9.6 THE USE OF TAMDAR (TROPOSPHERIC AIRBORNE METEOROLOGICAL DATA REPORTING) AS A CONVECTIVE FORECASTING SUPPLEMENT IN THE NORTHERN PLAINS AND UPPER MIDWEST

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1. INTRODUCTION

The thermodynamic evolution of the atmosphere over time is sensitive to changes in the vertical distribution of temperature and moisture. Successfully anticipating these changes is critical to the convective forecasting process, but can be difficult due to the relative paucity of upper air observations in space and time. In January 2005, TAMDAR (Tropospheric Airborne Meteorological Data Reporting) was developed with the goal of filling in these observational gaps, thus acting as a supplement to radiosonde observations (RAOBs) and Aircraft Communications Addressing and Reporting System (ACARS).

The Great Lakes Fleet Experiment (GLFE) was established as a means to develop and test TAMDAR. The GLFE was a collaborative effort between NASA, AirDat LLC, Mesaba Airlines, Forecast Systems Laboratory (FSL)—now known as Global Systems Division (GSD) of the Earth System Research Laboratory (ESRL), and the National Weather Service (NWS). TAMDAR sensors were installed on Mesaba Airlines' Saab 340 aircraft at locations east of the Rocky Mountains. These planes fly more frequently and at lower altitudes than larger commercial aircraft, allowing for numerous atmospheric observations. Unlike ACARS, TAMDAR sensors not only measure temperature and wind, but also relative humidity (RH); this is critical to its utility as a convective forecasting tool. Ultimately, NASA, FSL, and NWS meteorologists evaluated both the reliability and utility of TAMDAR in an operational forecast setting (Moninger et al. 2006).

Two noteworthy verification studies have been completed. A study by Moninger (2005) compared TAMDAR to RUC 1-hour forecasts over a two-week period. While model data is not equivalent to the state of the atmosphere, this method allowed a consistent and exhaustive verification of many sensors. The overall temperature and RH bias was shown to be small; however, ascent observations had a warm, dry bias and descent observations had a cool, moist bias. Somewhat higher errors were found in TAMDAR winds, especially upon descent.

The Cooperative Institute for Meteorological Satellite Studies (CIMMS) at the University of Wisconsin (Madison) performed the other study, consisting of two experiments verifying TAMDAR against RAOB launches over a two-week period at one site (Bedke et al. 2005). While the data set is more limited, this evaluation was significant due to its comparison with real-time upper air observations. The temperature bias was similar to that found in Moninger's verification. Meanwhile, ascent observations had "a slight dry bias throughout the boundary layer, and a strong moist bias at the top of the boundary layer;" and descent observations had "a strong dry bias at the top of the boundary layer." However, the study noted that "cumulative statistics of temperature and RH are not necessarily representative of instrument performance due to the non-normal distribution of data."

2. DATA AND SOFTWARE APPLICATION

Examination of TAMDAR in this study is accomplished via FSL's Java applet (http://amdar.noaa.gov/java/), whose interactive soundings can be seen in Fig. 2-4. The vertical resolution of the data is 10 mb through the lowest 100 mb, and 50 mb thereafter. The software application allows the user to select the temperature, dewpoint, and pressure level of a lifted air parcel. The parcel trace is then shown, and Lifted Condensation Level (LCL), Level of Free Convection (LFC), Convective Available Potential Energy (CAPE), and Convective Inhibition (CIN) are calculated. Because the data is only available in the lowest 25,000 feet, CAPE is often not fully integrated. Radiosonde observations can also be loaded, for which the interface computes additional thermodynamic variables as shown. Forecasters can select the range rings to plot either a hodograph based on the observed wind profile, or the bearing and range of the aircraft. Plotted RAOBs accordingly show the observed hodograph.

Users may find some limitations with the TAMDAR interface. First, as with any skew-T software application, the forecaster must be cognizant of which parcel is lifted when assessing thermodynamic calculations. This is crucial when assessing surface-based CIN (SBCIN) because the lowest observation on individual TAMDAR soundings does not always

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coincide with the earth's surface; near-surface data may be rejected during the quality control process for a number of reasons (Moninger, personal communication). Thus, users must take some care in modifying the soundings with adjacent METAR data; this includes not only temperature and dewpoint, but a reasonable estimate of the pressure surface at that location. These values ultimately dictate the parcel path and the associated thermodynamic output. In particular, CIN and LFC calculations are very sensitive to the chosen parcel. Inadvertent errors in parcel selection can have a significant operational impact, particularly in cases in which environmental CIN is "borderline" for cap breakage.

Though parcel selection is situation-dependant, SBCIN generally underestimates the cap to surface parcels when boundary layer moisture is relatively shallow. Conversely, lifting a mixed-layer parcel accounts for vertical mixing effects by using a mean temperature and dewpoint in the lower levels—typically, the lowest 100 mb. Therefore, mixed-layer CIN (MLCIN) may be more realistic than SBCIN. This is also fundamentally supported by the fact that mixed-layer Lifted Condensation Level (MLLCL) has been shown to better coincide with observed convective cloud bases than SBLCL (Craven et al. 2002). The TAMDAR interface does not allow a mixed-layer parcel to be lifted.

It is also noteworthy that the interface does not apply the virtual temperature (T_v) correction when lifting a parcel (Moninger, personal communication). The T_v correction adjusts parcel density based on water vapor content when calculating thermodynamic parameters such as CAPE and CIN (Doswell et al 1994). This results in a rightward shift of the parcel path, and thus typically computes comparatively lower (higher) values of CIN (CAPE). Forecasters at the Storm Prediction Center in Norman, OK have found non-corrected CIN to be generally superior in predicting convective initiation (John Hart, personal communication); however, there does not appear to be an absolute consensus among the operational and scientific community regarding which method is better. Users preferring the T_v correction should be aware that the TAMDAR interface accordingly produces larger values of CIN than applications that do use the correction.

Finally, forecasters must bear in mind that TAMDAR observations are taken over a particular distance from the airport. Thus, the data may not be exactly representative of the atmosphere at that point—namely, when the aircraft crosses a substantial horizontal gradient in temperature or moisture. Aircraft bearing should be noted when such an environment is anticipated.

Due to flight path effects and potential errors associated with the observations themselves, users can check the consistency and feasibility of the data by both 1) overlaying successive TAMDAR soundings from one or more airports, and 2) comparing the soundings with RAOBs and ACARS when possible. High frequency TAMDAR observations from the larger airports are especially useful in gaining confidence in the thermodynamic character of the atmosphere.

Considering the fundamental limitations of the TAMDAR interface as well as time constraints, forecasters may prefer to use the data as a guide alongside other observed and model data to adjust forecast reasoning if necessary, rather than to take computed thermodynamic values from TAMDAR soundings at face value.

3. TAMDAR UTILITY IN CONVECTIVE FORECASTING IN THE NORTHERN PLAINS AND UPPER MIDWEST

Increasing the frequency and density of low- and mid- level atmospheric sampling is valuable in many types of forecasting. It is at these altitudes where the strongest baroclinicity and moisture variation occur, and where numerical model forecast errors can have a significant impact upon sensible weather. Consequently, convective forecasters can specifically benefit from TAMDAR when the atmosphere is not homogenous in a horizontal plane.

In the Northern Plains and Upper Midwest, the low-level jet and elevated mixed layer (EML) are two primary means of temperature and moisture redistribution throughout much of the convective season. These phenomena can result in considerable variability among model solutions. In particular, assessing elevated instability and gauging cap strength can be troublesome over these areas. The occurrence of Mesoscale Convective Complexes (MCSs) is an added challenge, as these systems—and the effects they leave behind—are not particularly well-forecast by numerical models.

The weather pattern was seasonably complex with respect to convective forecasting across much of the northern Plains and upper Midwest during the period of July 20-24, which was manifested in a high variability among model forecasts of convective precipitation. Two case studies were examined during this time frame, each generally covering an 18-hour period beginning at 1200 UTC. Numerical model mass and kinematic fields from the 1200 UTC RUC, NAM (North American Mesoscale), GFS (Global Forecast System), and 0900 UTC NAM-KF (NAM with Kain-Fritsch convective parameterization) were investigated in each case to help anticipate the movement of synoptic scale and mesoscale features, as well as the evolution of vertical motion associated with them. The NAM, NAM-KF, and RUC model soundings were closely interrogated for each event. Thermodynamic computations contained within this study do not include the T_v correction. This ensures that CIN values given by RAOBs and numerical models are consistent with those given by the TAMDAR interface. N-AWIPS (NCEP Advanced Weather Interactive Processing System) model plan views of CIN are emphasized over values computed by NSHARP (N-AWIPS Skew-T Hodograph Analysis and Research Program) model soundings, because the former do not incorporate the T_v correction.

3.1 *Case Study: 20-21 July 2005 (Extreme southeastern SD, northeastern NE, northwestern IA)*

Upper air observations at 1200 UTC indicated a broad upper level ridge centered over the southwestern United States, with the primary belt of westerly flow extending from the Pacific Northwest through the northern Plains and into Ontario, Canada. Several disturbances were embedded within this flow, the most significant being a shortwave trough over western Ontario and a lower-amplitude shortwave over Minnesota. These features were well-depicted by water vapor imagery and 500 mb observations (refer to Fig. 21 in Appendix).

A baroclinic zone associated with the Canadian shortwave was located over the northern Plains (Fig. 1), with a surface wave over south-central South Dakota. A weak, shallow warm frontal boundary (not shown) was present from central Nebraska eastward through central Iowa. Surface dewpoints of 19-22°C (67-72°F) were common across eastern Nebraska, eastern Kansas, Iowa, and Missouri. A 20 m s^{-1} (40 kt) southwesterly low-level jet was evident in wind profilers, VAD wind data, and 850 mb upper air data (refer to Fig. 22), extending from western Kansas to western Iowa.

The thermodynamic environment over the central Plains was characterized by very steep (8-9.5°C/km^{-1}) 700-500 mb lapse rates associated with a strong EML. Observed 700 mb temperatures (refer to Fig. 23) included 18°C at North Platte (LBF), 15°C at Omaha (OAX), 16°C at Rapid City (UNR), 12°C at Aberdeen (ABR), 10°C at Minneapolis (MPX), and 8°C at Davenport (DVN). These values represented an increase of 1-2°C since 0000 UTC due to westerly flow having advected the EML eastward overnight. Meanwhile, the depth of boundary layer moisture had decreased at LBF and OAX, as evidenced by markedly more shallow moisture on 1200 UTC soundings than at 0000 UTC (Fig. 2). This was a result of the low-level jet veering in response to the passage of the Minnesota shortwave as well as typical nocturnal processes, ultimately resulting in negative moisture advection off the high Plains.

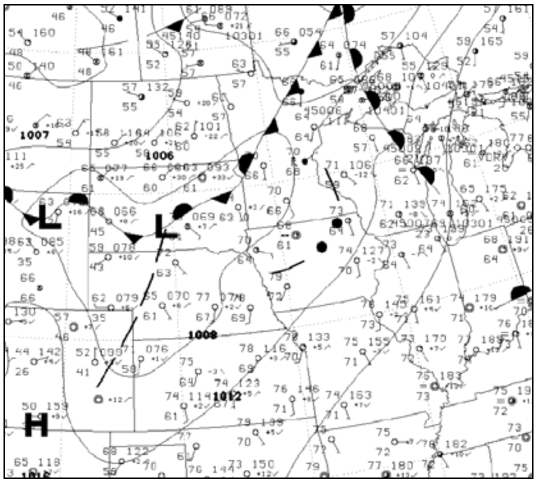
Fig. 1. Conventional surface station plot and HPC (Hydrometeorological Prediction Center) synoptic scale analysis at 1200 UTC 20 July 2005, with mean sea level pressure contoured every 4 mb.

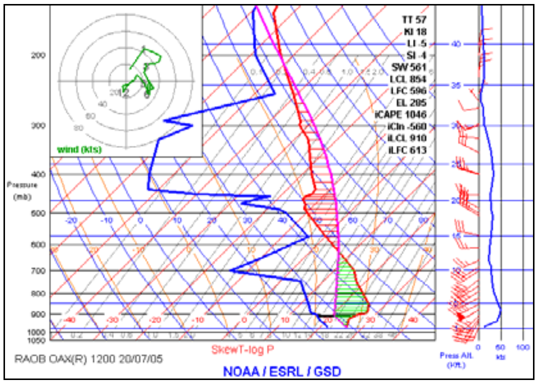

Fig. 2. 1200 UTC 20 July 2005 Omaha, Nebraska RAOB as viewed on FSL display. Temperature profile in red, dewpoint profile in blue, surface parcel trajectory in purple. LCL denoted by black horizontal line, CAPE by green hatched lines, and CIN by red hatched lines. Observed wind profile plotted on hodograph.

A linear MCS extended from the Minnesota-Iowa border area southwestward through west-central Iowa at 1200 UTC, immediately east of the strongest mid-level cap and well in advance of the cold front as shown by the leading outflow boundary in Fig. 2. The convection was supported by differential positive vorticity advection and difluent flow aloft associated with the shortwave trough, as well as moist, unstable inflow from the low-level jet. This MCS was expected to move eastward, as the supporting shortwave exited the region and large scale subsidence and continued 700 mb warming occurred in its wake. The northern plains baroclinic zone was expected to become ill-defined and stall by afternoon from southern Minnesota to southern South Dakota. The warm frontal boundary would move slowly northward, as model guidance forecast a diurnal strengthening of southerly flow across Kansas and southern Nebraska.

The warm front, along with remnant outflow boundaries from the departing MCS, would serve as potential foci for surface-based thunderstorms later in the day across the area of concern if the cap could be broken. With strong heating likely, extreme values of instability (Lifted Indices of -10°C to -12°C) were expected; thus, convection could pose a threat for large hail and damaging winds. This was supported by the Storm Prediction Center (SPC) issuing a Slight Risk for the area in the 1200 UTC, 1300 UTC, and 1630 UTC Day 1 Convective Outlooks. Indeed, the NAM, NAM-KF, and RUC models all indicated that strong capping associated with the EML would weaken considerably by late day. The former two models forecast small amounts of convective precipitation over the area from the late afternoon through late evening morning hours.

This thermodynamic evolution was uncertain due to the anticipated strength of the EML and the synoptic pattern. Temperatures at 700 mb were forecast to increase to 15-17°C by 1800 UTC, which appeared feasible due to upstream RAOBs and the forecast persistence of westerly trajectories at that level. These very warm temperatures are climatologically unfavorable for surface-based convection in the eastern Plains and upper Midwest due to the potential of a strong convective cap.

Synoptic scale lift to aid in weakening the cap was not anticipated. The upper ridge would amplify slightly, with 50 m 12-hour 500 mb height rises expected at 0000 UTC. A weak shortwave trough was forecast to develop in the northern Rockies and move east-southeastward atop the subtropical ridge from Wyoming to western South Dakota by 0000 UTC July 21. Though the vigor and timing of this disturbance was uncertain based on model discrepancies and its anticipated location south of the strongest westerlies, forcing for ascent associated with this feature was unlikely to affect the area until after dark, if at all.

Additionally, because 1200 UTC LBF and OAX RAOBs indicated shallow moisture, the breachability of the cap would also be strongly dependent on considerable moisture recovery. This recovery would be aided by the forecast weakening and redevelopment farther west of the 1200 UTC observed low-level jet, which would back 850 mb flow to southeasterly over the area.

3.1.1 Morning TAMDAR and model thermodynamic output

Two TAMDAR airports—Sioux City, Iowa (SUX) and Sioux Falls, South Dakota (FSD)—were located within the area of concern. A total of seven soundings were available from 1300-1600 UTC (Fig. 3-4). The observations were particularly useful due to sampling an environment that in this case was not immediately proximal to a RAOB site. The soundings showed a reasonable degree of continuity with one another.

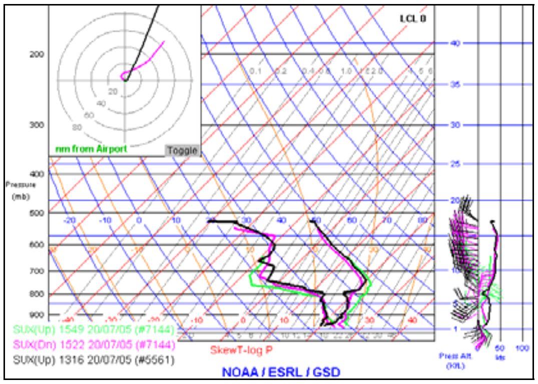

Fig. 3. Morning TAMDAR series at Sioux City, Iowa as viewed on FSL display. Colors denote different individual observations, with time in UTC and Up (Dn) indicating an ascent (descent) sounding. Aircraft bearing and range indicated in upper left-hand corner.

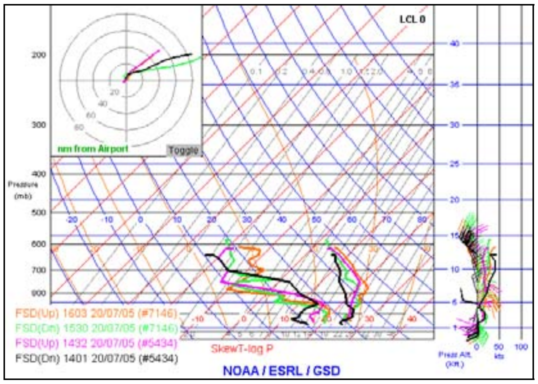

Fig. 4. Morning TAMDAR series at Sioux Falls, South Dakota.

The moisture profiles indicated that a horizontal maximum in moisture depth—including 850 mb dewpoints of 13-16°C—was present relative to adjacent areas in the Plains and Midwest as sampled by 1200 UTC RAOBs. The moisture was feasible due the following: 1) the quality of the moist axis over the central Plains at 0000 UTC July 20; and 2) the optimal position of the nocturnal low-level jet relative to the moist axis, which prolonged moisture advection into northeastern Nebraska and northern Iowa. Moisture depth over this area was under-initialized by the 1200 UTC guidance, likely because the relative maximum was not sampled by RAOBs for ingestion into the models. Because of the under-initialization, as well as TAMDAR showing moisture maintained by the time the low-level jet had dramatically weakened, model forecasts of deep moisture return (e.g., 850 mb dewpoints increasing to 14-19°C) by afternoon appeared more reasonable than before.

The TAMDAR soundings indicated a significant capping layer from roughly 800-650 mb, whose magnitude appeared realistic in comparison with the OAX RAOB. The ascent observations were slightly warmer (and thus more strongly capped) than the descent observations, which was consistent with verification studies. Notably, each the ascent soundings and the descent soundings showed a warming trend in the capping layer through the period; this continuity suggested the 700 mb cap was increasing, regardless of the exact strength.

The NAM and NAM-KF forecast sounding structures at Sioux City (SUX) were generally consistent. Despite warming the 700 mb cap through 1800 UTC and then maintaining it through 0000 UTC, both models forecast strong MLCIN at 1800 UTC (150-350 J kg^{-1}) to erode to 20-60 J kg^{-1} by 2100-0000 UTC. As shown in Fig. 5, this was accomplished by two forecast processes: 1) primarily, substantial cooling of the capping layer (notably, 3-5°C of 750-800 mb cooling from 1800-0000 UTC), and 2) deepening of boundary layer moisture. While the latter process appeared possible based on the morning TAMDAR observations, the former process appeared suspect. Very weak vertical mixing was forecast within the capping layer, and forcing for ascent to aid in cooling this layer was not expected.

Meanwhile, the 1200 and 1500 UTC SUX RUC soundings looked more reasonable in that they maintained the strength of the 800-650 mb cap. However, though moisture return by late day was not as rich as in the other two models, MLCIN was still forecast to be reduced to 40-70 J kg^{-1} by 2100 UTC. This was accomplished by strongly heating the surface-800 mb layer to nearly a dry-adiabatic lapse rate (Fig. 6). This boundary layer evolution was an outlier in comparison to the NAM and NAM-KF, and was questionable due to expected weak mixing and an easterly component to the boundary layer flow. The 1800 UTC solution was very similar; the CIN removal was simply delayed 1-2 hours, due to a more realistic boundary layer initialization in comparison to previous runs' 1800 UTC forecasts.

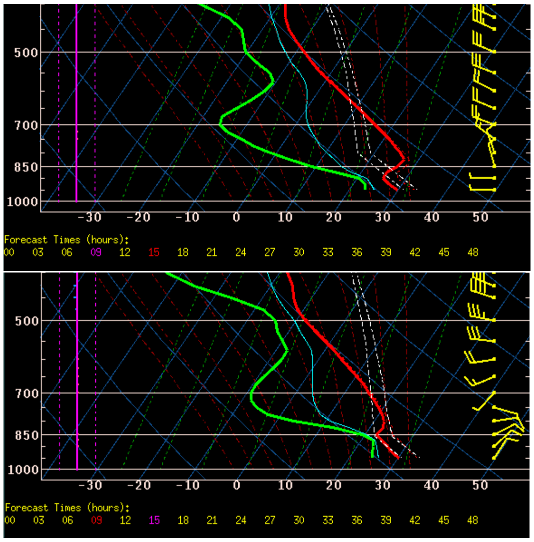

Fig. 5. 1200 UTC 20 July 2005 Sioux City NAM-KF model soundings at 1800 UTC (top) and 0000 UTC (bottom) as viewed on NSHARP. Data shown through 400mb level. Temperature profile in red and dewpoint profile in green. Hatched gray line indicates 100 mb mixed-layer lifted parcel trajectory, with both T_v-corrected (right-most) and non-corrected (left-most) parcel paths shown.

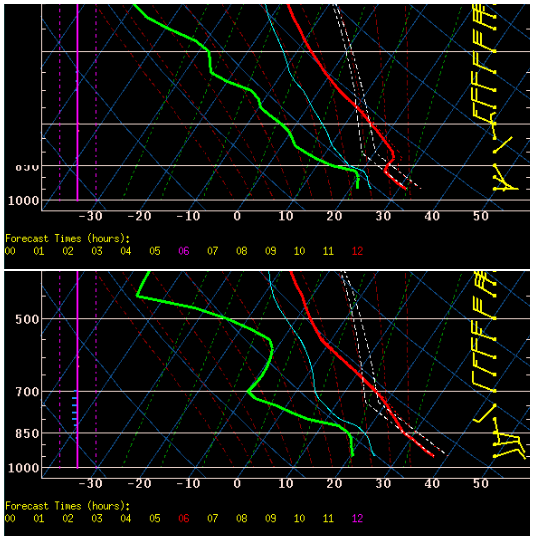

Fig 6. 1200 UTC 20 July 2005 Sioux City RUC model soundings at 1800 UTC (top) and 0000 UTC (bottom).

3.1.2 Afternoon and evening evolution

Surface observations at 2100 UTC revealed a complicated pattern with generally weak flow over much of the central Plains. The warm front had drifted slightly northward (Fig. 7), focusing weak moisture convergence primarily across east-central Nebraska. A weaker boundary was apparent from northeastern Nebraska through extreme northwestern Iowa, passing through the Sioux City vicinity. This boundary was characterized by surface temperatures of 31-35°C (89-94°F) and dewpoints of 21-25°C (70-77°F). No outflow boundaries were evident. Visible satellite indicated cumulus clouds had developed strictly along and north of the weaker boundary by 1930 UTC, but did not exhibit vertical development over time. Water vapor imagery indicated a very dry mid- to upper-level air mass across the central Plains. Profilers and VAD winds helped to confirm that synoptic scale ascent was likely absent.

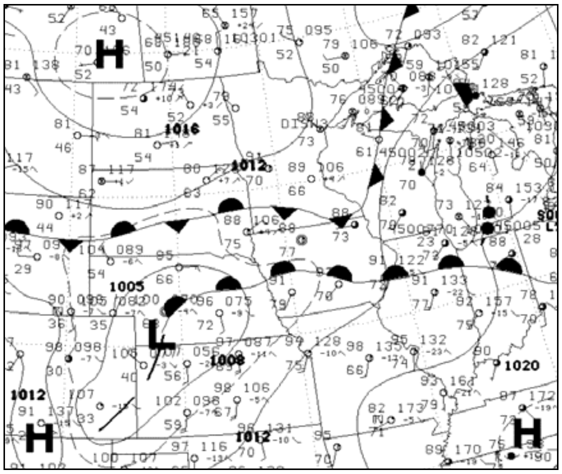

Fig. 7. 2100 UTC 20 July 2005 surface station plot and HPC synoptic scale analysis.

Two TAMDAR soundings from Sioux City became available at 2200 UTC. These observations indicated that, while boundary layer moisture was favorably rich and deep, 800-650 mb temperatures had increased further and the cap was indeed strong. Temperatures sampled at 700 mb were 16.8°C (2144 UTC descent) and 18.1°C (2205 UTC ascent), which indicated a 1.4-1.7°C rise since 1500-1600 UTC. The sounding structure verified that the thermal evolutions forecast by the NAM, NAM-KF, and RUC models with respect to CIN removal were in fact in error.

Modifying the descent TAMDAR with Sioux City's 2100-2200 UTC observed temperature and dewpoint yielded the following SBCIN: descent, 147 J kg^{-1} (Fig. 8); and ascent, 244 J kg^{-1}. The degree of capping suggested that the short-term probability of convection over the area was near-zero. This was true even eastward into north-central Iowa where boundary layer theta-e remained nearly as high in the presence of cooler 700 mb temperatures—which was verified by TAMDAR soundings from Mason City and Des Moines. Additionally, the Sioux City TAMDAR soundings were modified using surface observations from east-central Nebraska, where stronger vertical mixing yielded temperatures near 38°C (100°F) where 700 mb temperatures were similar to those at Sioux City. Still, CIN was no weaker, due to somewhat drier surface air in that region. In the end, no thunderstorms occurred in southeastern South Dakota, eastern Nebraska, and western Iowa through 0400 UTC July 21.

The 0000 UTC OAX RAOB ultimately sampled a 700 mb temperature of 16.6°C and SBCIN of 201 J kg^{-1} (Fig. 9). The 2144 UTC SUX TAMDAR temperature profile showed excellent continuity with the RAOB. The only notable difference was that the RAOB showed vertical mixing through a deeper layer (790mb), as was expected. Meanwhile, the 2205 UTC SUX sounding (not shown) appeared to be a little too warm, but its moist layer was deeper and likely more representative of the local environment than that of the 2144 UTC sounding.

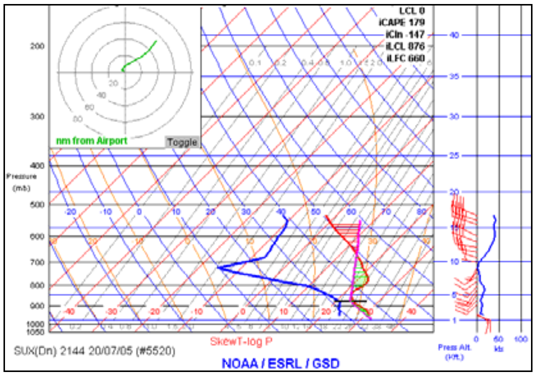

Fig. 8. 2144 UTC 20 July 2005 Sioux City TAMDAR.

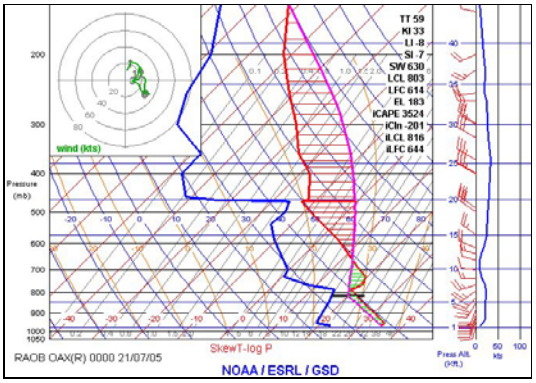

Fig. 9. 0000 UTC 21 July 2005 Omaha RAOB.

3.2 *Case Study: 23-24 July 2005 (Extreme southeastern ND, northeastern SD, west-central MN)*

By 1200 UTC July 23, the subtropical ridge had shifted northeastward and strengthened, and dominated much of the southern two-thirds of the continental United States. Two significant disturbances within the westerlies were evident in upper air observations and water vapor imagery (refer to Fig. 24); an elongated shortwave trough over Alberta, and a shortwave flattening the upper ridge over North Dakota. The latter feature was associated with an unseasonably strong 25-30 m s^{-1} (50-60 kt) 500 mb jet steak.

A weak occluded/cold front driven by the Alberta shortwave extended from low pressure over Saskatchewan through Montana (Fig. 10). A warm frontal boundary extended from southeastern Montana through South Dakota and into northwestern Iowa, with a lee trough in the high plains of Nebraska and Colorado. A warm and very moist air mass existed along and north of the front, with 18-24°C (65-75°F) surface dewpoints over southeastern North Dakota, eastern South Dakota, southern Minnesota, and Iowa. An 18 m s^{-1} (35 kt) west-southwesterly low-level jet was located over the western portions of South Dakota and Nebraska (refer to Fig. 25), coincident with a strong 850 mb thermal ridge.

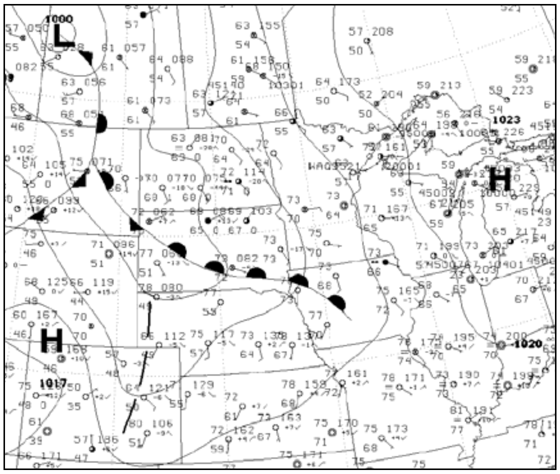

Fig. 10. 1200 UTC 23 July 2005 surface station plot and HPC synoptic scale analysis.

The EML had shifted northward (Fig. 26) with the amplifying upper ridge over the past few days. Temperatures observed at 700 mb included 19°C at UNR, 15°C at ABR, 12°C at BIS and MPX, and 8°C at International Falls. A northwest-to-southeast band of moderate to strong elevated instability was present immediately north of the front, as sampled by the 1200 UTC ABR RAOB (Fig. 11). This air mass was characterized by very rich 850 mb dewpoints (16-20°C) and steep 700-500 mb lapse rates (7.5-8.5°C km^{-1}) associated with the EML.

A compact MCS was evolving at 1200 UTC over southeastern North Dakota and extreme northeastern South Dakota, supported by strong environmental deep-layer shear. This complex had gradually developed overnight while traveling eastward along the band of elevated instability, and was in the process of accelerating and rapidly turning into a severe bow echo. The MCS was also maintained by forcing for ascent from the North Dakota shortwave trough and broadscale lower-tropospheric warm air advection, and was traveling along the northeastern edge of the strong 700 mb cap.

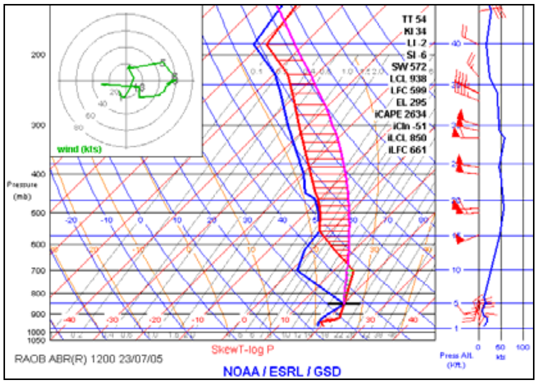

Fig. 11. 1200 UTC 23 July 2005 Aberdeen, South Dakota RAOB.

The warm front was forecast to redevelop northeastward toward central Minnesota as the cold front moved into North Dakota and western South Dakota. The lee trough would move eastward through the Plains, with an associated thermal low deepening over the eastern half of South Dakota as diurnal mixing pushed surface temperatures in excess of 38°C (100°F) across much of the state. A triple point would develop northeastward away from the thermal low and serve as the primary convective focus by late day over the area of concern. The 1200 UTC NAM and RUC were consistent in forecasting this feature to be near Fergus Falls, Minnesota (FFM) at 2100 UTC. (In comparison, the 0900 UTC NAM-KF was a major outlier—being too progressive with the surface low and cold front). Strong heating was forecast in the wake of the MCS, with the mid-level wind max exiting the region and the 850-700 mb thermal ridge shifting eastward and strengthening the cap.

The 1200 UTC NAM produced significant convective precipitation (0.5-1.0 cm) over west-central Minnesota from 2100-0000 UTC, in spite of retaining substantial capping over the area. The RUC and NAM-KF produced convective precipitation farther north (primarily near the international border) only, but both models indicated CIN would be similarly reduced near the triple point by 0000 UTC. The forecast environment would be characterized by strong potential instability (Lifted Indices of -6°C to -9°C). Strong deep layer shear would exist as well, with 500 mb flow of 18-23 m s^{-1} (35-45 kt) maintained over the area. The 1300 UTC and 1630 UTC SPC Day 1 Convective Outlooks included a Moderate Risk of severe weather across central Minnesota and northern Wisconsin, forecasting the potential for tornadic supercells transitioning into another damaging MCS.

The 1200 UTC guidance forecast 700 mb temperatures to increase to 15-17°C over the area of concern by afternoon. This was feasible based on anticipated trajectories and the strength of the thermal ridge immediately upstream. As with the July 20 event, thunderstorm potential was uncertain due to the possibility of a strong cap to surface parcels; this was heightened by the fact that models retained considerable CIN over the area through 0000 UTC. However, forcing for ascent would be stronger than in the previous case. Strong moisture convergence and low-level theta-e advection was likely near and ahead of the triple point, along with potential synoptic scale lift via low-amplitude disturbances within the westerlies. Strong upward vertical motion was forecast by the NAM, but the degree of positive vorticity advection was not yet evident; the area would generally remain behind the departing North Dakota shortwave and well downstream of the Alberta shortwave.

3.2.1 Morning through early afternoon TAMDAR and model thermodynamic output

Three TAMDAR airports existed over the area: Aberdeen and Watertown, South Dakota (ATY) on the western periphery, and Brainerd, Minnesota (BRD) on the eastern periphery. Two upstream sites—Pierre (PIR) in central South Dakota and Jamestown (JMS) in southeastern North Dakota—would also be beneficial in monitoring the thermodynamic evolution throughout the day.

Of primary concern after the first TAMDAR became available at Pierre (1207 UTC) was the depth and strength of the capping inversion associated with the EML. This sounding was consistent with the UNR RAOB, and indicated that a well-mixed, hot, and very dry 850-700 mb air mass was poised to advect into northeastern South Dakota on moderate west-southwesterly winds (Fig. 12). Comparing the Pierre sounding with the ABR RAOB established that a very strong 850 mb moisture gradient was in place across South Dakota, which had already been suggested by the objective analysis in Figure 19. The 1200 UTC observed low-level jet was oriented nearly perpendicular to the 850 mb moist axis, and was acting to erode this moisture from the west.

In fact, a 1234 UTC ABR TAMDAR indicated that CIN—associated with marked 800 mb warming—had already strengthened since the time at which the 1200 UTC RAOB was launched. Subsequent TAMDAR soundings from Aberdeen verified that the strong capping layer sampled at Pierre was advecting into the area, as shown by intense 850 mb warm air advection and a trend of increasingly shallow boundary layer moisture (Fig. 13).

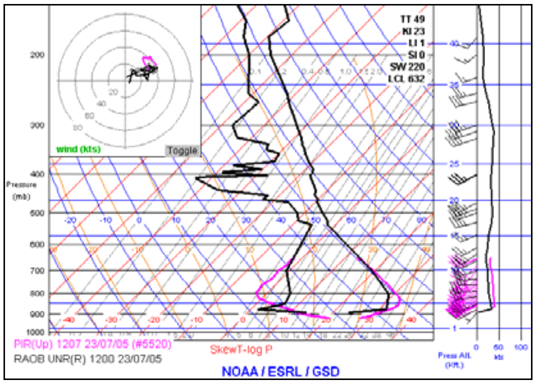

Fig. 12. 1200 UTC 23 July 2005 Rapid City, South Dakota RAOB and 1207 UTC Pierre, South Dakota TAMDAR.

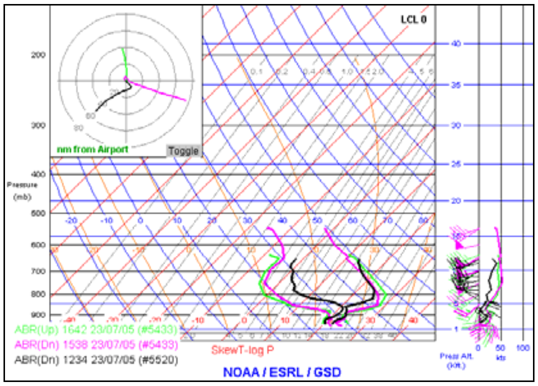

Fig. 13. Morning TAMDAR series at Aberdeen.

The 1200 UTC NAM model maintained very strong MLCIN (150-350 J kg^{-1}) through 1800 UTC. By 2100 UTC, capping was forecast to weaken throughout the northern Plains and upper Mississippi valley, especially over eastern North Dakota and northern Minnesota—north of the strongest 700mb cap. Thus, a substantial north-to-south MLCIN gradient was forecast across central Minnesota, within which the model produced its strong convective signal near and ahead of the triple point. This forecast environment was characterized by MLCIN as high as 50-100 J kg^{-1} in the presence of strong low-level convergence and strong 700 mb vertical velocities. By 0000 UTC, modeled convection was located over all of central Minnesota, making sounding interrogation difficult due to convective adjustments that occur within the Betts-Miller-Janjic (BMJ) scheme. Regardless, the NAM generally indicated that the cap to surface parcels might be difficult to overcome. (Though the placement was farther to the northeast due to surface forecast differences, the NAM-KF solution was generally similar; however, it didn't weaken the cap until 0000 UTC).

Specifically, NAM soundings at Fergus Falls showed increasingly shallow moisture between 1200 and 1800 UTC, generally consistent with TAMDAR trends shown upstream. Moisture depth was then forecast to recover rapidly, including 850 mb dewpoints increasing to 17-21°C by 2100 UTC (Fig. 14). In fact, the NAM-KF forecast a swath of even richer moisture (20-22°C 850 mb dewpoints) from the triple point southeastward along the warm front. This rapid moisture recovery in the presence of strong forecast heating contributed to the NAM and NAM-KF forecasts of substantially decreasing MLCIN by 2100-0000 UTC. While evapotranspiration would enhance near-surface moisture throughout the day, subsequent TAMDAR observations would have to be monitored to help ascertain whether such rich boundary layer dewpoints could be realized in spite of the dry 850 mb source region.

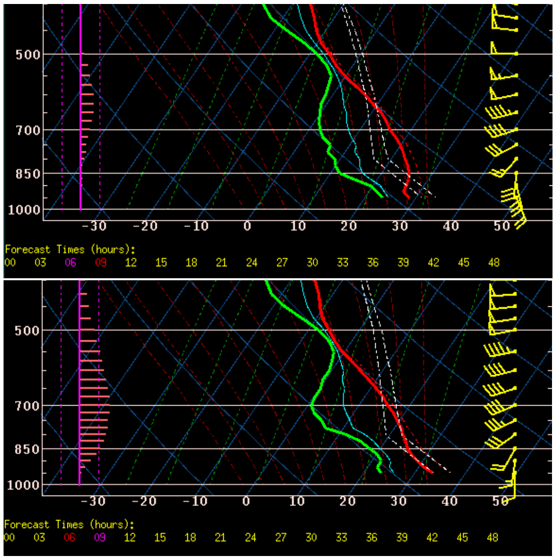

Fig 14. 1200 UTC 23 July 2005 Fergus Falls, Minnesota NAM model soundings at 1800 UTC (top) and 2100 UTC (bottom).

The 1200 UTC RUC forecast MLCIN to rapidly erode to 40-80 j/kg near the triple point by 2200 UTC. The model's trend of moisture becoming increasingly shallow through about 1800 UTC was similar to that of the NAM. Thereafter, the RUC forecast that moisture would attempt to deepen, but not as markedly with 850 mb dewpoints climbing to 14-16°C. Accordingly, it reduced the cap in the same fashion as in the previous case study: by more strongly heating the surface-800 mb layer, resulting in very steep low-level lapse rates (not shown).

The 1500 UTC RUC produced a considerably different thermodynamic solution. Although the model continued to unrealistically heat and dry out the boundary layer near the triple point, it retained very strong MLCIN over much of the rest of the area through 0300 UTC July 24. This was a result of the model having initialized—and then maintained—a cooler and more stable boundary layer associated with the air mass beneath and in the wake of the MCS. Consequently, the 1500 UTC RUC forecast the triple point at 2100 UTC to be 75-100 nm farther southwest of the previous run—over far northeastern South Dakota. This was due to its forecast of the retreating warm front being slowed significantly by the MCS outflow. The model also produced no convective precipitation over the area of concern, or the remainder of Minnesota, through 0300 UTC.

By 1800 UTC, the MCS had pushed entirely through Minnesota and into western Wisconsin. Surface observations indicated the triple point was becoming defined southwest of Aberdeen. Moisture convergence with this feature was increasing due to two factors: 1) diurnal strengthening of southwesterly flow within the low-level thermal axis, and 2) pressure falls acting to isallobarically maintain southeasterly winds in advance of the triple point. The latter process also aided the influx of 21-24°C (70-75°F) surface dewpoints ahead of the feature. Visible satellite indicated some mid-level debris cloud remained over northeastern South Dakota and west-central Minnesota but was advecting eastward, suggesting that strong heating would soon ensue. Meanwhile, lower clouds persisted across much of east-central Minnesota within the rain-cooled air mass behind the departing MCS. This stable air—and its associated easterly surface flow—was in fact serving to both reinforce and slow the northward motion of the warm front, which extended from far northeastern South Dakota to southeastern Minnesota.

An 1800 UTC special RAOB from Aberdeen (Fig. 15) was remarkably consistent with 1642 and 1818 UTC ABR ascent soundings, with the only substantial difference being the warming of the boundary layer over time. The RAOB showed a 60 mb deep moist layer strongly capped by very warm and dry air, with 850 mb and 700 mb temperatures of 31°C and 17°C respectively. The sounding thus indicated extremely strong SBCIN (552 J kg^{-1}). The RAOB also verified 15-20 m s^{-1} (30-40 kt) southwesterly flow throughout the entire capping layer, which would assure continued advection of this air mass downstream as the triple point continued to move east-northeastward. An ascent and descent TAMDAR sounding were available from Jamestown as well; they sampled nearly as warm 850-700 mb temperatures atop similarly shallow moisture, which gave credence to the horizontal homogeneity of the capping layer.

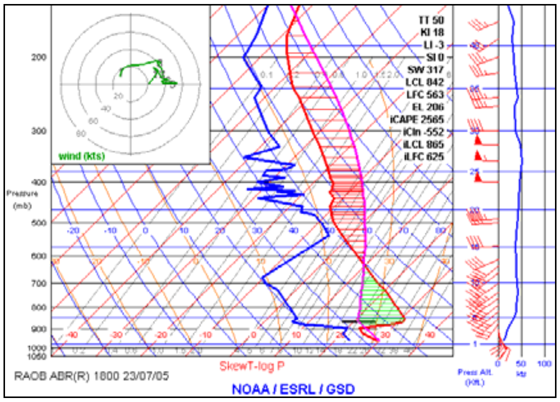

Fig. 15. 1800 UTC 23 July 2005 Aberdeen RAOB.

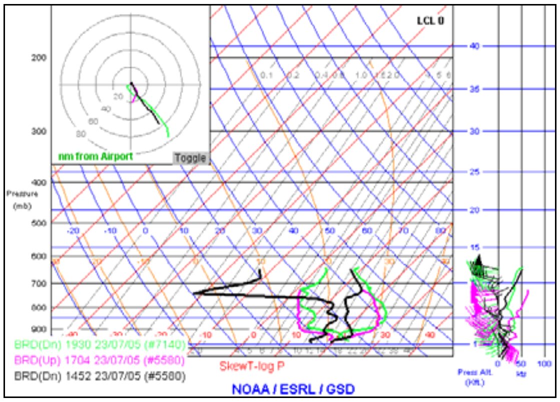

Fig. 16. Morning through afternoon TAMDAR series at Brainerd, Minnesota.

Meanwhile, downstream observations from Brainerd showed that a warm, dry 850-700 mb air mass had already advected into that area, immediately behind the departing MCS (Fig. 16). The ABR, JMS, and BRD observations strongly supported that the capping layer had overspread the entire area of concern. In fact, BRD TAMDAR data in addition to that from Minneapolis and Bemidji, Minnesota indicated a higher-CIN air mass than was present in northeastern South Dakota, due to cooler surface temperatures persisting in the cloudy region along and north of the warm front.

Based on the strength of the observed cap, thunderstorm potential through 0000 UTC would likely be confined to the path of the triple point, where insolation had already ensued and moisture convergence would be maximized. However, the degree of inhibition would necessitate several hours of sustained convergence and significant moistening if convection were to be realized. This forecast scenario was in general agreement with the 1500 UTC RUC guidance. Meanwhile, despite the convective signal forecast by the NAM, the remainder of the area would remain very strongly capped in the wake of the MCS. Any potential for additional elevated convection atop the surface stable layer would occur either much later if moistening could occur, or well to the northeast where TAMDAR indicated deeper moisture profiles and weaker mid-level capping away from the 700 mb thermal ridge.

3.2.2 Afternoon/nocturnal evolution

By 2100 UTC, surface observations and objective analysis indicated a well-defined triple point about 30 nm east of Aberdeen (Fig. 17-18), where the prefrontal trof intersected the outflow-

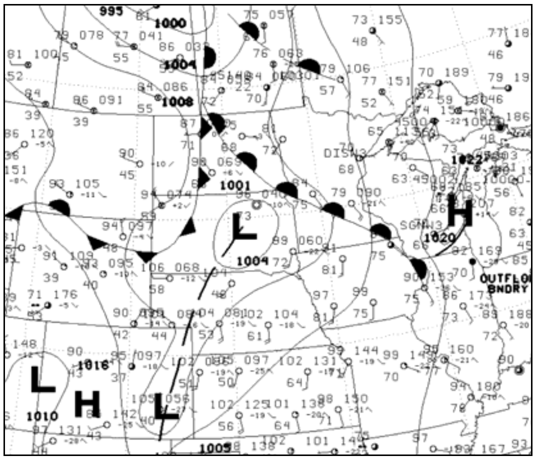

Fig. 17. 2100 UTC 23 July 2005 surface station plot and HPC synoptic scale analysis.

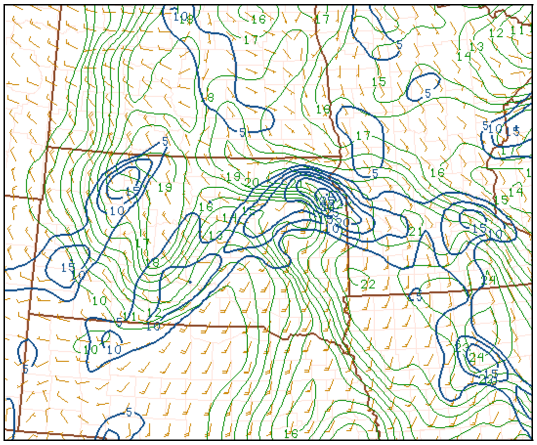

Fig. 18. 2100 UTC 23 July 2005 objective analysis of surface moisture convergence (blue contours every 5 g/kg/10 hr), mixing ratio (green contours every 1 g/kg), and surface winds. Image from SPC Mesoanalysis Page.

reinforced warm front. The position of this feature had been well-forecast by the 1500 UTC RUC. Visible satellite imagery indicated wave clouds had developed immediately to the cool side of the warm front after the departure of the mid-level cloud debris, from extreme southeastern North Dakota through central Minnesota. These clouds were a manifestation of the stable air mass in that area. However, nearly all of northeastern South Dakota had received 2-3 hours of strong insolation. Surface temperatures had warmed to 36°C (96°F) near and ahead of the triple point, where dewpoints were still holding above 21°C (70°F). There was no cumulus development, despite strong convergence near and in advance of the triple point.

A 2033 UTC descent and 2113 UTC ascent sounding were available from Aberdeen. The profiles were consistent in indicating that CIN had weakened since 1800 UTC, due to vertical mixing to nearly the 850 mb level accompanied by an increase in moisture depth (Fig. 19). The ascent sounding was considerably warmer than the descent sounding; this was either reflective of typical TAMDAR biases, or of the capping layer actually cooling with time. The latter process was feasible since observed winds showed that a backing-with-height profile had evolved below 800 mb. This effectively aided in weakening the cap, as cool advection overspread the high theta-e surface air pooled immediately behind the triple point. However, moisture convergence associated with the triple point was shifting away from the area, and surface winds turned northeasterly at Aberdeen by 2200 UTC bringing cooler surface temperatures and thus stronger CIN.

Even the more weakly-capped descent TAMDAR indicated 131 J kg^{-1} of SBCIN when modified with the 2100 UTC ABR surface observation, which was also where the highest surface theta-e in the region was observed. In fact, a 2206 UTC PIR TAMDAR showed that respectable CIN also remained across central South Dakota due to the strength of the EML, despite steep low-level lapse rates and surface temperatures well above 38°C (100°F). Visible satellite indicated no cumulus development occurring in central South Dakota along the prefrontal trough.

A few TAMDAR soundings were available from Watertown, South Dakota (ATY) beginning at 1930 UTC (Fig. 20), which was useful because the triple point passed immediately north of Watertown between 2100 UTC and 0000 UTC. Similar to trends at Aberdeen, the ATY observations showed gradual deep-layer moistening amidst fairly strong southwesterly 850-700 mb flow. By 2300 UTC, extreme values of surface theta-e were evident with ATY reporting a temperature and dewpoint of 37°C (98°F) and 24°C (75°F) respectively. The 2159 UTC descent sounding was the least capped of the three, and showed excellent continuity with the 2113 UTC ABR TAMDAR—aside from the cool advection apparent in that sounding. Modification of the 2159 UTC TAMDAR indicated SBCIN had decreased to 79 J kg^{-1}. Though this was a substantial improvement over the 1800 UTC environment, it was still likely an underestimation of capping due to the locally shallow nature of environmental moisture, within which a mixed-layer parcel would more realistically estimate cap strength—in this case, stronger CIN. This was validated by the fact that visible satellite still showed no cumulus development.

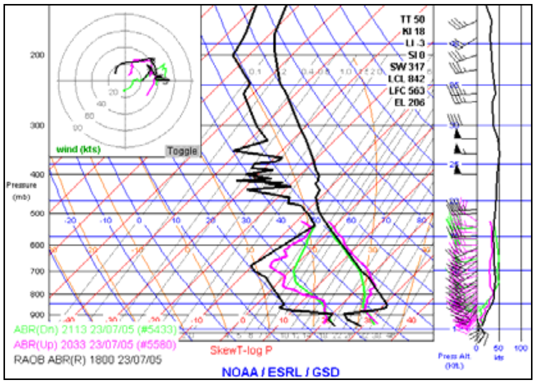

Fig. 19. Afternoon TAMDAR series at Aberdeen overlaid on 1800 UTC Aberdeen RAOB. Observed wind profiles from TAMDAR plotted on range rings.

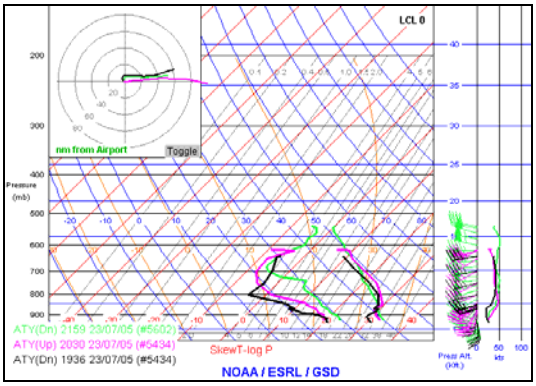

Fig. 20. Afternoon TAMDAR series at Watertown, South Dakota.

With the onset of surface cooling, convection appeared highly unlikely in the near-term over the area of concern. Due to no elevated CAPE evident in RAOB or TAMDAR data as a result of very steep lapse rates atop shallow moisture, any threat for thunderstorms overnight would necessitate dramatic moistening and/or cooling of the 700 mb cap. Indeed, no convection occurred over far northeastern South Dakota and west-central Minnesota through 1200 UTC July 24.

With an attendant counterclockwise hodograph through 815 mb, the 0000 UTC ABR RAOB (not shown) confirmed the trend of cool advection occurring in the wake of the triple point. Aside from further low-level cooling having occurred, the RAOB was consistent with the 2113 UTC ABR and 2159 UTC ATY TAMDAR soundings. Moisture was shown to be a little shallower on the RAOB, however. The ABR and MPX RAOBs suggested that the richest boundary layer moisture was not able to deepen up to the 850 mb level. Regardless, the NAM and NAM-KF solutions of robust moisture recovery were far too aggressive. The richest 850 mb dewpoint observed by ABR and ATY TAMDAR soundings was 16°C, with ABR and MPX 0000 UTC RAOBs sampling 12°C and 10° respectively.

4. CONCLUSION

TAMDAR provides a significant increase in the density and frequency of upper air sampling. As a result, forecasters are better equipped to evaluate how well numerical models have initialized the thermodynamic state of the atmosphere, and then directly observe how the atmosphere is evolving. Short-term convective forecasters may especially benefit from TAMDAR when vertical temperature and moisture profiles are changing with time.

Models contain inherent thermodynamic biases, which TAMDAR also helps to identify and resolve. In the two presented case studies, the RUC showed its documented boundary layer bias of being too warm and dry, generally due to unrealistically deep mixing over time. This was noted mainly within the western portion of the moist axis, which in both cases was co-located with the area of concern. The NAM also exhibited biases that are operationally observed from time to time, which led to unrealistic CIN erosion in each event.

In the July 20 case, convective potential existed along a retreating warm front beneath an amplifying subtropical ridge. Despite the presence of a very warm EML, the models erroneously reduced CIN by late day. Both models showed improvements to moisture depth occurring by late day. The NAM and NAM-KF forecast strong cooling of the capping layer, while the RUC heated the surface-800 mb layer too strongly. Subsequent RUC model runs did not change significantly until 2100 UTC. Observations from TAMDAR helped to verify that moisture recovery appeared feasible, but the other forecast processes did not; thus CIN was stronger than forecast and no convection occurred.

The July 23 event occurred within a stronger flow pattern on the northern periphery of the ridge. A long-lived MCS was in its early stages over the area at 1200 UTC, but moved rapidly southeastward and set the stage for renewed convection associated with a strongly convergent surface triple point. The 1200 UTC models reduced CINH to 40-100 j kg^{-1} by late day in the presence of a strong 700mb cap. The NAM—including the 1800 UTC run, even after having ingested special RAOBs and other data—also forecast convective precipitation with this feature. TAMDAR helped to verify that thunderstorms would be unlikely due to even stronger capping than was forecast. The RUC model was superior, picking up on this scenario by time of the 1500 UTC run. Ultimately, the NAM and NAM-KF overestimations of CIN removal resulted from overly strong heating in the wake of the MCS, as well as rapid deepening of boundary layer moisture despite very shallow moisture upstream.

5. ACKNOWLEDGEMENTS

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7. APPENDIX: SUPPLEMENTARY IMAGES

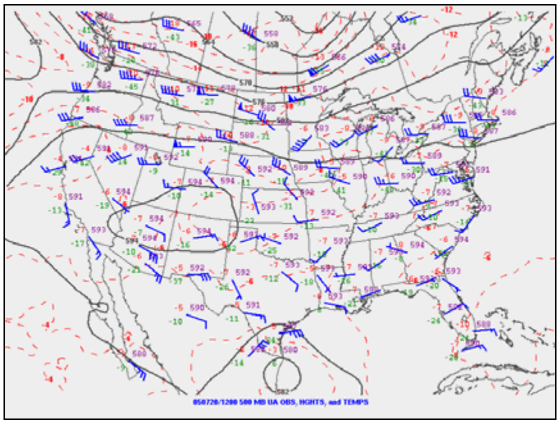

Fig. 21. 1200 UTC 20 July 2005 500 mb objective analysis. Geopotential height (black) contoured every 60 m and temperature (red) contoured every 2°C. Image from SPC.

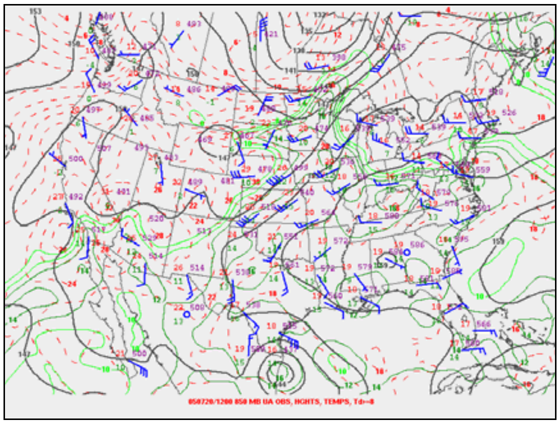

Fig. 22. 1200 UTC 20 July 2005 850 mb objective analysis. Geopotential height contoured every 30 m, and temperature and dewpoint (green) contoured every 2°C.

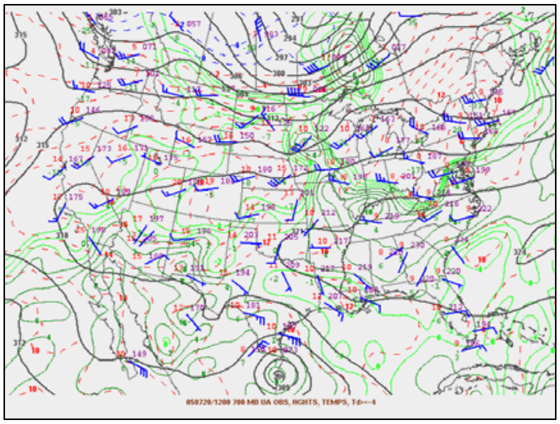

Fig. 23. 1200 UTC 20 July 2005 700 mb objective analysis. Contouring same as Fig. 22.

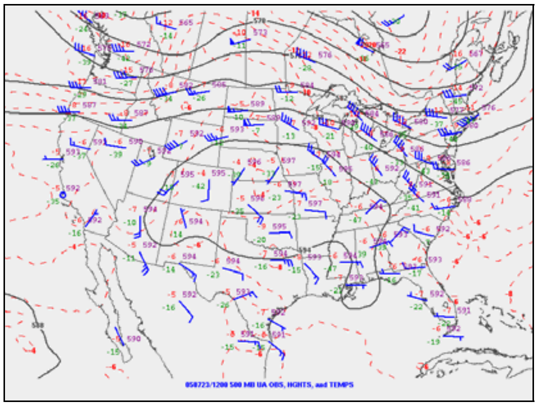

Fig. 24. 1200 UTC 23 July 2005 500 mb objective analysis.

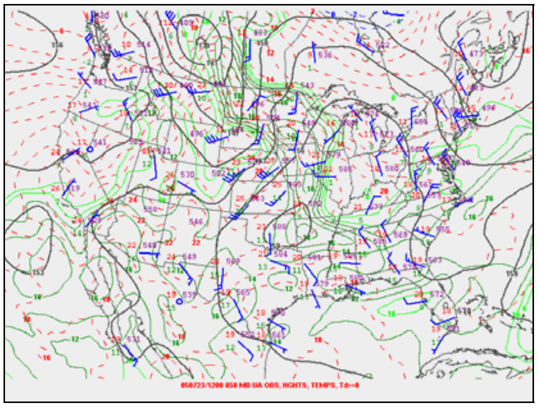

Fig. 25. 1200 UTC 20 July 2005 850 mb objective analysis.

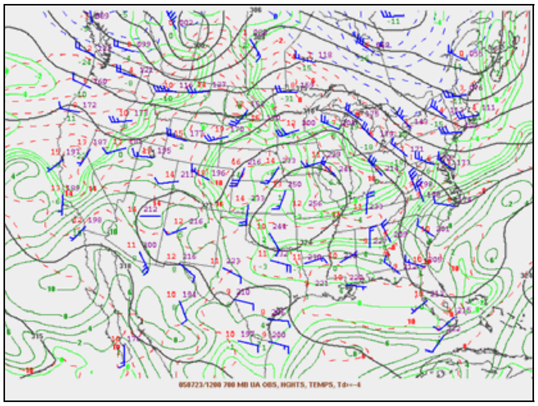

Fig. 26. 1200 UTC 23 July 2005 700 mb objective analysis