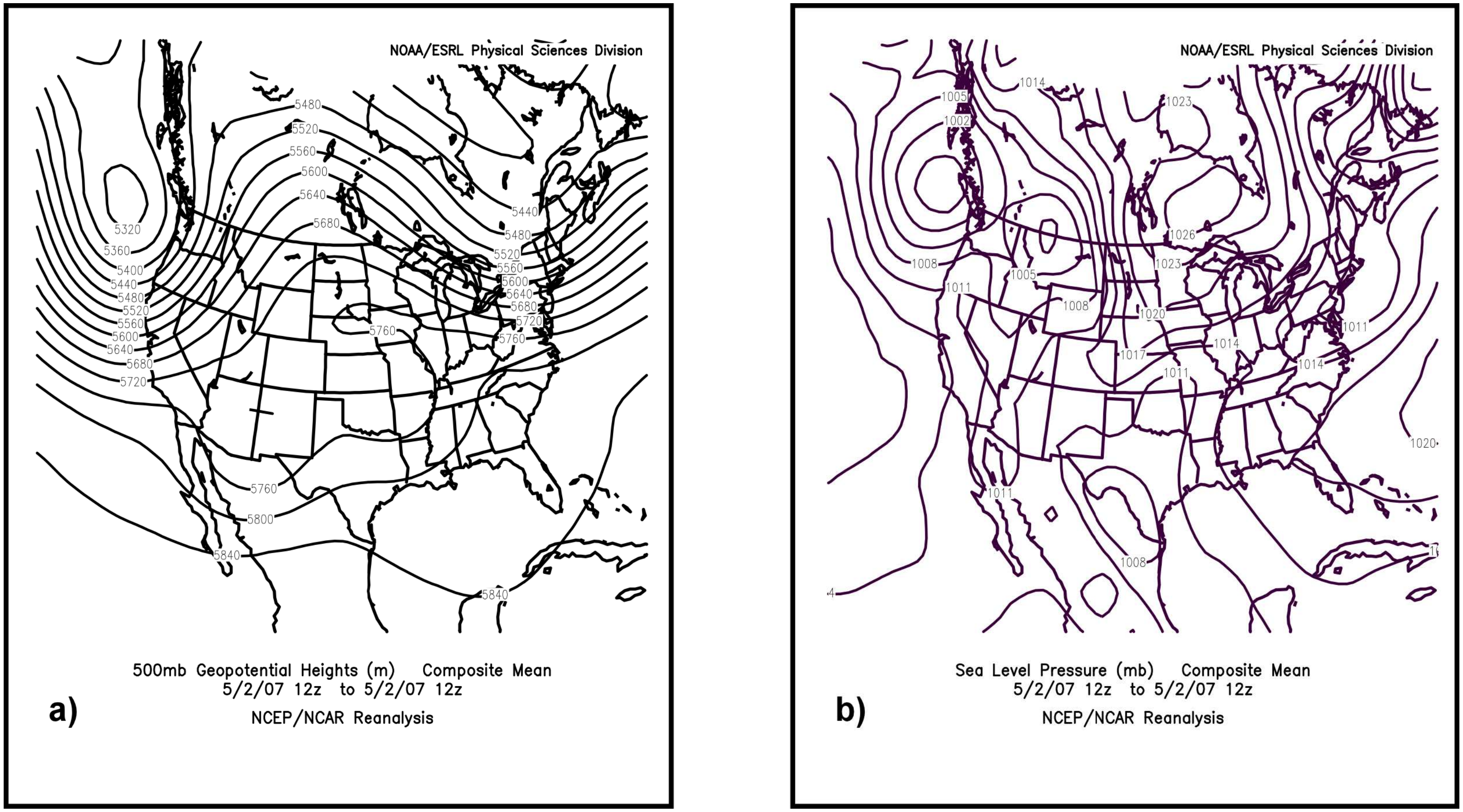

Figure 3.12. For Figure 3.11 but for 1200 UTC 2 May 2007. a) As for Fig 3.11a. b) As for Fig. 3.11b. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

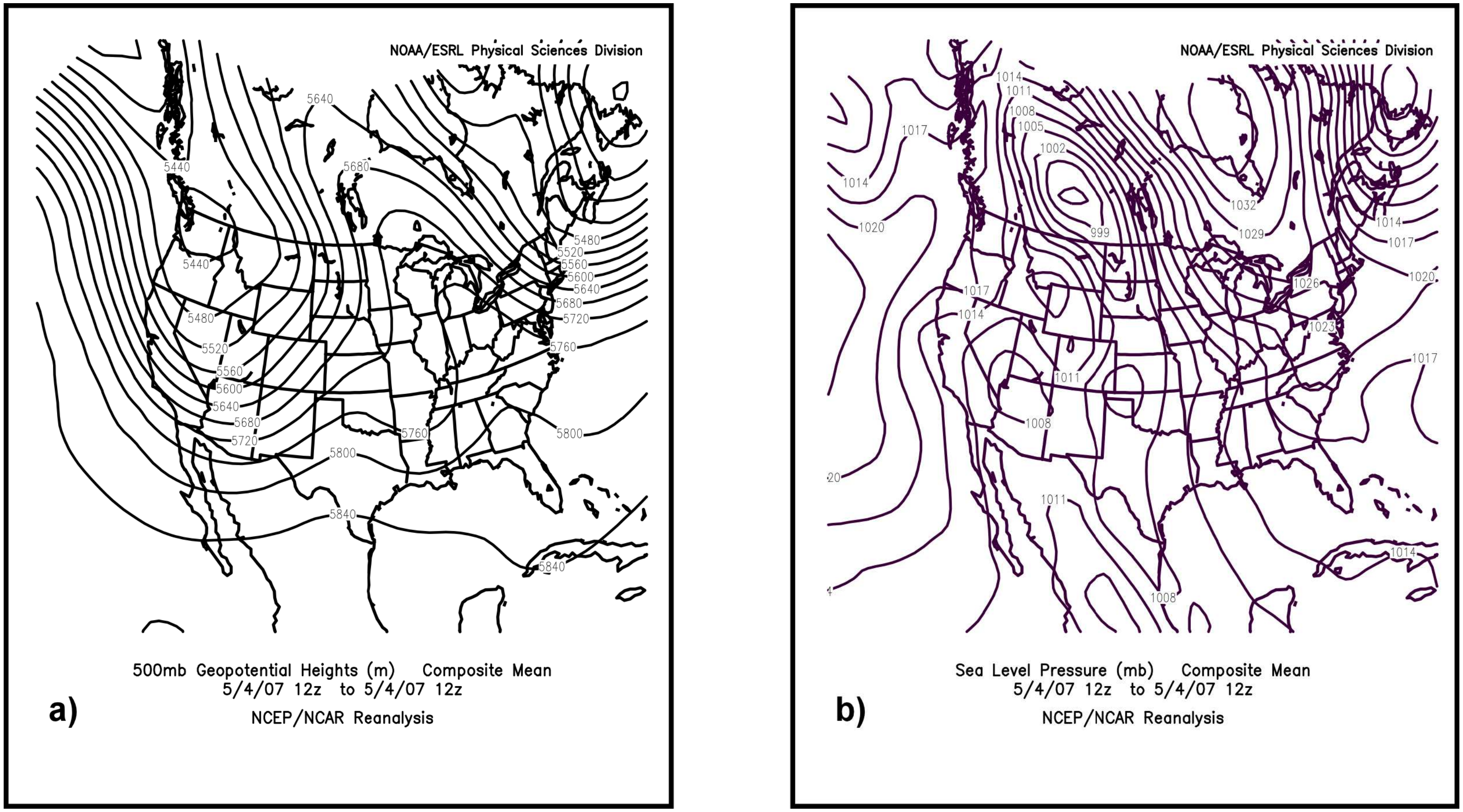

Figure 3.13. For Figure 3.11 but for 1200 UTC 4 May 2007. a) As for Fig 3.11a. b) As for Fig. 3.11b. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

Bay (Fig. 3.13b). At the same time a strong surface cyclone developed over eastern Alberta which contributed to the development of a strong surface pressure gradient in the Ham Lake region. By 1200 UTC 5 May the ridge became less negatively tilted and amplified further over the same location as a deep 500 hPa trough moved east over the Great Basin region of the U.S. (Fig. 3.14a). At the same time the surface high moved slightly southward and became centered over James Bay, Canada (Fig. 3.14b). A strong surface pressure gradient remained over the Ham Lake area as an additional surface cyclone developed in the lee of the Colorado Rockies. The surface high was at its most intense stage on the 5th and it slowly weakened over the next couple of days as the 500 hPa ridge weakened and continued to move to the east.

The pattern at 1200 UTC 5 May is again only vaguely similar to previously identified patterns identified for high fire danger or large fires. This fire occurs in the southwest quadrant of the high pressure system to its east/northeast and thus falls into the "other" category of fires for the Eastern U.S. according to the study done by Brotak and Reifsnyder (1977). Whether or not the surface high pressure system was classified as of Hudson Bay origin or Pacific origin, the high fire danger occurred in a different location than previously identified by Schroeder et al. (1964). The 1200 UTC 5 May pattern of an amplified slightly negatively tilted ridge centered over the upper Great Lakes and central Canada brought northwesterly flow at upper levels to the eastern Great Lakes. This is slightly further to the east than identified by Schroeder et al. (1964). In addition, the pattern is more of an amplified version and centered farther west then circulation pattern 2, which Heilman (1995) identified for the region east of Minnesota, but not for Minnesota.

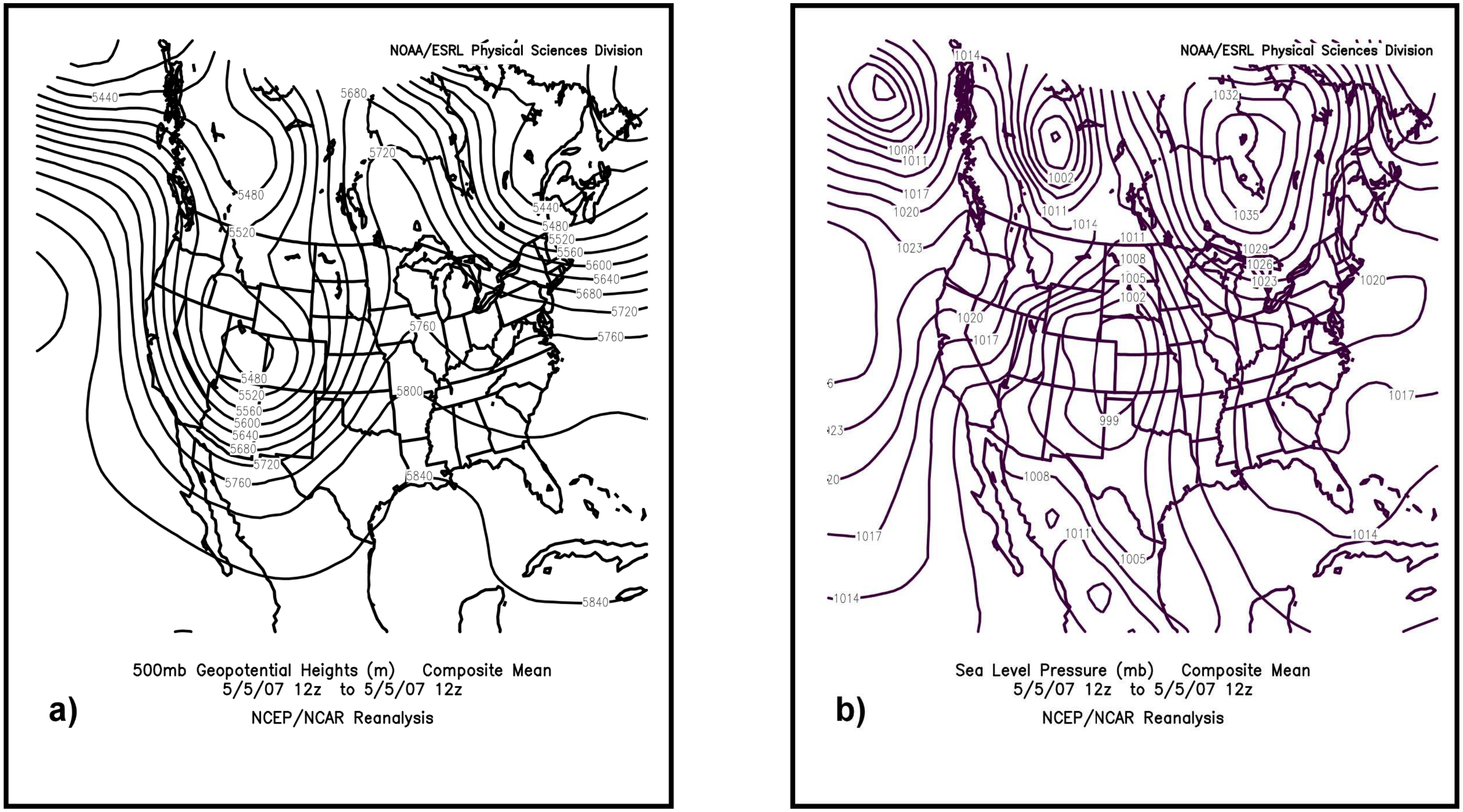

Figure 3.14. For Figure 3.11 but for 1200 UTC 5 May 2007. a) As for Fig 3.11a. b) As for Fig. 3.11b. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

To further analyze the atmospheric conditions and connections between the upper level ridge and surface high with the Ham Lake Fire, output from the numerical models outlined earlier will be used. A 36 km horizontal resolution single domain of the WRF-ARW model initialized at 1800 UTC 2 May 2007 and run for 84 hours centered over the Ham Lake area is used for analysis of the large scale features (refer back to Fig. 3.5). As seen earlier with the Mack Lake case the WRF-ARW does a reasonable job in simulating the actual atmospheric conditions. Thus the output from the model is used to provide a detailed analysis of the Ham Lake Fire.

3. Subsidence

So the question arises, from where did the boundary layer dry air, characterizing the Ham Lake fire environment, originate? It appears that there are four different drops in relative humidity during the first few days of this event. The first three drops are analyzed here in depth. The first drop in relative humidity occurred the day before the fire, the second on the day of the fire, and the third on the second day of the fire when the fire charred a significant amount of land. These drops in relative humidity can be seen on a 5 day meteorogram (Fig. 3.15) of temperature, dewpoint, and relative humidity from the Seagull RAWS. The first significant drying occurred at 1800 UTC 4 May. At this time Ham Lake was in the center of the 500 hPa ridge axis; not a particularly favorable location for synoptic scale vertical motion. Thus, at first glance one might be tempted to conclude that subsidence and associated warming would not play a major role in producing low relative humidity air at this time. To ascertain the source of the dry air intrusions, backward trajectories of the air

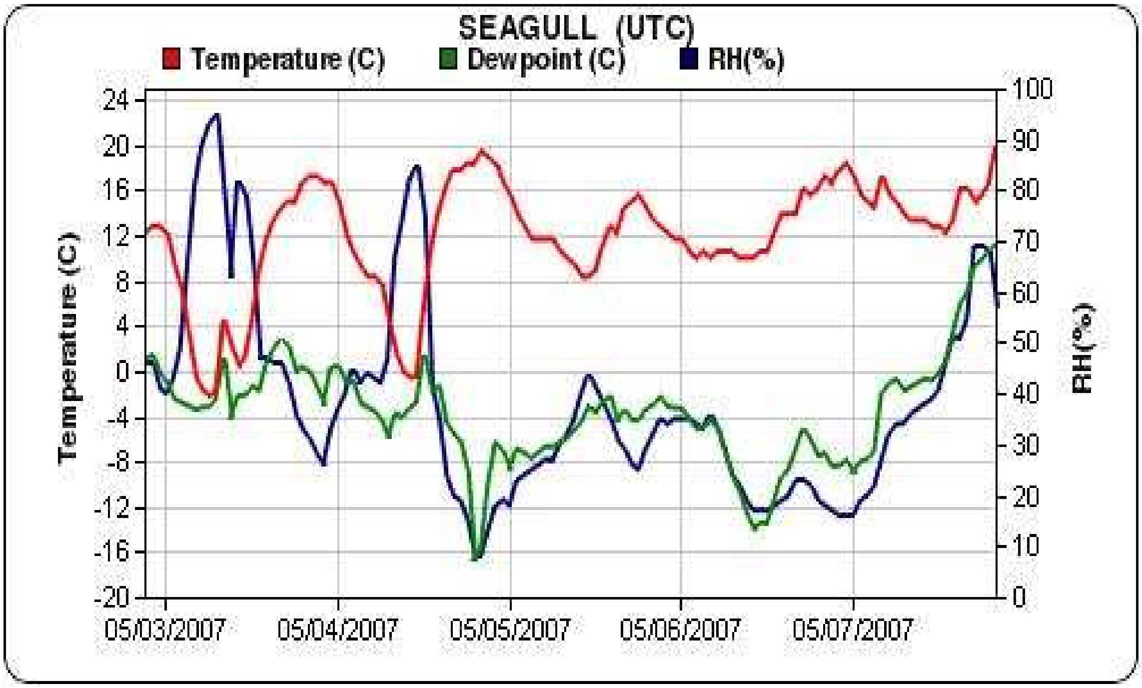

Figure 3.15. Meteorogram observed at Seagull RAWS near Ham Lake for the period of 2100 UTC 2 May 2007 to 2100 UTC 7 May 2007 for temperature °C with red line, dewpoint °C with green line, and Relative Humidity % with blue line.

parcels located in and just above the boundary layer (875 hPa to 700 hPa) in the Ham Lake region at 1800 UTC 4 May were calculated using the WRF-ARW model, as shown in Fig. 3.16. It can be seen that significant subsidence occurred southeast of the Ham Lake region the day before; beginning at 1800 UTC 3 May (Fig. 3.16). This happened downstream of the ridge axis, which as previously shown is associated with downward vertical motion in the column below 500 hPa (Fig. 3.17). Thus as the air subsided it adiabatically warmed and its relative humidity decreased. The intense and large pool of dry air in the region of subsidence is manifest in the relative humidity distribution at 700 hPa (Fig. 3.17). By 0600 UTC 4 May the air parcels stopped sinking as they reached the western edge of a lower tropospheric (850 hPa) high pressure system (Fig. 3.16), which is not a region usually preferred for any type of

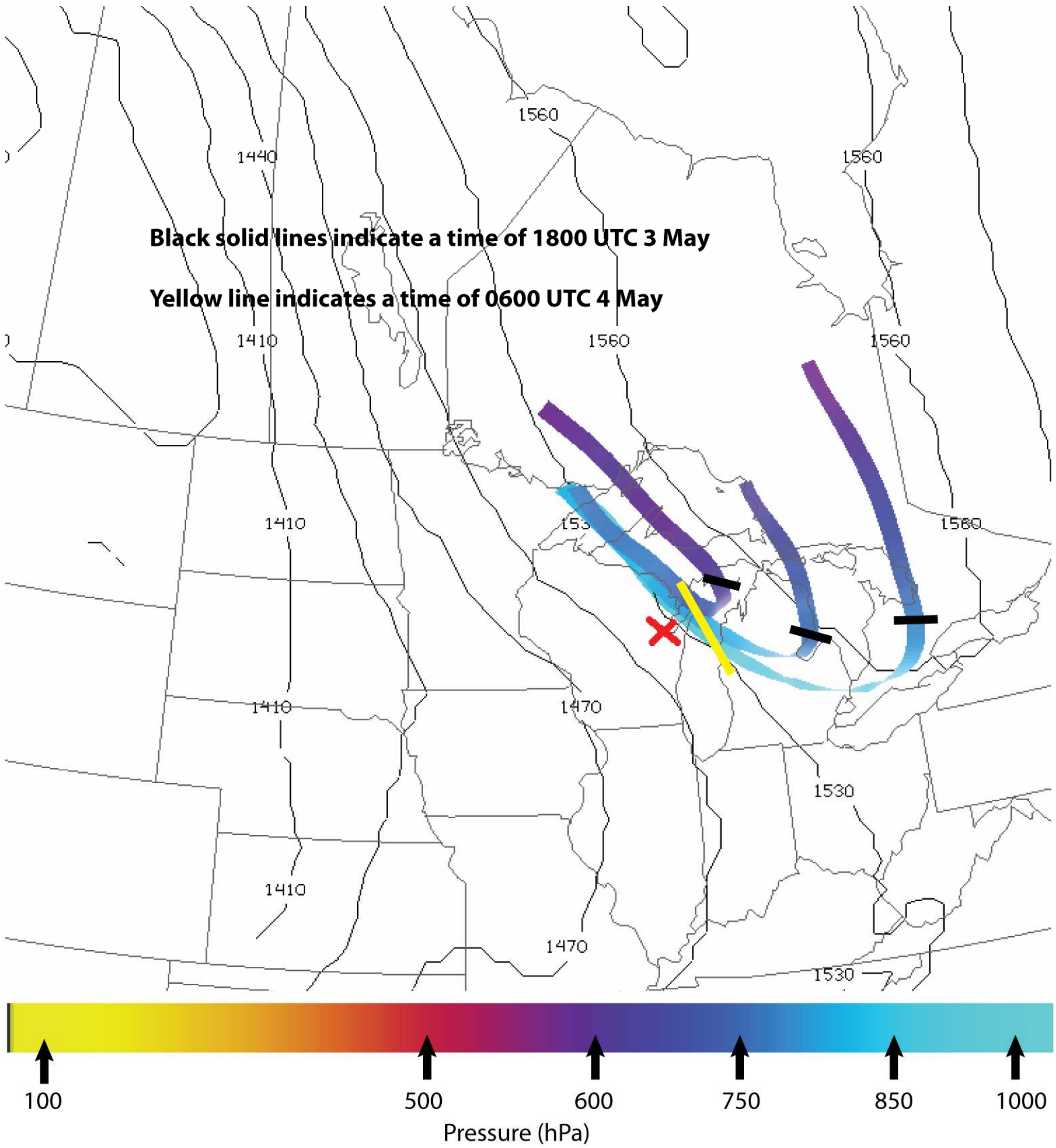

Figure 3.16. 48 hr backward trajectories ending at 1800 UTC 4 May 2007 at Ham Lake. The trajectories are shaded based on the pressure level at which they reside. The red x marks the spot where the Green Bay sounding in Figure 3.19 was taken. Black contours are 850 hPa geopotential heights contoured with black lines every 30 m at 0600 UTC 4 May 2007.

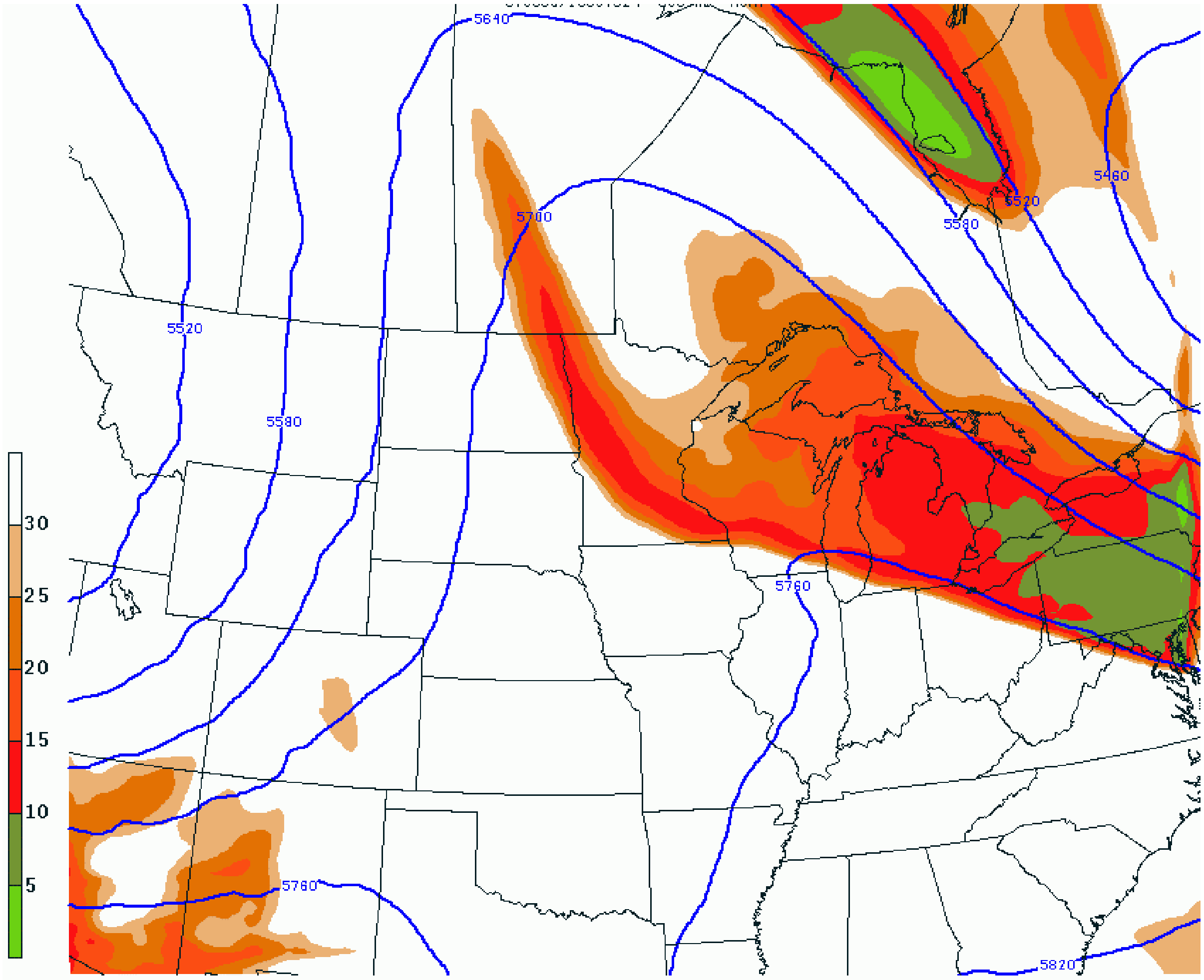

Figure 3.17. 500 hPa geopotential heights contoured with blue lines every 60 m at 1800 UTC 3 May 2007 from the 24 hr forecast of the WRF-ARW. In addition, 700 hPa relative humidity shaded every 5% with a maximum of 30% at 0000 UTC 4 May 2007 from the 30 hr forecast of the WRF-ARW.

synoptic scale vertical motion. The air was then advected by the southeasterly lower-level tropospheric flow northwestwards to the Ham Lake area.

An observed sounding at 1200 UTC 4 May from Green Bay, WI (shown with an X on Fig. 3.18), taken as the historically subsided air moved through the Green Bay area, shows extremely dry air with dewpoints approaching -30°C in the lower troposphere (850 hPa to

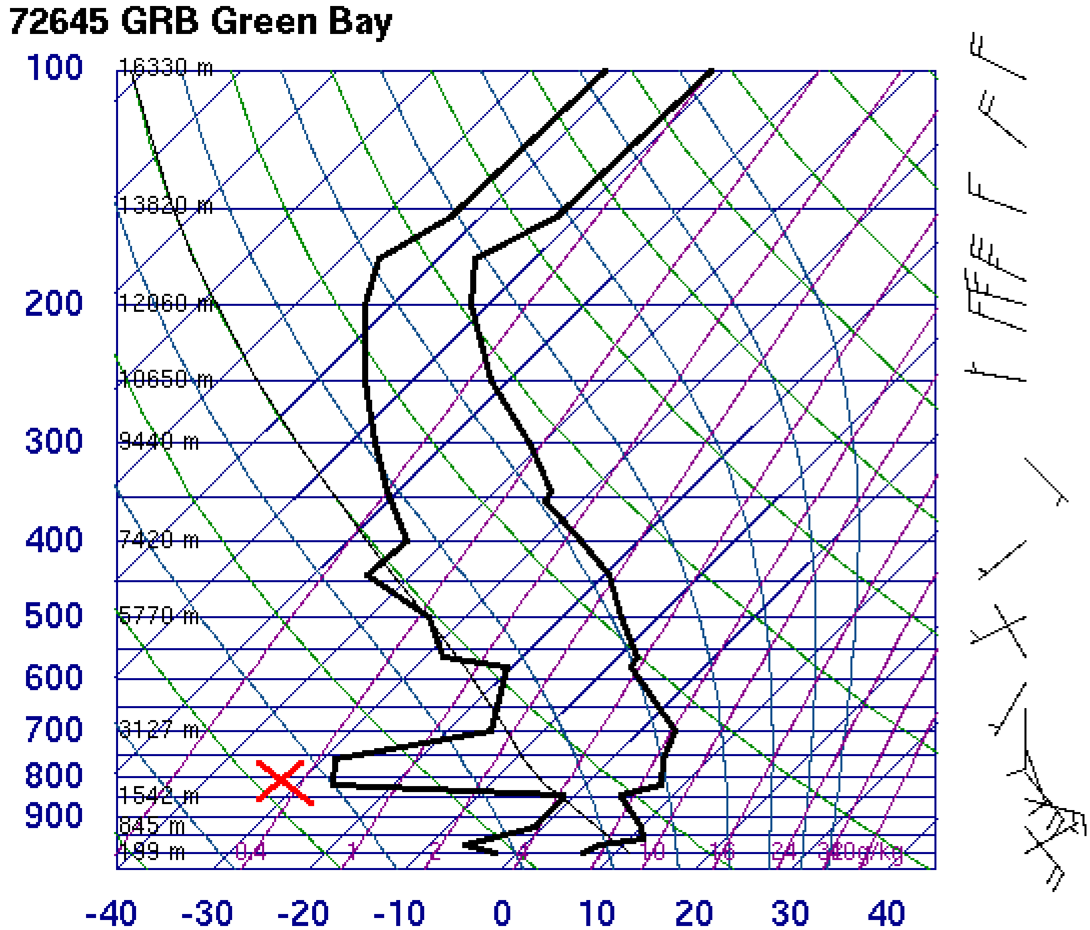

Figure 3.18. Skew-T log-p diagram from 1200 UTC 4 May 2007 at Green Bay, WI (courtesy of University of Wyoming Department of Atmospheric Science). Temperature is the right black line and dewpoint is the left black line. Temperature is labeled in degrees Celsius on the x-axis with pressure in hPa on the y-axis. Wind barbs are in knots. The red x marks the level where the air parcels headed towards Ham Lake pass Green Bay.

700 hPa). In addition, a strong surface nocturnal inversion was present at Green Bay. At the same time a sounding at the Ham Lake area from the WRF-ARW model shows a strong nocturnal inversion at the surface with dry air above the inversion (Fig. 3.19). The dry air above the inversion at Ham Lake had dewpoint temperatures in the range of -15°C to -20°C. The Green Bay sounding emphasizes that the air moving through the area at 1200 UTC 4

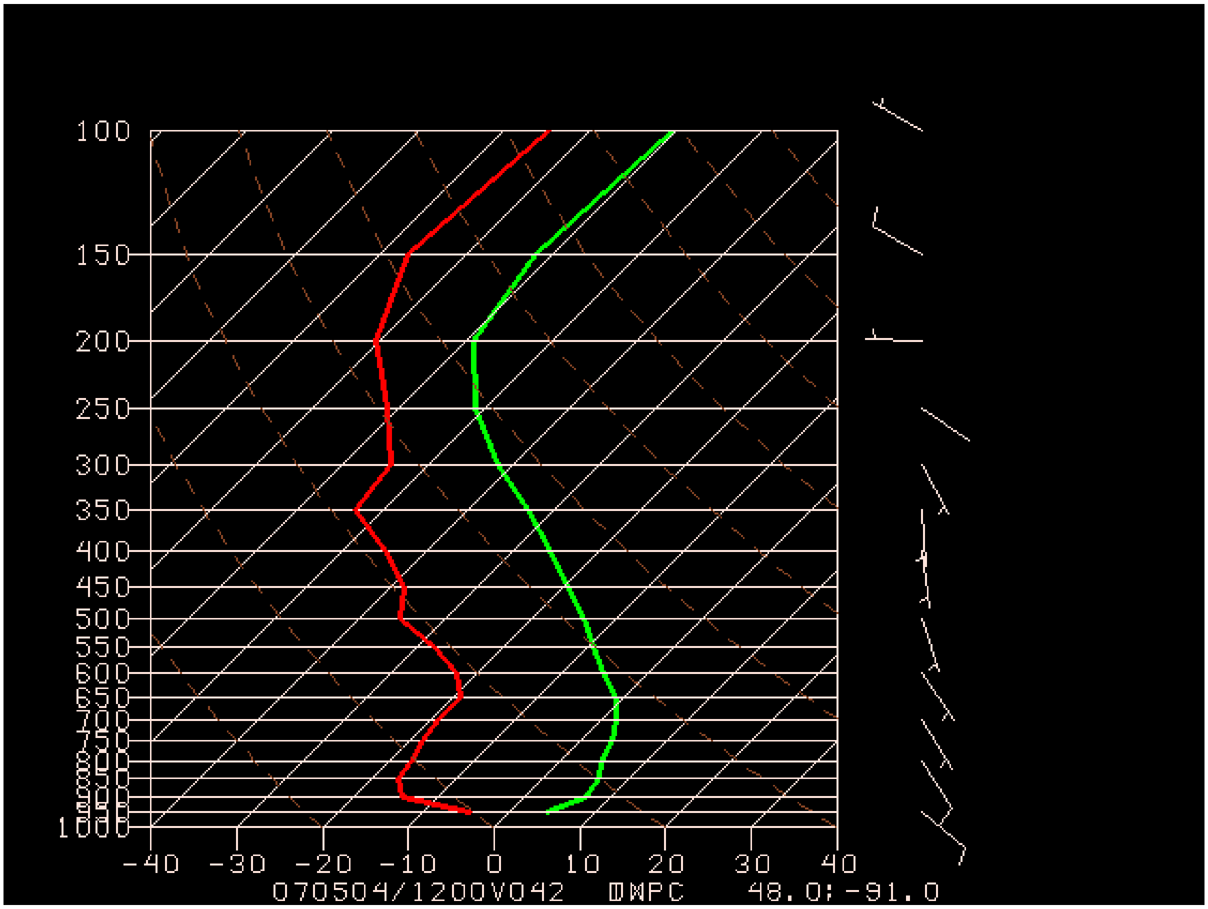

Figure 3.19. Skew-T log-p diagram from 1200 UTC 4 May 2007 at Ham Lake from the 42 hr forecast of the WRF-ARW. Temperature is the green line and dewpoint is the red line. Temperature is labeled in degrees Celsius on the x-axis with pressure in hPa on the y-axis. Wind barbs are in m s^{-1}.

May and towards Ham Lake by 1800 UTC 4 May was very dry. The two soundings also indicate that strong daytime heating was needed to overcome the pronounced surface nocturnal inversions, and mix the existing dry air and approaching very dry air to the surface. The Seagull RAWS meteorogram near Ham Lake from 4 May between 1200 UTC and 1800 UTC recorded strong daytime heating from 0°C to 20°C coincident with the intense drying around 1800 UTC at the surface. A similar dry air intrusion at the same time was seen in the observations from the Grand Marais/ Cook County Airport ASOS (not shown) 52.3 km to the southeast, which emphasizes that the drying observed at the Seagull RAWS was not particular to that one station. The forecast sounding at 1800 UTC 4 May from the WRF-ARW has a hard time capturing the significant drying near the surface, but as stated before models often have problems representing the actual surface conditions for a variety of reasons (Case et al. 2008)

The night of May 4th into the morning of the 5th remained dry in the Ham Lake region with continued subsidence downstream. Dry air continued to be advected into the Ham Lake region with little change in the upper and lower tropospheric patterns. The wind remained a factor during the night with wind gusts above 6.7 m s^{-1}. The wind gusts were accompanied by clouds, which had moved in from the southwest. The combination of the gusty winds and clouds inhibited the formation of a nocturnal stable layer and allowed for continued mixing of the dry air from above the surface. The continual drying was evidenced by the temperature being 5.8°C above the normal nighttime low[11] and the relative humidity only rising to near 45% during the night, well below normal values above 70%[12] (Seagull RAWS). As day broke over Ham Lake on 5 May, an area of light rain showers moved into northeast Minnesota (Duluth, MN radar courtesy of NCDC, not shown). The Seagull RAWS right near Ham Lake received no precipitation from these light showers. This was most likely a result of the low relative humidities already present at Ham Lake. If the rain had not evaporated the fire at the campsite might never have burned out of control. As these rain showers exited the region the temperature rose 4°C and the relative humidity lowered

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[11] Average nighttime low temperature from International Falls, MN used for comparison. Information gathered from the NWS in Duluth, MN.

[12] Based on the nearest climate station of Duluth, MN and its May early morning (7 a.m. local standard time) average relative humidity of 75% (NCDC).

significantly for a second time from near 45% to just below 30%. In addition the winds started to gust to 16.1 m s^{-1} (Seagull RAWS). This all coincided with the initial run of the Ham Lake Fire and contributed to the fire being very hard to control (Schierenbeck, personal communication).

A third and final dry intrusion, that is investigated, occurred at Ham Lake around 0600 UTC 6 May. The meteorogram from the Seagull RAWS shows a drop in dewpoints from -4°C to -14°C around this time. To determine the source of the air parcels in the lower troposphere, around 850 hPa (this level is representative of the subsidence that occurred in the entire lower troposphere), a backward trajectory was completed for a parcel moving into the Ham Lake region at 0600 UTC 6 May (Fig. 3.20). The trajectory indicates long term subsidence (Fig 3.20) again on the eastern side of an amplified 500 hPa ridge (Fig 3.21). The parcel trajectory indicates sinking from near 500 hPa down to 800 hPa over eastern Ontario (Fig. 3.20). The air stops sinking just north of Lake Huron at 1500 UTC 5 May. The very intense reservoir of dry air related to the subsidence is shown with relative humidities below 15% (Fig. 3.21). From there the air was advected toward Ham Lake on the western side of the surface high pressure system. Even with the transport of very dry air into the Ham Lake region at 0600 UTC 6 May it still is an unexpected result to see such intense drying at night when normally a nocturnal surface inversion develops due to radiational cooling. For a

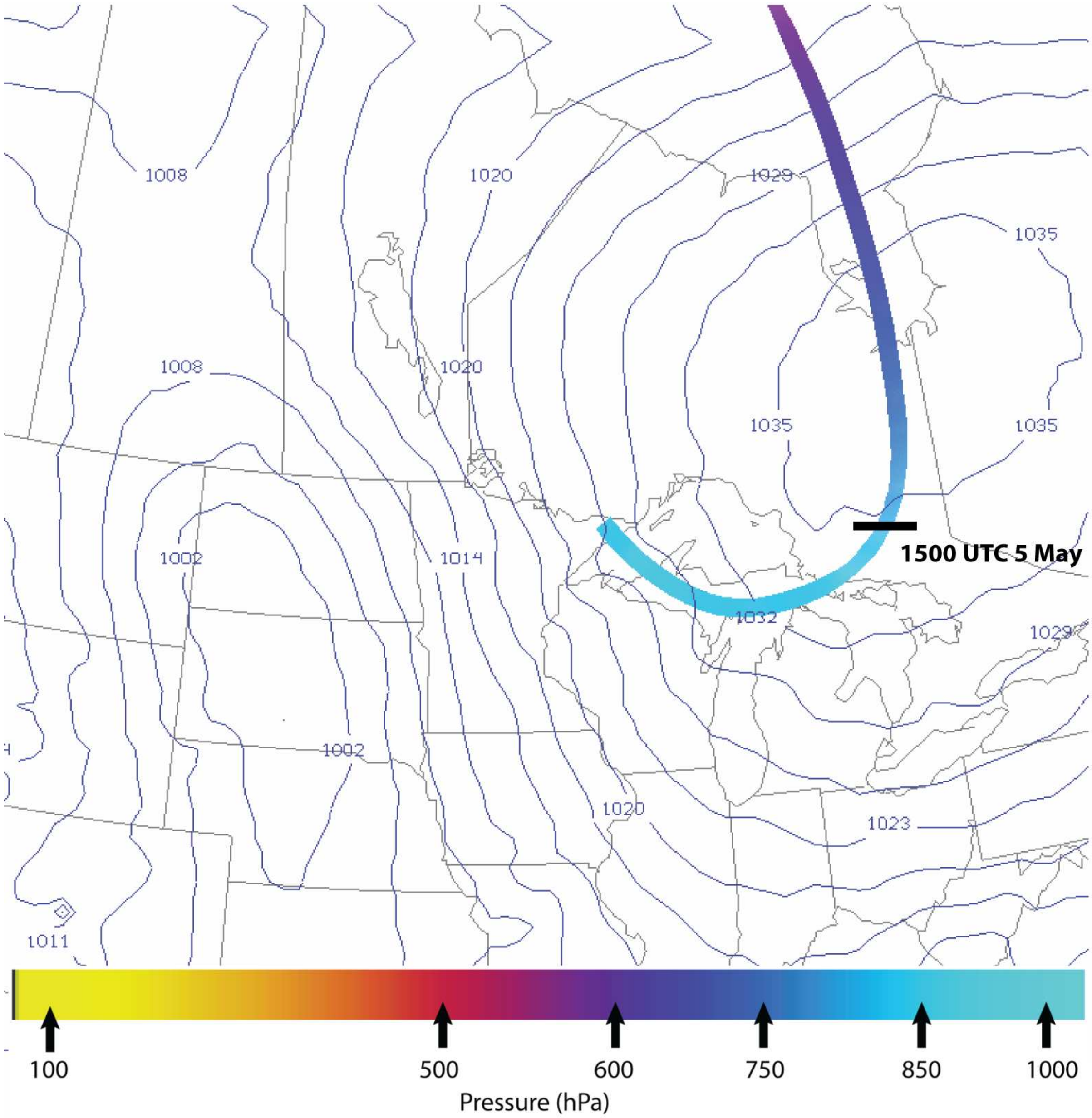

Figure 3.20. 84 hr backward trajectory ending at 0600 UTC 6 May 2007 at Ham Lake. The trajectory is shaded based on the pressure level which it resides. Additionally, sea level pressure in hPa contoured in blue every 3 hPa at 0600 UTC 6 May.

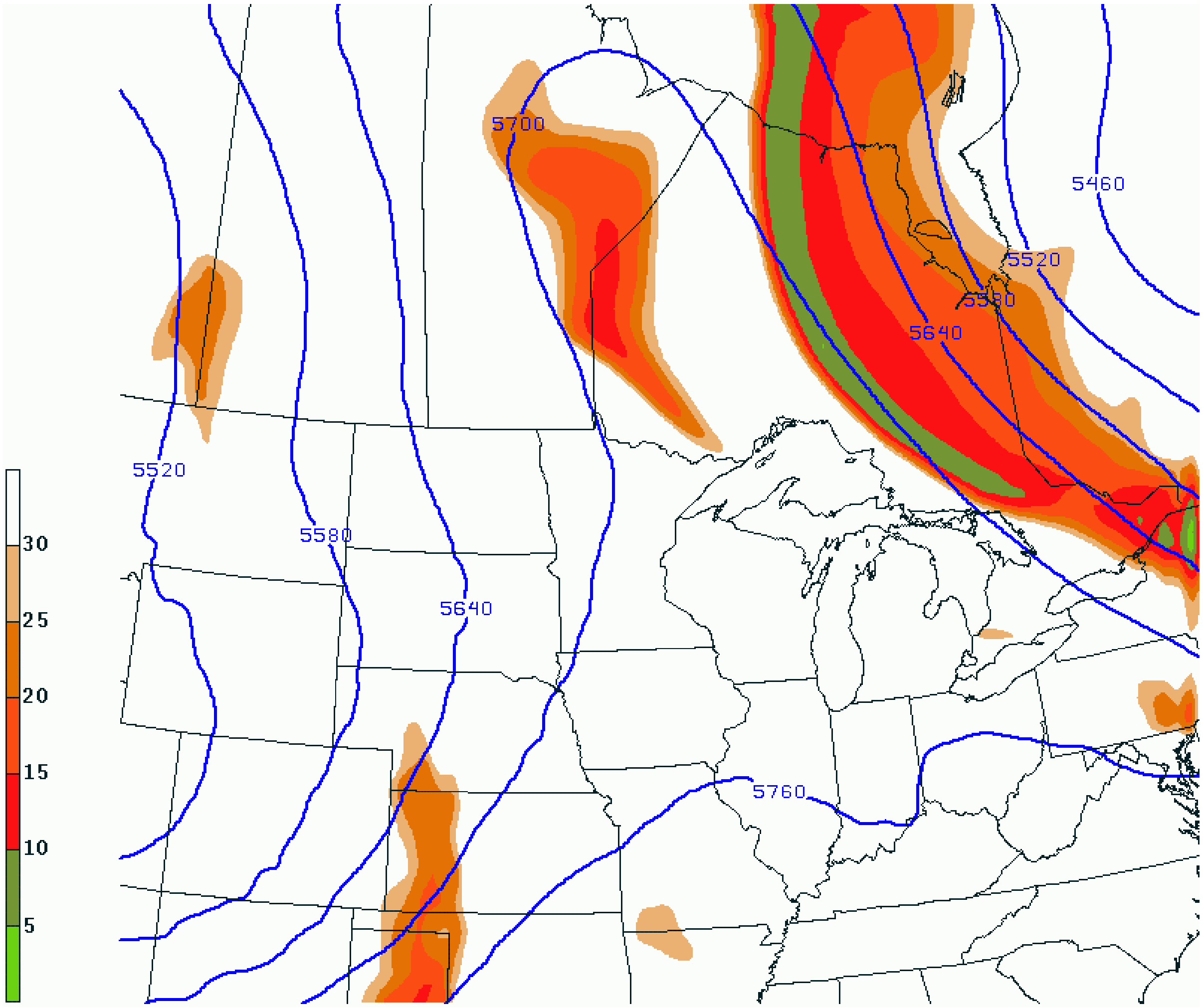

Figure 3.21. 500 hPa geopotential heights contoured with blue lines every 60 m at 0600 UTC 5 May 2007 from the 60 hr forecast of the WRF-ARW. In addition, 800 hPa relative humidity shaded every 5% with a maximum of 30% at 1500 UTC 5 May 2007 from the 69 hr forecast of the WRF-ARW.

second straight night a nocturnal inversion was inhibited from developing by strong surface winds of 5 m s^{-1} gusting to 10.7 m s^{-1} at and just above the surface (Seagull RAWS). The strong winds were due to a strong surface pressure gradient that had developed over the Ham Lake area (Fig. 3.20). The strong winds kept the air temperature from dropping substantially and caused the dewpoints to crash by mixing in the warm dry air that had been advected into the region at ~1 km above sea-level. All this contributed to an aggressively burning fire on the night of May 6th (Schierenbeck, personal communication).

4. Discussion

The Ham Lake Fire serves as an example of a large Great Lakes fire influenced by subsidence associated with synoptic scale upper level downward motion on the eastern side of a 500 hPa ridge and anticylonic shear side of a 500 hPa jet stream. This subsidence brought dry air down from upper levels and enhanced the dryness through adiabatic compression and warming, which led to air with very low relative humidities. This dry air was then advected toward the Ham Lake region by the southeasterly flow pattern present near the surface from May 4th-6th on the southwestern side of the surface high to the northeast of Ham Lake. Once transported to the fire region the dry air was mixed downwards towards the surface by diurnal surface heating during the days of May 4th and May 5th. A third dry air intrusion was enabled by the development of a strong near surface pressure gradient, which created strong winds that inhibited the formation of a nocturnal stable layer and allowed for continued boundary layer mixing during the early morning hours of May 6th. The 3-D circulation, centered on the downstream side of an upper-level ridge, provided both the large scale subsidence necessary to lower the relative humidity of the subsiding air as well as the horizontal, near surface winds necessary to transport the dry air toward the Ham Lake Fire region. The extreme dryness with relative humidities below 30% and even below 10% on May 4th, coupled with already existing long-term drought conditions and plentiful dead, dried fuels set the stage for an explosive wildfire upon ignition that even a large suppression effort could not control.

c. Black River Falls and Pinery Fires, May 2009

1. Fire characteristics and observed atmospheric conditions

The Black River Falls and Pinery Fires both began late in the afternoon of May 20th, 2009 and burned areas in the central and western parts of the Upper Peninsula of Michigan. These fires were considerably smaller in scale then the Mack Lake and Ham Lake events. The Black River Falls Fire was located in Marquette County, 11.3 km southwest of the town of Ishpeming while the Pinery Fire was located in Baraga County just northeast of the city of L'Anse (location G and H, Fig. 2.1). The days and night before the fires had been cool with high relative humidities, but on the morning of the 20th a warm front progressed northward (detailed later) and while temperatures warmed significantly during the day and approached 32.2°C degrees in both locations, dewpoints also dropped approximately 8 to 9 degrees from their morning peaks (Marquette, Sawyer International Airport ASOS, L'Anse Citizen Weather Observer (CWO), and Negaunee CWO). Upon ignition the fires quickly grew to approximately 800 acres (Black River Falls Fire) and 700 acres (Pinery Fire) before being contained with the help of rain late in the afternoon of 21 May (NICC). The Black River Falls Fire was reported to have charred 100 acres in just a couple of hours after starting on the evening of the 20th (WLUC-TV[13]). It destroyed 21 homes and likely started as result of a downed power line, while the Pinery Fire, in a more rural area of American Indian land, destroyed one home and currently has no listed cause (WLUC-TV[13]). Both fires burned pine forests and a grass and timber understory was also involved in the Black River Falls Fire. The fact that the fire danger rating from the NFDRS jumped from moderate on the 19th of May to very high on the 20th of May (Wildland Fire Assessment System, U.S. Forest Service) indicated a significant short-term change that was most likely due to the warm front and associated changing atmospheric conditions from May 19th to the 20th. The quickly changing burning conditions along with influx of warm, dry air provide the motivation to examine how the variable atmospheric conditions before and on the day of the fires produced the low relative humidity and high wind speeds in the vicinity of the fires.

2. Atmospheric conditions preceding fire

Long term drought was not a large factor in these fires as their locations were only in the first stage of drought on May 19th (NDMC) and had high 1000 hour fuel moisture contents (WFAS- U.S. Forest Service). It is notable, however, that as a result of the little precipitation that had been observed since 8.1 mm fell at Marquette on 16 May, the 100 hour fuel moisture contents[14] were somewhat low (NWS). So what atmospheric set-up led to the brief period of very high fire danger on May 20th, 2009 over the Upper Peninsula of Michigan? At 1200 UTC 15 May 2009 a 500 hPa upper ridge moved eastward and amplified

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13 www.uppermichiganssource.com

14 100 hour fuel moisture makes use of an appropriate version of the Fickian diffusion equation to represent the percentage water content of medium sized (1 to 3’’ in diameter), dead fuels (WFAS- U.S. Forest Service).

just off of the Pacific Coast of North America (Fig. 3.22a). This led to a portion of the surface Pacific high pressure system breaking off and moving inland over southern British Columbia and northern Washington (Fig. 3.22b). By 1200 UTC 17 May the upper ridge had moved eastward into the Great Basin of the U.S. (Fig. 3.23a). As a result, the surface high pressure system became dominant over the entire central U.S. and was centered over the Iowa/Illinois border (Fig. 3.23b). The ridge eventually broadened further and by 1200 UTC 19 May it dominated the entire U.S. from the Rocky Mountains to the eastern Great Lakes (Fig. 3.24a). This led to a broad region of high pressure from the coast of Maine southwestward to the Mexican Plateau and southern Rocky Mountains (Fig. 3.24b). At the same time a sharp trough was moving inland to the northern U.S. from the Pacific. This led to the development of a surface cyclone just north of Idaho on the Alberta/ British Columbia border. By 1200 UTC 20 May the upper level ridge progressed eastward and centered itself over the Ohio River valley north of a cut-off low over the Gulf of Mexico (Fig. 3.25a). The surface high progressed to the east as well and it became centered over the Delmarva Peninsula with an influence all the way back towards Texas (Fig. 3.25b). In addition a strong pressure gradient developed over the western Great Lakes states on the eastern side of a strengthening surface low centered over eastern North and South Dakota. A warm front extended eastward from the surface low through Minnesota, the northern portion of the Upper Peninsula of Michigan, and over Lake Huron with a cold front extending back to the southwest through Rapid City (Fig. 3.25b). Note that most of the upper peninsula of Michigan was just south of the warm front including the areas of the Black River Falls and Pinery Fires. In addition a slight pressure trough extended to the south from the surface low center.

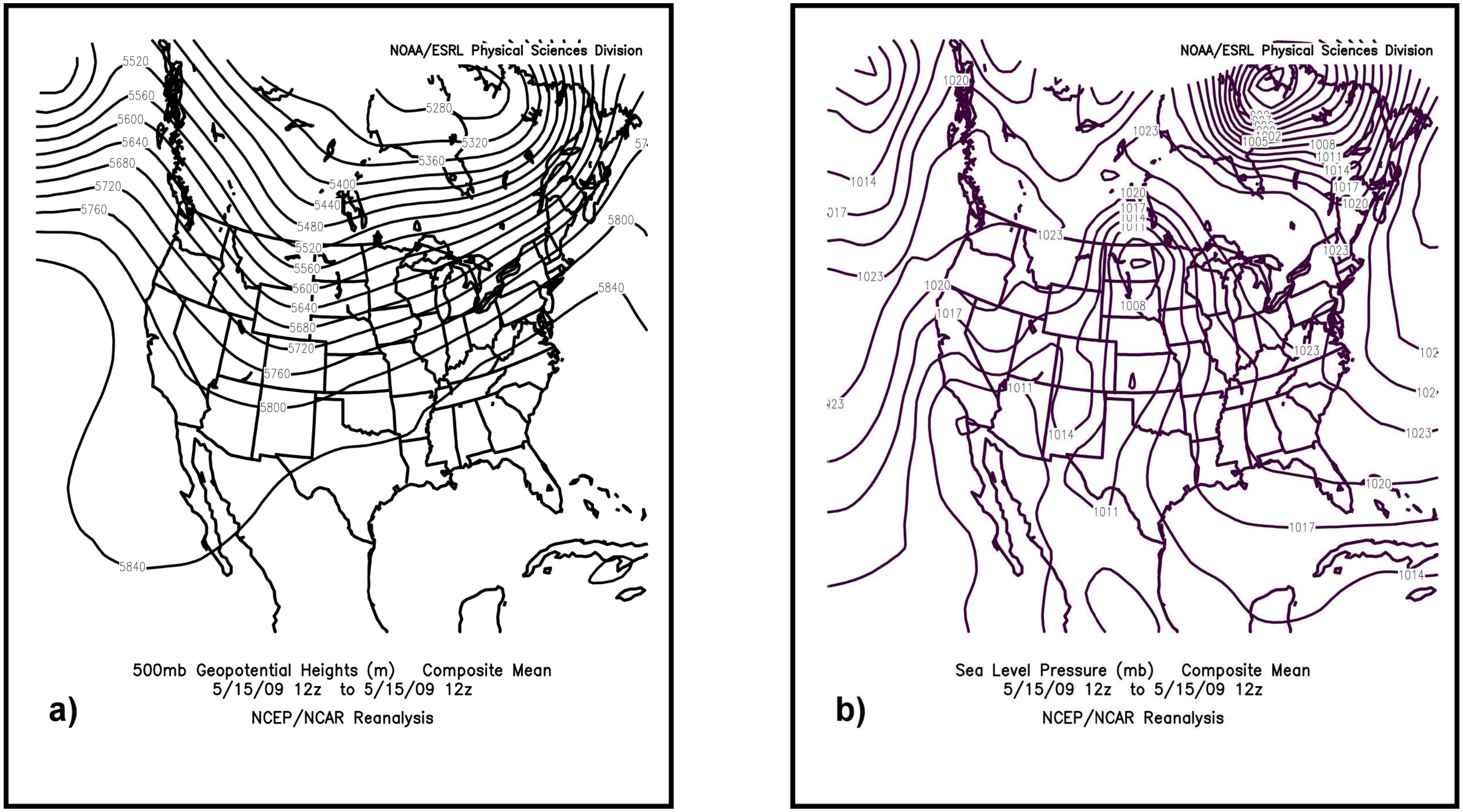

Figure 3.22. Maps showing locations of upper-level and surface features for 1200 UTC 15 May 2009. a) 500 hPa geopotential heights contoured every 40 m from the NCEP/NCAR Reanalysis dataset. b) As for Fig. 3.22a except for mean sea level pressure contoured every 3 hPa. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

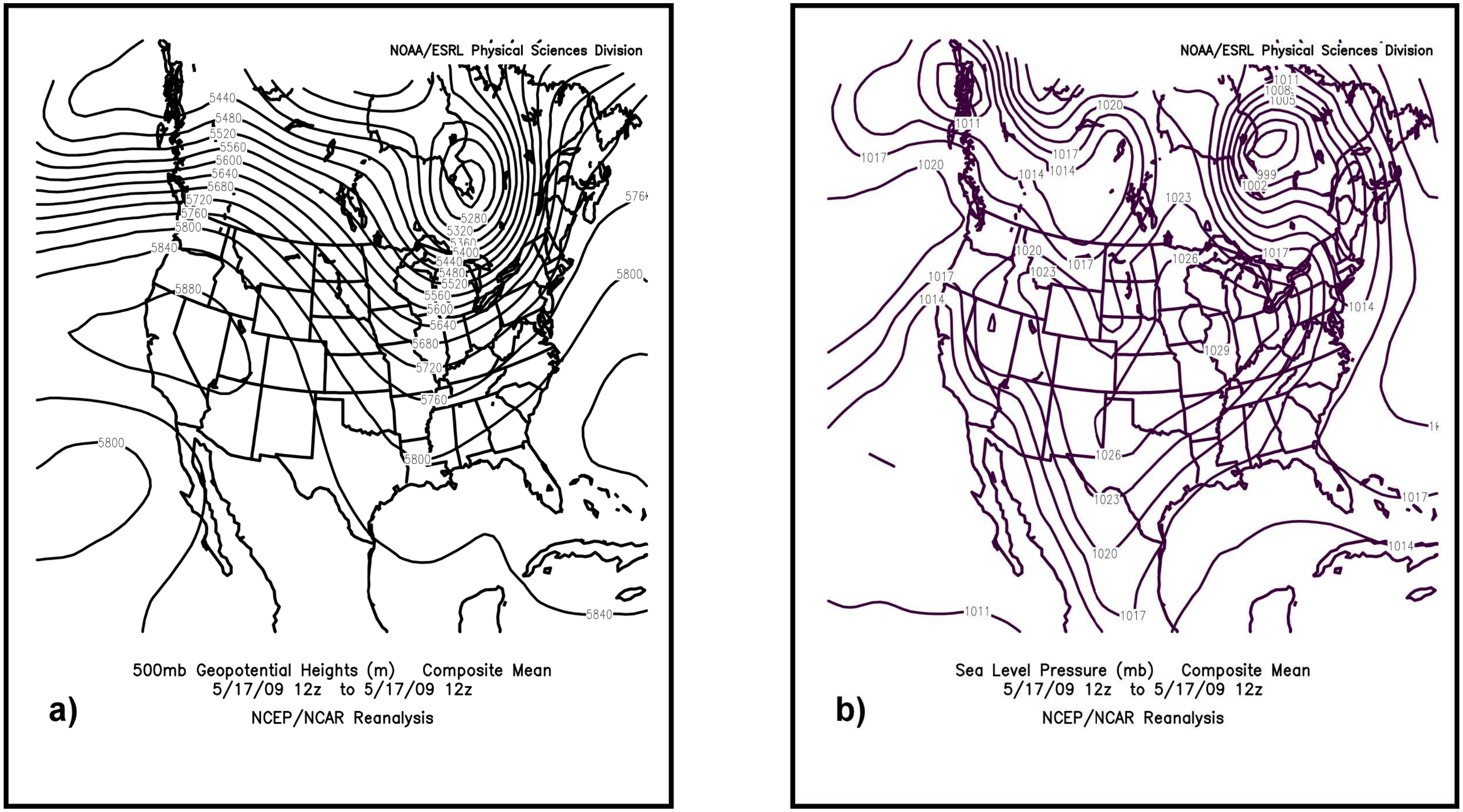

Figure 3.23. For Figure 3.22 but for 1200 UTC 17 May 2009. a) As for Fig 3.22a. b) As for Fig. 3.22b. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

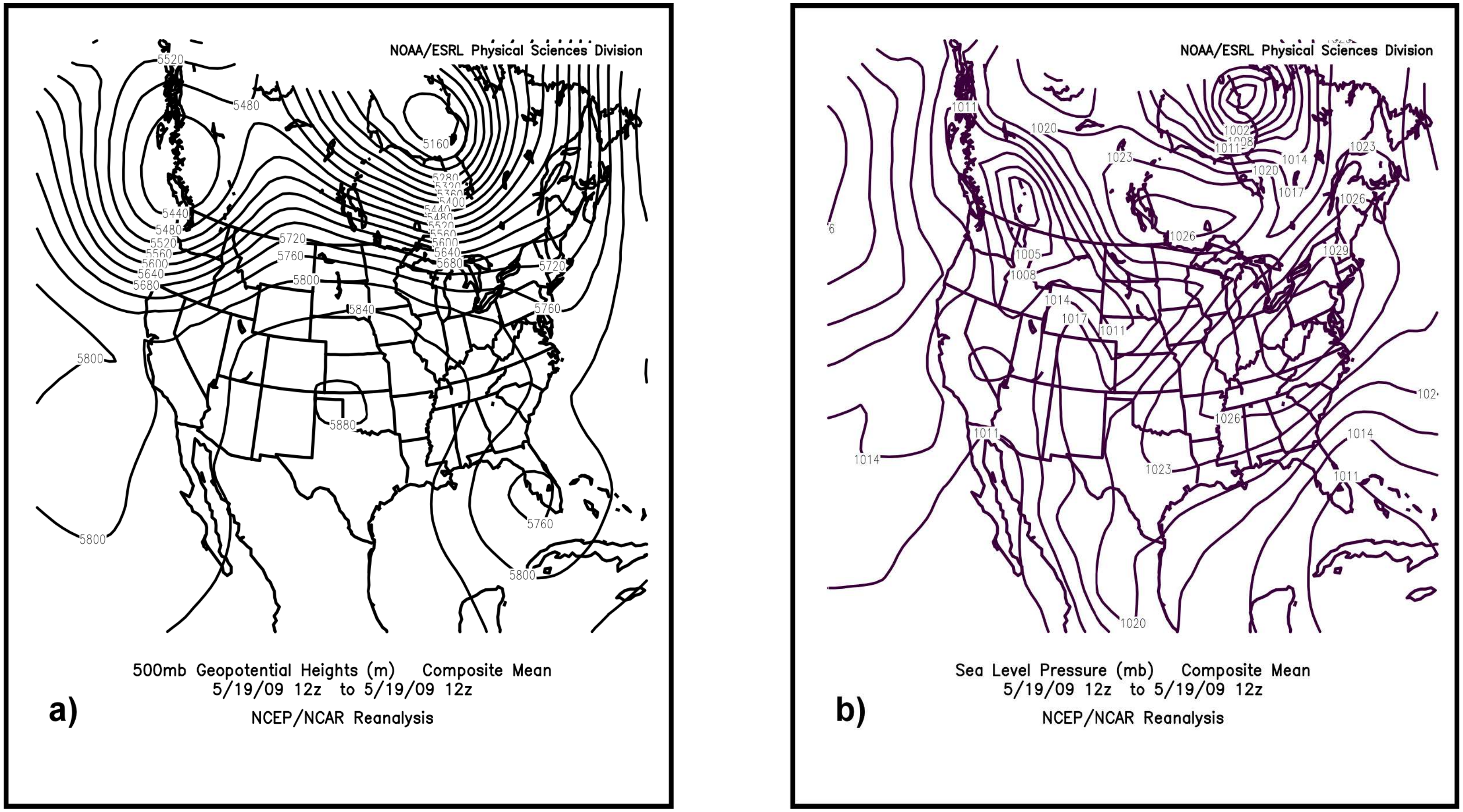

Figure 3.24. For Figure 3.22 but for 1200 UTC 19 May 2009. a) As for Fig 3.22a. b) As for Fig. 3.22b. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

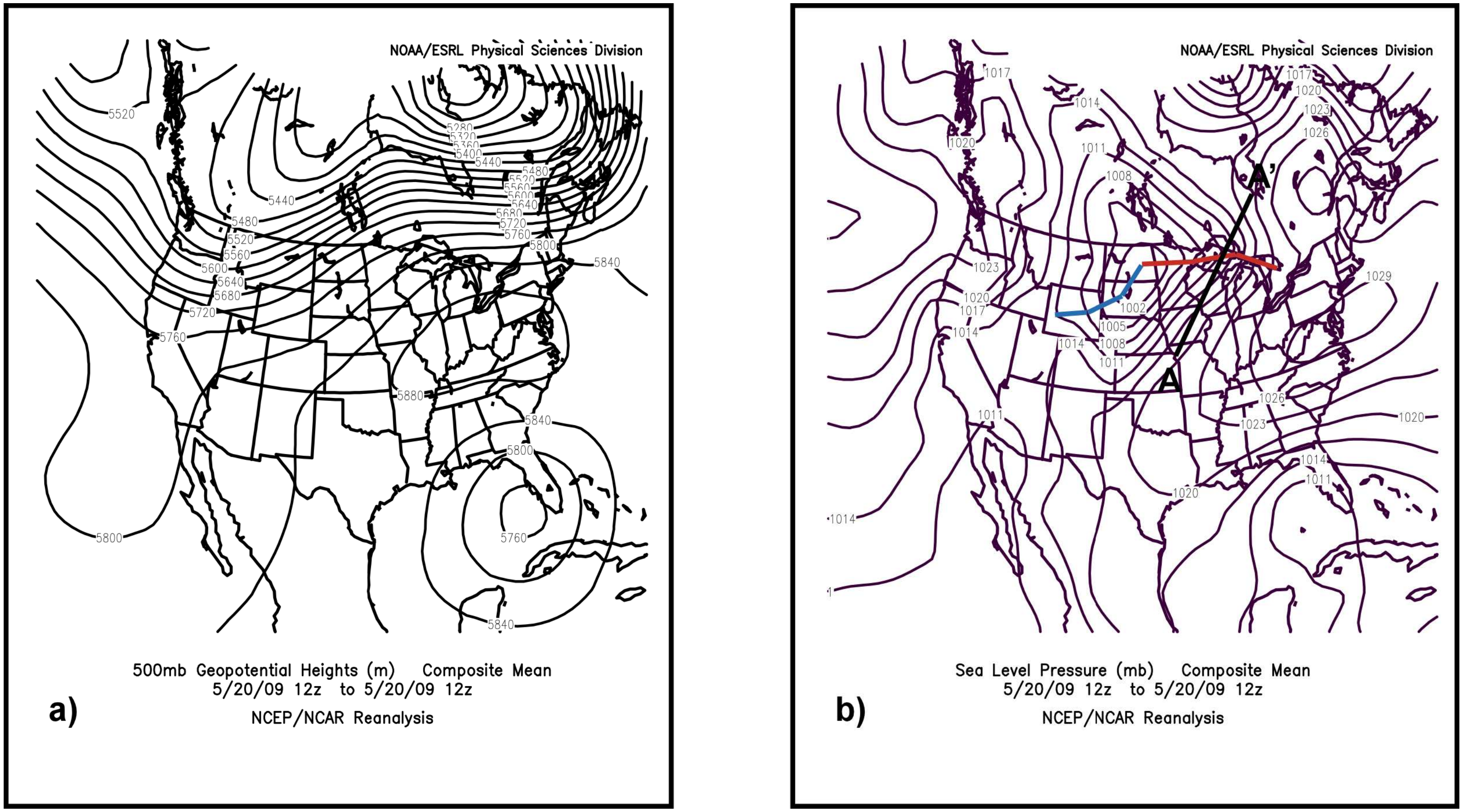

Figure 3.25. For Figure 3.22 but for 1200 UTC 20 May 2009. a) As for Fig 3.22a. b) As for Fig. 3.22b, but with the analyzed warm frontal position demarcated by the red line. (Maps courtesy of NOAA/ESRL Physical Sciences Division).

The pattern at 1200 UTC 20 May, 2009 is similar in some ways to previously identified patterns in Schroeder et al. (1964), Brotak and Reifsnyder (1977), and Heilman (1995). This fire occurs in the warm sector of the low pressure system to the west and thus falls into a category of only 12% of fires for the Eastern U.S. according to the study done by Brotak and Reifsnyder (1977). The 1200 UTC 20 May pattern of a broad ridge over the eastern U.S. with a trough over the west coast of the U.S. brought southwesterly flow at upper levels to the western Great Lakes states. This is different from the mean northwesterly flow identified in Schroeder's analysis of days in the Great Lakes region with high fire danger. The 1200 UTC 20 May upper air pattern is similar though, to circulation pattern 2 that Heilman (1995) identified as a common pattern existing on the day of large (>1000 acres) wildfires in *his* region 3, which includes the Upper Peninsula of Michigan.

To further analyze the atmospheric conditions and connections between the upper level ridge and surface high with the Black River Falls and Pinery Fires, output from the numerical model outlined earlier will be used. A 39 km horizontal resolution domain of the WRF-ARW model initialized at 1200 UTC 17 May 2009 and run for 96 hours centered over the Upper Peninsula of Michigan is used (refer back to figure 3.5).

3. Subsidence

How did the surface air on the Upper Peninsula dry out so much on May 20th after the warm front moved north of the area? To obtain a more complete picture a vertical cross section (along the line A-A' in Fig. 3.25b) normal to the surface warm front and in the same direction as the lower tropospheric flow pattern is produced. At 1800 UTC 20 May the cross section shows that very low RH air <=10% existed above the fire locations (Fig. 3.26). As stated before, the models misrepresent the temperature and dewpoint of the lowest layers slightly so the high relative humidities just above the surface may be ignored. At the same time a sharp decrease in relative humidity was observed at all three stations near the fires (Marquette ASOS, L'Anse CWO, and Negaunee CWO). The decrease in the relative humidities was not due just to the warm front moving north through the Upper Peninsula. The movement of the warm front northward is shown with two meteorograms (Fig 3.27a- temperature, Fig. 3.27b- wind) from one of the examined stations located in the Upper Peninsula (Marquette ASOS) (L'Anse CWO, and Negaunee CWO also recorded similar observations but are not shown here). A wind shift, an increase in wind speed and a steady to slightly rising pre-dawn temperature (warm air advection likely was countered by nighttime radiational cooling) indicated the passage of the warm front at all three stations just after 0600 UTC 20 May. After sunrise the surface temperatures rose continuously at all three stations. The dewpoints rose continuously after the passage of the warm front, but as soon as the temperatures reached a critical level the dewpoints quickly dropped 7 to 9 degrees Celsius. Surface advection can be ruled out as a cause of the dewpoint drop because the dewpoints upstream to the south over Wisconsin were higher (Antigo RAWS, not shown). Thus there must have been mixing from above. We hypothesize that as the temperatures increased, dry convective mixing increased as well and the boundary layer deepened. Due to the warmer temperatures over the Upper Peninsula as opposed to the lower temperatures over Wisconsin more mixing and dry convection was able to take place, which helped to erode any subsidence inversion. A sounding from Green Bay, WI at 0000 UTC 21 May is provided as further evidence to support our hypothesis (Fig. 3.28). The sounding shows a

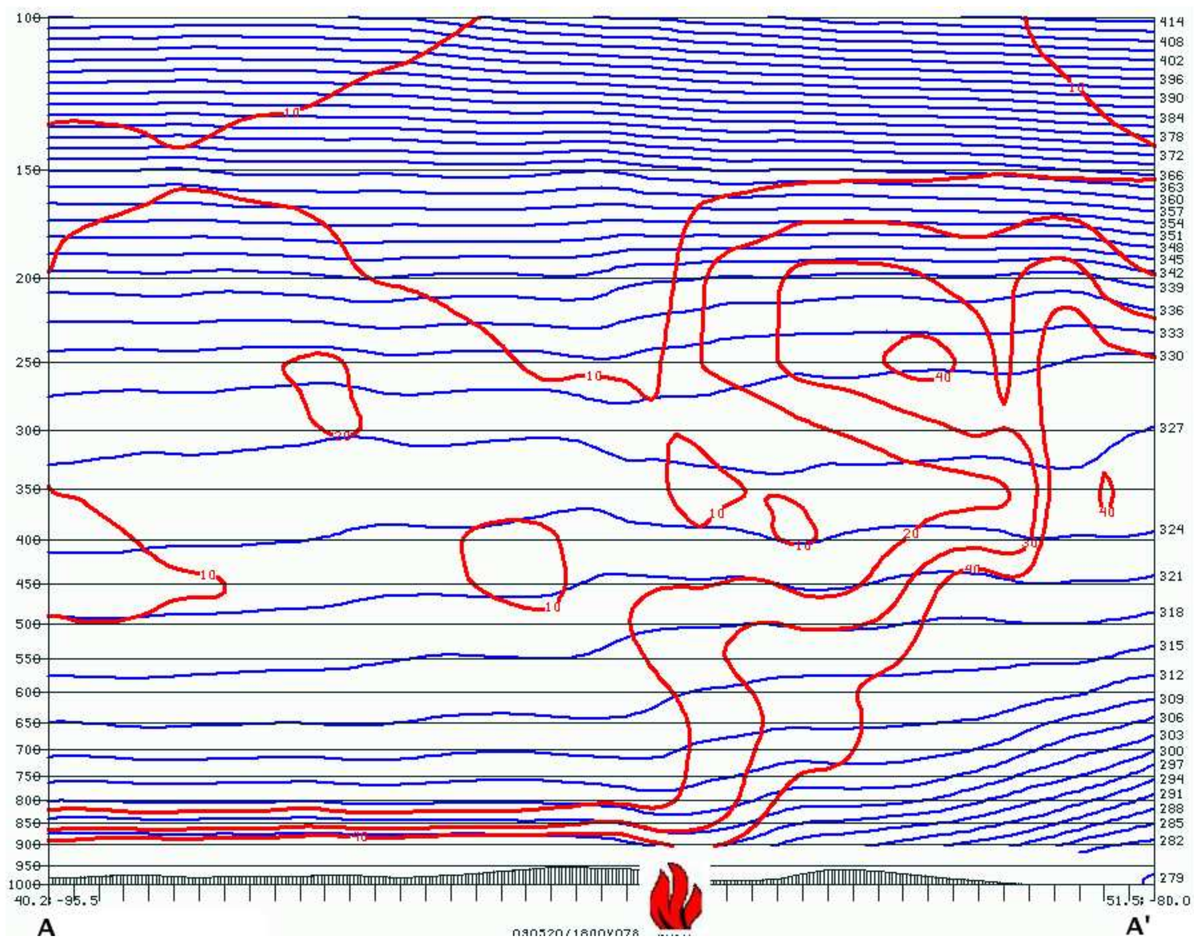

Figure 3.26. Vertical cross section along the line A-A’ shown in Fig. 3.26b of potential temperature, and relative humidity from the 78 hr forecast of the WRF-ARW valid at 1800 UTC 5 May 1980. Theta is labeled in K every 3 K with blue lines and RH is labeled every 10% with a maximum of 40% in red lines. The Black River Falls and Pinery Fire locations are denoted by the red fire icon.

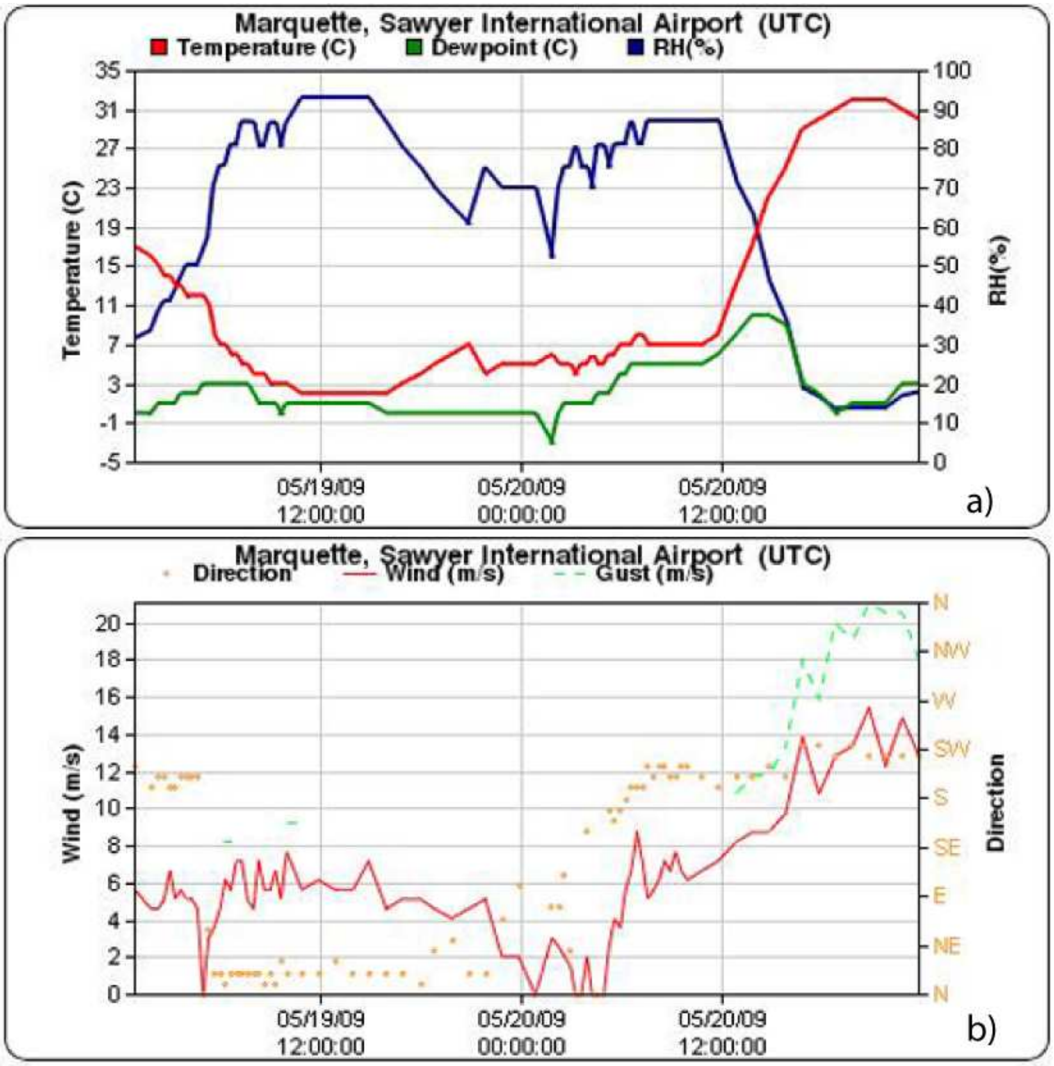

Figure 3.27. Meteorograms for Marquette ASOS from 0000 UTC 19 May to 0000 UTC 21 May a) Temperature °C with red line, dewpoint °C with green line, and Relative Humidity % with blue line b) wind m s^{-1} with red line, wind direction with yellow dots, and wind gust with green dashed line.

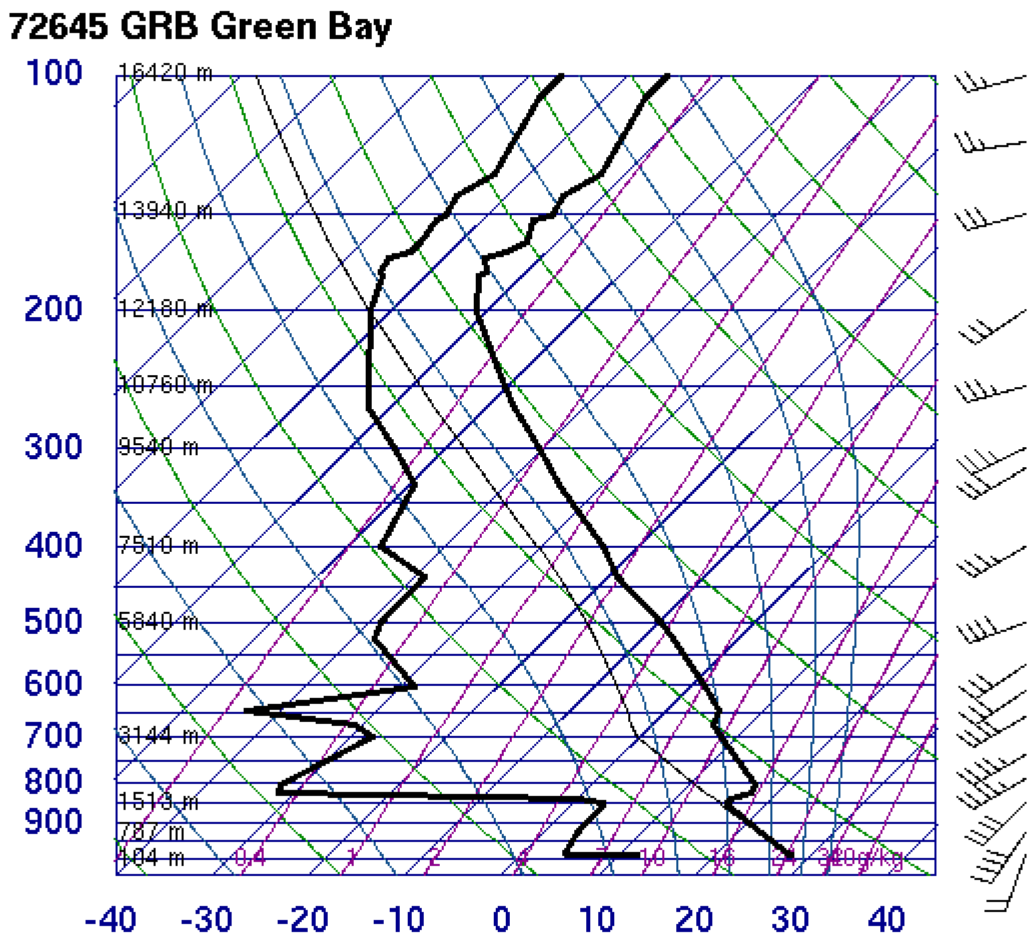

Figure 3.28. Skew-T log-p diagram from 0000 UTC 21 May 2009 at Green Bay, WI (courtesy of University of Wyoming Department of Atmospheric Science). Temperature is the right black line and dewpoint is the left black line. Temperature is labeled in degrees Celsius on the x-axis with pressure in hPa on the y-axis. Wind barbs are in knots.

subsidence inversion around 850 hPa, a lower surface temperature, and extremely dry air above 850 hPa. This lends credence to the hypothesis that increased mixing of dry air from above occurred over the Upper Peninsula due to the warmer surface temperatures.

Again, to determine the source of the dry air, backward air trajectories were calculated using the WRF-ARW model simulation for this case. Only one source point in the

Upper Peninsula for the air near the two fires will be shown here. The fires are close enough together that there is no synoptic scale weather or topographical barriers between them and the large scale patterns are the same for both fires.

Backward trajectories of parcels arriving in the Upper Peninsula at 0000 UTC 20 May, taken before the warm front passed to the north, show that when the air parcels reached the warm front they were lifted isentropically (Figure 3.29). This lifting led to adiabatic cooling, which resulted in the parcels having higher relative humidities. The warm front and the higher relative humidity air to the north of the warm frontal boundary along with the lower relative humidity to the south of the boundary are shown in the 1800 UTC 20 May vertical cross section (Figure 3.26). The cross section provides further evidence of the location of the warm front to the north of the Upper Peninsula at 1800 UTC 20 May. With the warm front to the north of the Upper Peninsula there was no longer a boundary to air sinking into the region around the periphery of the 500 hPa ridge that was present over the south-central U.S. in the days before the fires. Looking at trajectories for air that sank into the region between 1800-2100 UTC 20 May it is seen that the air parcels subsided (Fig. 3.30), adiabatically warmed, and dried on the eastern side of the 500 hPa ridge axis over southern Kansas and Oklahoma at 1800 UTC 18 May (Fig. 3.31). As stated previously, this area is a favored region of convergence aloft and thus sinking motion in the column (Martin, 2006). By 0600 UTC 19 May the sinking stopped at 650 hPa over Oklahoma and northern Texas as the ridge progressed eastward across the south-central United States. In the wake of the sinking, the relative humidity of the subsiding air that eventually would progress to the fire locations was less then 25% (Fig. 3.31).

At 1800 UTC 19 May as the upper ridge slowly progressed further to the east the air

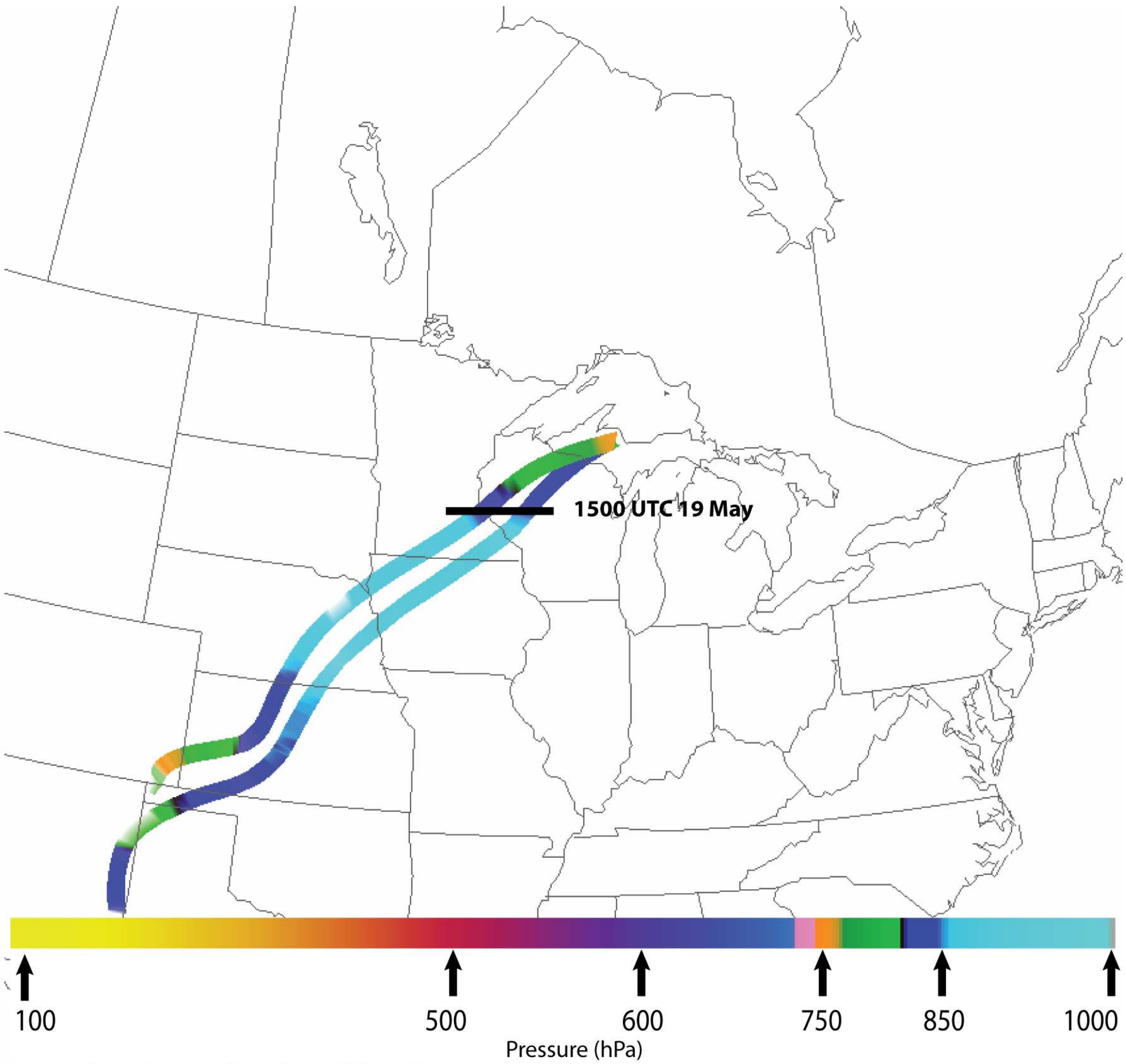

Figure 3.29. 60 hr backward trajectories ending at 0000 UTC 20 May 2009 near the Black River Falls and Pinery Fires. The trajectories are shaded based on the pressure level at which they reside.

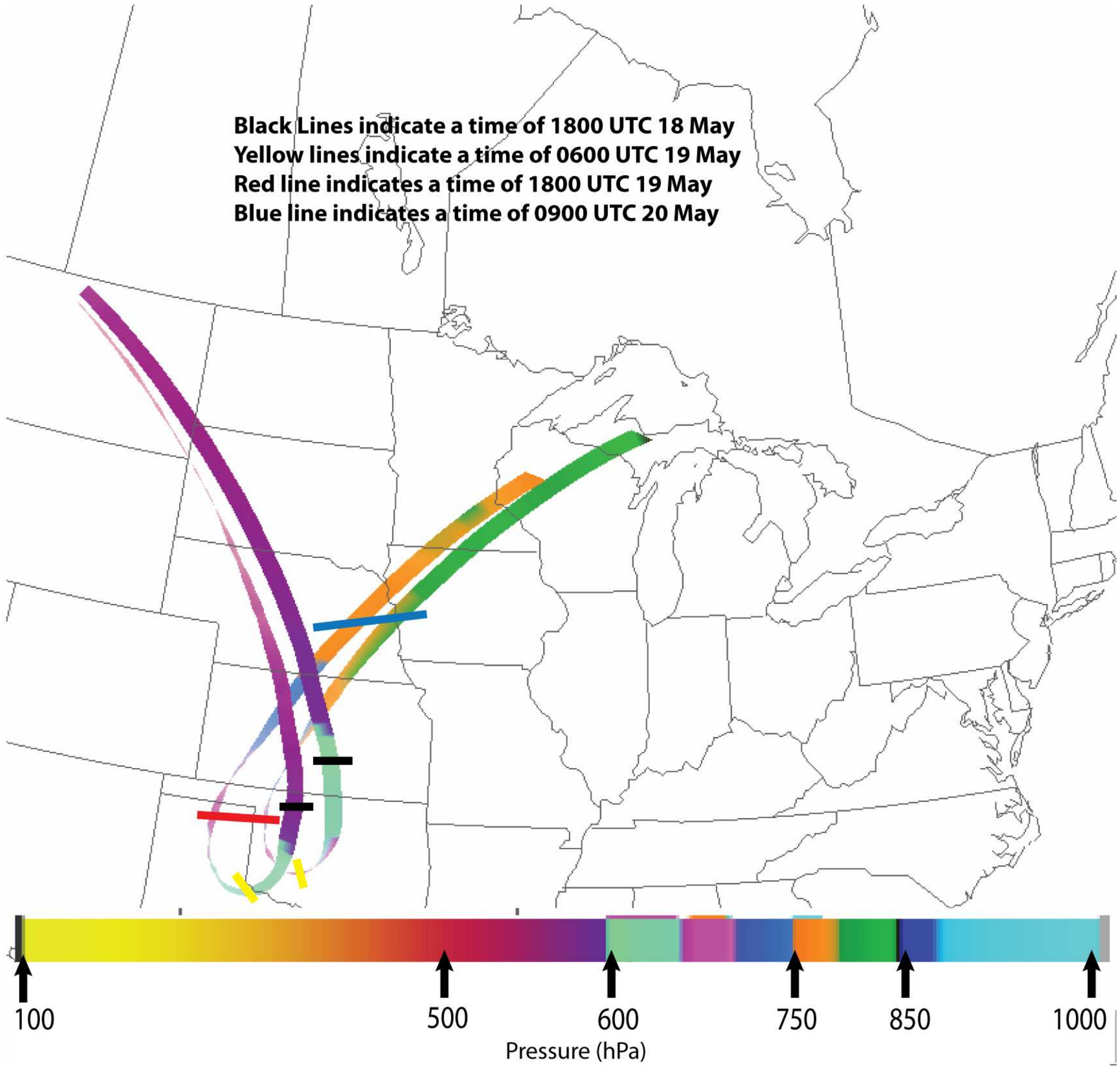

Figure 3.30. 78-81 hr backward trajectories ending at 1800-2100 UTC 20 May 2009 near the Black River Falls and Pinery Fires. The trajectories are shaded based on the pressure level they reside.

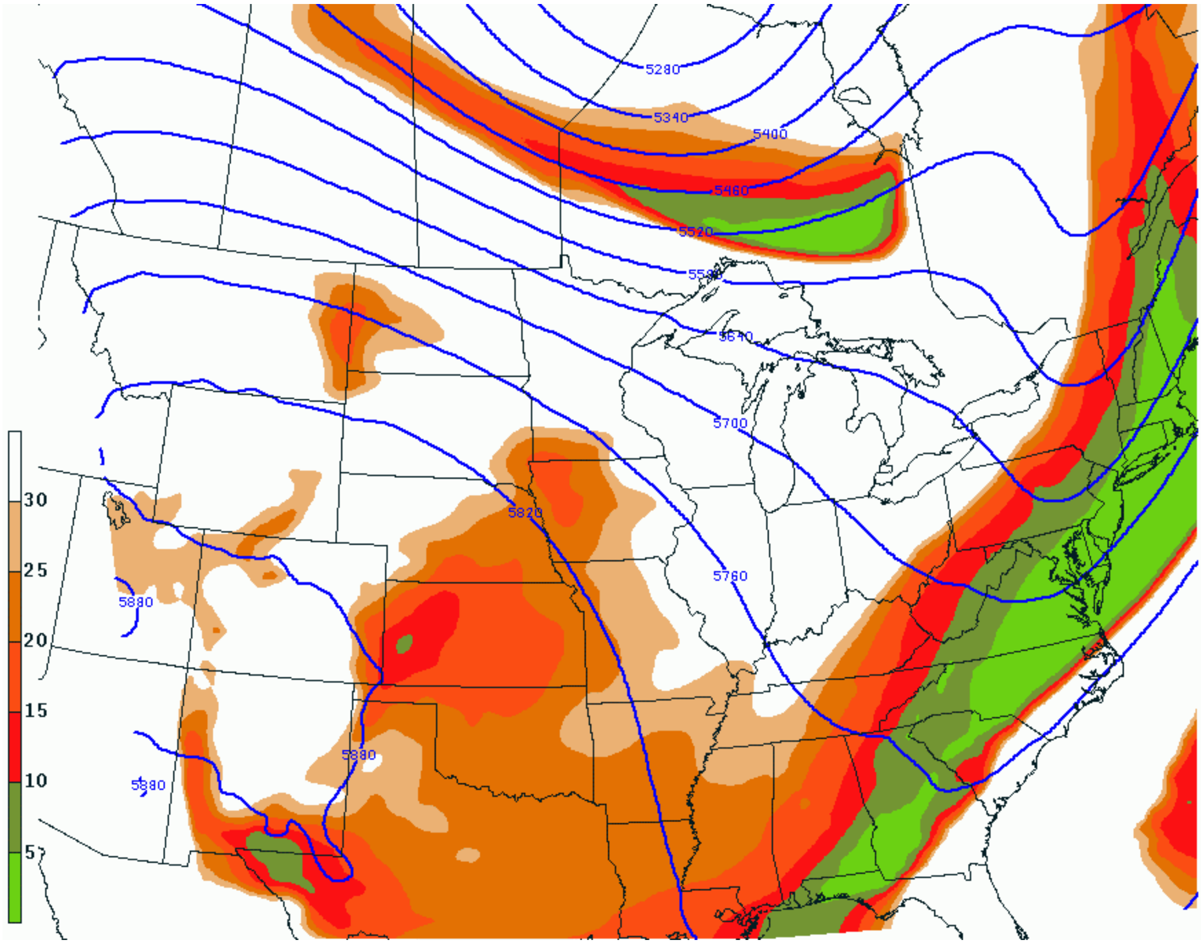

Figure 3.31. 500 hPa geopotential heights contoured with blue lines every 60 m at 1800 UTC 18 May 2009 from the 30 hr forecast of the WRF-ARW. In addition, 650 hPa relative humidity shaded every 5% with a maximum of 30% at 0600 UTC 19 May 2009 from the 42 hr forecast of the WRF-ARW.

parcels ended up on the western edge of the 700 hPa height maximum (Fig. 3.32), and began to subside even further (Fig. 3.30). The western side of a ridge is not usually thought of as an area of sinking. Ageostrophic divergence occurs upstream of the ridge axis and thus the western side of the ridge is usually thought of as an area of upward vertical motion (Martin, 2006). In this case though, the geographical location of the air parcels played a role in the additional sinking. The additional sinking was likely due to orographic subsidence in the lee of the Rocky Mountains. Orographic subsidence can only occur when the mid-level flow is quasi-perpendicular to the orientation of the mountain range. The 700 hPa flow at 1800 UTC 19 May, 2009 had the appropriate orientation for lee-subsidence as air moved straight across the Colorado Rockies from the southwest to the northeast. Just three hours later at 2100 UTC 19 May a lee trough was present over Colorado and Wyoming (Fig. 3.33). This lee trough was a product of the 700 hPa flow across the Rocky Mountains and testifies to the existence of orographic subsidence on 19 May 2009. As a result of the flow across the Rocky Mountains the column stretched and the static stability decreased. The decrease in static stability was attended by an increase in absolute vorticity in order that the potential vorticity be conserved; and this resulted in production of the leeside pressure trough (Martin, 2006). This trough was coincident with the warmest air because of the air being forced to subside and thus adiabatically warm in the lee of the Rockies. By 0900 UTC 20 May the sinking slowed as the air parcels moved towards the region of the fires and away from the influence of the orography. By this time the air parcels were located on the central Nebraska/Kansas border at 750 hPa. In the wake of the further sinking the relative humidities of the air parcels had dropped further to below 20% (Fig. 3.32).

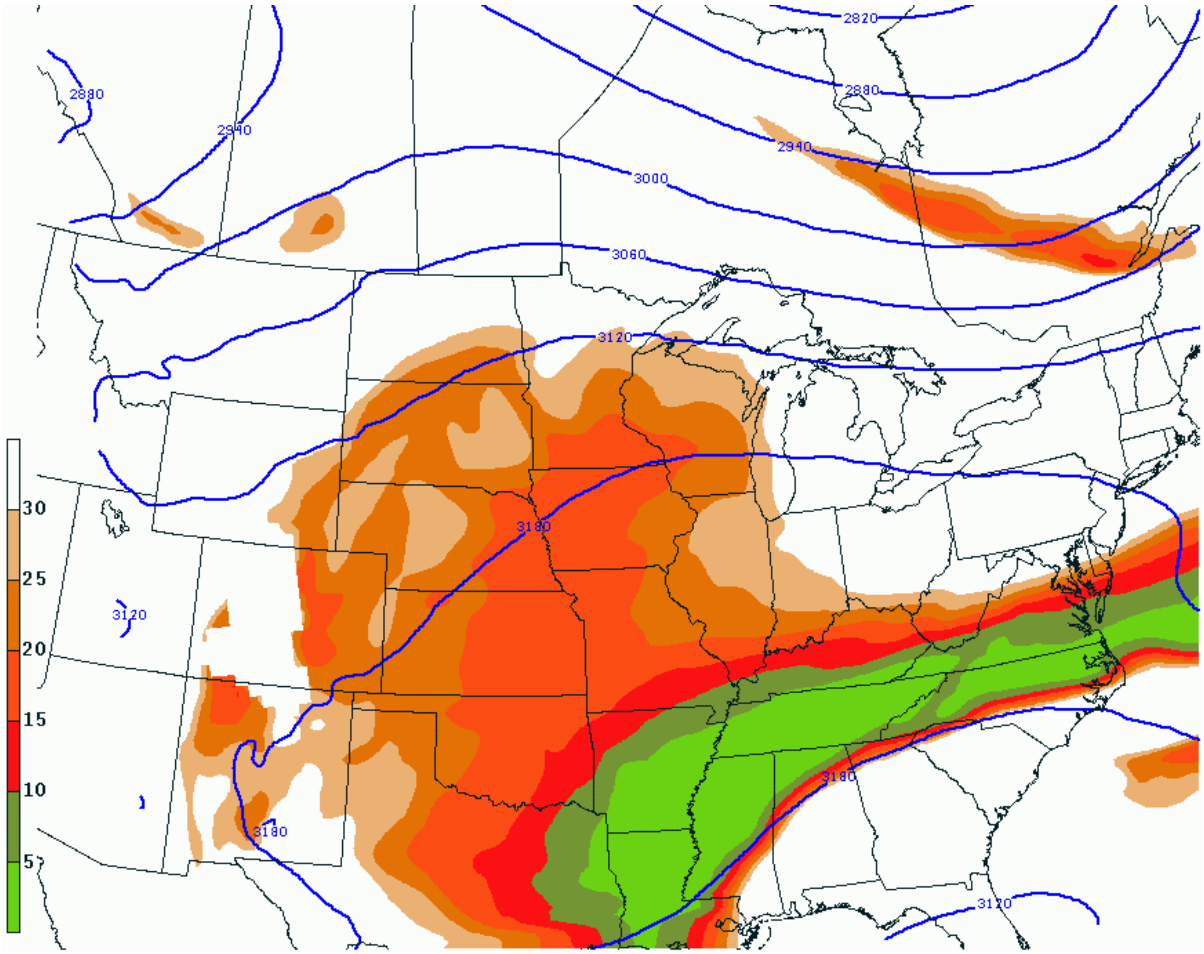

Figure 3.32. 700 hPa geopotential heights contoured with blue lines every 60 m at 1800 UTC 19 May 2009 from the 54 hr forecast of the WRF-ARW. In addition, 750 hPa relative humidity shaded every 5% with a maximum of 30% at 0600 UTC 20 May 2009 from the 66 hr forecast of the WRF-ARW.

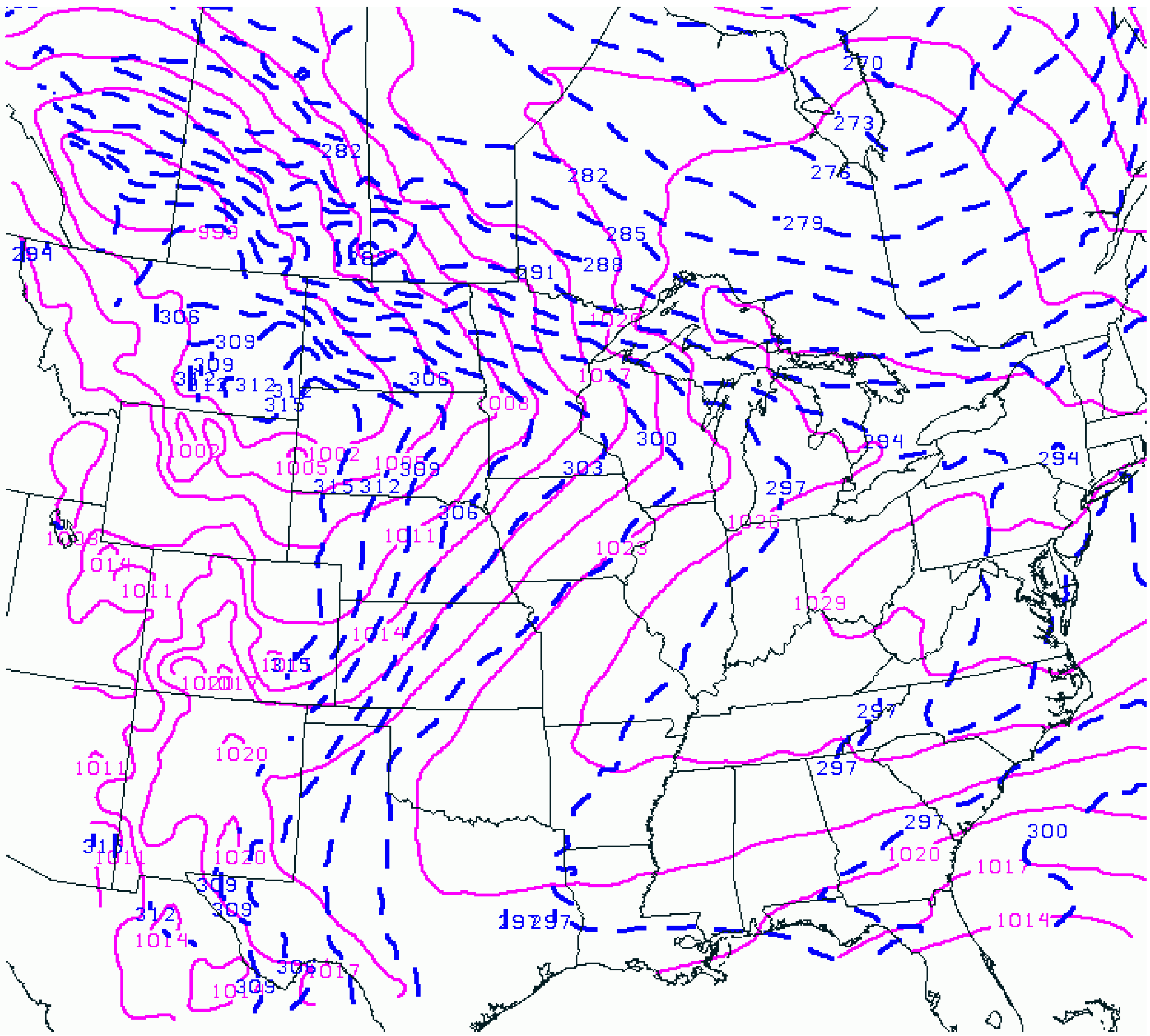

Fig. 3.33. Lee trough over Colorado and Wyoming at 2100 UTC 19 May 2009 from the 57 hour forecast of the WRF-ARW. Mean sea level pressure in hPa contoured in pink lines every 3 hPa with 850 hPa potential temperature in K contoured every 3 K in blue dashed lines at.

From the Nebraska/Kansas border the air parcels were advected towards the fire location along the western edge of the surface high and southeastern edge of the developing low pressure system east of the Rockies. The air parcels arrived at the location of the fires from 1800-2100 UTC 20 May. By this time the warm front had passed to the north, and the very warm temperatures over the Upper Peninsula allowed for quick mixing of the dry air into the boundary layer and down to the surface.

4. Discussion

The Black River Falls and Pinery Fires serve as more examples of subsidence induced by synoptic processes, which produce dry air that is advected into a region where the boundary layer characteristics allow for mixing of the dry air to the surface. These two fire cases were more complicated than the previously identified Great Lakes fires. In addition to the subsidence on the eastern side of a 500 hPa ridge there was also orographic subsidence in the lee of the Rocky Mountains. Also, the mixing of the dry air down to the surface was not due solely to daytime heating reducing the surface nocturnal inversion, but instead a warm frontal passage allowed for historically subsided air to be advected into the region without the effect of the isentropic lift and adiabatic cooling that occurred north of the warm front. In addition, warm air advection associated with the warm frontal passage also helped to warm the daytime temperatures and reduce the surface inversion. Finally, the strong gusty winds associated with the strong surface pressure gradient helped to blow down a power line that caused one of the fires (WLUC-TV[13]) and likely contributed to the quick growth of each fire before rain arrived May 21st with the subsequent cold front that helped to put out the flames. Thus the dry air previously seen in the 1800 UTC 20 May vertical cross section was produced by a 3-D circulation; one component of which provided the large scale subsidence necessary to lower the relative humidity of the subsiding air on the downstream side of an upper ridge and in the lee of the Rocky Mountains. Another component of this 3-D circulation induced northward movement of a surface warm front that was instrumental in the transport of dry, well mixed, air northward toward the region of the fires.

Chapter 4. Discussion

a. Conclusions

Wildfires are dangerous and very costly phenomena that typically affect the western Great Lakes region from April to October (Schroeder et al. 1964) with most fires occurring in April and May (Cardille and Ventura, 2001). Past research such as work done by Schroeder et al. (1964), Brotak and Reifsnyder (1977), and Heilman (1995) have found direct correlations between regularly occurring synoptic weather patterns and high fire danger or large fires. These weather patterns, components of which include upper ridges and surface high pressure systems in the days leading up to high fire danger or large fires, were shown to be associated with a superposition of meteorological variables characteristic of high fire danger. This past work however, did not investigate or emphasize the physical processes characteristic of these synoptic weather patterns. The case studies presented in this thesis have suggested a plausible connection between these recurring patterns and their associated physical processes.

With the use of numerical model simulations, the atmospheric conditions found in association with, and in the vicinity of, four historical fires were modeled. The results of all the case studies show that the 3-D flow downstream of upper level ridge axes provides: 1) large-scale subsidence and drying, which leads to development of reservoirs of dry air just above the Planetary Boundary Layer (PBL), 2) surface anticyclones and their associated clockwise circulations that in each of the examined cases provided the means to advect the subsided air toward the fire environment. In addition, two other May fires from the western

Great Lakes not examined in detail in this thesis showed similar 3-D evolutions. Placement of the mid-level dry reservoir in the near vicinity of the fires, though necessary is not sufficient to lower the near surface relative humidity. In order for this final step to occur, meso and micro-scale boundary layer processes must operate as well.

The boundary layer processes identified differed in each case study, and even differed at different times during a single case. For the Mack Lake Fire strong daytime heating ahead of a surface cold front eroded the nocturnal surface inversion to a point where the air began to rise and mix with the dry air present above the surface. For the Ham Lake Fire the first dry intrusion at the surface was also forced by daytime heating, which reduced the nocturnal surface inversion. The second and third dry intrusions in the Ham Lake case were forced by strong winds and increased cloudiness which kept surface air temperatures from cooling substantially and thus allowed for continual mixing of dry air even at night. Finally, for the Black River Falls and Pinery cases the passage of a warm front to the north had two effects. First it removed the mid-level stable layer (represented by the frontal zone) that prevented historically subsided air from entering the region. Second, the associated warm air advection, combined with daytime heating, conspired to further deepen the mixed layer near the fire. This allowed for similar mixing with the dry air above the surface as in the Mack Lake case and the first dry intrusion noted in the Ham Lake case.

In all three of the cases, strong surface winds, related to the development of large horizontal surface pressure gradients helped to not only mix the dry air into the boundary layer, but also to “fan the flames” once the fires were ignited. These strong horizontal pressure gradients, which were also components of the 3-D circulation system, resulted from the varied synoptic evolutions of the upper ridges and surface anticyclones in each case in relation to the location of the fires. In the Mack Lake case a developing surface cyclone and approaching cold front led to the strong horizontal pressure gradient. In the Ham Lake case the strong horizontal pressure gradient occurred between a strong surface cyclone to the southwest and strong surface anticyclone to the northeast. Finally, in the Black River Falls and Pinery Fires the strong horizontal pressure gradient was present in the warm sector of a strong surface cyclone to the west.

Most of the time, the different synoptic evolutions that were described in each case did not follow the previously established synoptic weather patterns and “types”. In addition the subsidence described was not usually associated with any frontal or post-frontal circulations as was previously identified in similar studies done by Zimet et al. (2007), Kaplan et al. (2008), and Huang et al. (2009). This emphasizes the importance of the identification of 3-D circulations associated with surface anticyclogenesis in helping to predict future high fire danger and large fires in the western Great Lakes region.

b. Future work

This work has opened the door to more questions and possible research topics relating to fire weather in the western Great Lakes. The first thing to do would be to examine more fires in the western Great Lakes to acquire an even more comprehensive dataset that would allow for further quantification of how often fires in the western Great Lakes are associated with these basic circulatory elements of mid-latitude anticylogenesis. This would increase the credibility of using such elements as predictors of future high fire danger or explosive growth of ignited fires. Additionally, because all the fires examined occurred in May there is reason to believe that some climatological feature may lead to the specific processes identified. Thus a climatology of these specific synoptic and mesoscale processes may give some insight into whether or not these features are anomalously high or low when they lead to high fire danger or large fires. Finally, examining some of these cases in further detail with better modeling of the boundary layer processes may allow for further understanding of the interactions between the dry air present above the boundary layer and the surface air. Even further detailed modeling could also show how an actual fire may influence the “normal” boundary layer processes.

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