THE USE OF VAS SATELLITE DATA IN WEATHER ANALYSIS, PREDICTION, AND DIAGNOSIS

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ABSTRACT

Satellite images and retrieved soundings obtained using the VISSR Atmospheric Sounder (VAS) aboard GOES-5 are presented. Emphasis is directed both toward the immediate utility of the imagery in forecasting small scale weather events, as well as the potential usefulness of derived sounding in augmenting the temporal and spatial resolution available from conventional quantitative data sources. VAS data received on 13 July 1981 are analyzed to specifically address the following points:

a) Qualitative interpretation of imagery from various VAS channels, with emphasis on moisture channel images

b) Quantitative use of sounding derived from the full array of VAS channels

c) Assessment of the use of VAS data combined with conventional data.

Discussion of the satellite imagery is centered around an analysis of the time evolution of the mid-tropospheric moisture field observed using the satellite's 6.7 μm mid-tropospheric water vapor channel and the combined 11 μm-12 μm channel "split-window" low-level moisture calculation procedure. Particular examples illustrate the ability to isolate the development of small areas of potential convective instability related to severe weather development not easily detected with conventional data.

Quantitative results will illustrate the potential for augmenting the space and time resolution limits of conventional radiosonde data. The geosynchronous nature of the VAS allows time continuous observations over limited geographical areas not previously available from polar orbiting satellites and, as such, offers analysis update capabilities. Additionally, the versatility of current retrieval techniques allows for the inclusion of hourly surface data to improve the synthetic soundings near the earth's surface. The ability of the sounder data to better define the location and movement of frontal structures and moisture fields related to incipient mesoscale weather events will be illustrated. Horizontal analyses and vertical cross-sections using these data will be contrasted with detailed analyses of conventional data to better assess the utility and potential of existing sounding systems as examples of possible tools for use in future interactive forecasting systems.

1. INTRODUCTION

The analysis and forecasting of meso- to synoptic-scale weather events has been changed dramatically since the advent of geostationary meteorological satellites. Time sequences of visual and infrared images allow forecasters and researchers to observe the evolution and growth of features not resolved using conventional data sources, especially over the oceans. The latest advance in geostationary satellite observations took place recently when the first two of a series of experimental instruments were included aboard the Geostationary Operational Environmental Satellites (GOES). These instruments, called the Visible Infrared Spin-Scan Radiometer (VISSR) Atmospheric Sounders (VAS), allow simultaneous observation of the atmosphere in up to 12 infrared channels in addition to the currently available visible channel. While observations made from some of these channels have been available from polar-orbiting satellites for over a decade, VAS now presents an opportunity to observe sequences of images over the same geographical area in a variety of spectral regions with a temporal resolution of 15 to 30 min (5).

While meteorologists have relied on conventional radiosonde data to provide information on the vertical distribution of water vapor related to severe weather events, the timing and spacing of these observations is all too often inadequate to successfully monitor the development and progression of localized regions of convective instability. Barnes and Lilly (6) found that most of the variance in water vapor exists at scales less than 200 km for a convective environment. Even in a non-convective environment, 30% of the variance exists at scales less than 200 km. Significant differences in the amount of precipitation predicted by a numerical model have also been noted when the initial moisture fields contain detailed mesoscale structure (7). The precipitation amounts within simulated squall lines were significantly enhanced for experiments in which the initial state was specified to contain mesoscale moisture variations. These experiments suggest that improved mesoscale water vapor observations could have a significant impact upon the analysis and prediction of those processes which lead to the development of convective storm systems.

In this paper, images of mid- and low-tropospheric moisture derived from selected VAS channels will be presented to illustrate the ability of VAS to monitor the mesoscale structure inherent within upper and lower tropospheric moisture fields and the utility of these images as subjective forecasting tools. Later discussion will then focus on the impact of mesoscale temperature and moisture soundings derived from the 12 VAS infrared channels in the analysis of a pre-convective environment.

2. DESCRIPTION OF THE VAS INSTRUMENT

The VAS represents a major improvement over the standard operational VISSR used on GOES over the last decade. While soundings derived from multi-spectral infrared and microwave measurements from polar-orbiting satellites have been combined with conventional upper-air observations for numerical simulations of large scale atmospheric motions, multiple infrared observations obtained from a geostationary satellite offer the opportunity for much more frequent observations of smaller domains associated with meso- and subsynoptic-scale weather events. As will become apparent, interactions between the various scale weather events can also be isolated.

Unlike previous geostationary satellite systems, observations from the various VAS infrared channels are available in two modes. In the Dwell Sounding (DS) mode, any or all of the 12 infrared channels between 4 and 15 microns can be programmed at any time to scale selected portions of the earth. Multiple passes of individual channels who signal-to-noise ratios are relatively small may also be chosen to enhance the signal content of the data. The 12 channels, each of which senses upwelling radiance with approximately 5 km vertical and 15 km horizontal resolution, were chosen specifically to monitor atmospheric temperature, cloud cover and moisture. The DS mode typically requires about 30 minutes to observe a swath of the globe extending 20 degrees in latitude. Once the DS sounding data are received, the multiple channel observations can be combined using a variety of techniques to produce soundings of both temperature and moisture, as will be shown later (8,9).

A Multi-Spectral Imaging (MSI) mode is also available to allow multiple infrared channel observations while under operational time constraints. In this configuration, two channels of the infrared array can be received simultaneously with the conventional .9 km resolution visible and 6.9 km 11.2 micron infrared data. While this system limits the total number of observing channels and precludes multiple passes of the same channel, the speed of the MSI mode permits full disk coverage in an 18 minute time frame. With this observing frequency, time sequences of images can be produced in a variety of spectral bands without affecting operational schedules and can be used in studies conducted for a variety of scales.

The intent of this paper is to use a case study approach to exploit the imaging capability of the VAS instrument by delineating regions of mid-level dryness and low-level moisture, and to test the quantitative sounding capabilities of the instrument in indicated regions of convective potential. While only one case is shown here, additional cases being investigated show consistent results and will be reported on in subsequent papers.

3. CASE STUDY DESCRIPTION

Synoptic and radar maps for 13 July 1981 are shown in Figure 1. At 1200 GMT, a weak surface wave was drifting slowly from eastern Colorado toward Nebraska along a stagnant surface front extending through northern Illinois into southern Michigan. Precipitation in the Midwest was confined to several regions of thunderstorms in South Dakota, eastern Iowa, and the Texas-Louisiana coastal area. The 850 mb analysis (Figure 2) was dominated during the 12 hour period by a broad anticyclone centered over Alabama. The accompanying circulation was forcing a broad band of weak southerly flow west of the Mississippi, enveloping a wedge of maximum temperatures in the region of the surface frontal zone. To the northeast of the Great Lakes, a short wave was propagating rapidly southeastward toward Maine. The upper level support for this short wave is clearly visible at 300 mb as a moderately intense jet streak continued to extend southeastward across New York State and towards the Atlantic seaboard by 0000 GMT. Over the Mississippi Valley and the Great Plains, however, the flow pattern remains weak and disorganized south of the major upper-level ridge.

By 1800 GMT, the effects of surface heating and southerly flow had forced surface temperatures to rise well above 30°C and dewpoints to surpass 20°C over almost the entire southeastern half of the country. The area of thunderstorms over Iowa had disintegrated almost completely as it moved into northern Illinois, while the Dakota precipitation area had moved northward and diminished. Thunderstorms along the Gulf continued to strengthen, while numerous other areas of rain were found east of the Mississippi. By 0000 GMT, radar reports showed scattered regions of thunderstorms over much of the western Mississippi Valley. Of particular interest to this study, however, are the 16,780 m (55,000 foot) high storms which developed in less than 2 hours over eastern Iowa, approximately 150 km ahead of the weak surface front and in an area devoid of any particularly strong dynamical forcing. A detailed discussion of some qualitative and quantitative results obtained using the VAS observation of this storm system will now be presented.

4. DISCUSSION OF SATELLITE IMAGERY FOR THE PERIOD 1500 TO 2300 GMT 13 JULY 1981

Both the Dwell Sounding and Multi-Spectral Imaging modes of the VAS were activated during daylight hours over the central United States. Visible observations taken at approximately three hour intervals (Figure 3) verify the progression and development of precipitation activity already shown on the radar summaries. The sequence of images from the 6.7 micron mid-tropospheric water vapor sensing channel however, portray a strikingly more continuous picture (Figure 4 and left column of Figure 7). Even in the cloud free regions, a distinctly banded structure is present as broad regions of moist air (gray) are punctuated by narrow bands of dryness (dark). The time sequence of the water vapor images clearly reveals distinctive features of the circulation pattern. For example, the cyclonic gyre initially north of the Texas panhandle breaks down during the day, while the banded features west of the Mississippi drift slightly northward and slowly rotate anticyclonically. Simultaneously, a band of very dry air associated with the jet streak north of the Great Lakes is observed propagating rapidly southeastward.

Since the weighting function of the 6.7 micron channel extends through a large depth of the atmosphere (Figure 5), confusion can arise regarding the precise altitude of a single layer of high moisture content. Because the amount of radiation received by the satellite is a function of both water vapor content and temperature, differing amounts of water vapor at varying temperature can give almost identical signals. Nevertheless, in areas where little or no water vapor is present, the interpretation of the dryness indicated in the satellite image is unambiguous, since the warm low-level air observed through the mid-level dryness will provide a distinct and sharply contrasting signal. The 1200 GMT radiosonde soundings in Figure 6 are shown (1) to illustrate ambiguity which can exist in the presence of water vapor and (2) to verify the satellite's ability to observe regions of mid-tropospheric dryness which, as shown by the imagery, often exist at a horizontal scale below that observable using conventional radiosonde data. As observed by comparing the first three panels of Figure 6 with the 1200 GMT water vapor image, the existence of either a single layer of moisture (around 600 mb at BNA and above 400 mb at INL) or multiple layers anywhere in the middle or upper troposphere from approximately 300 to 600 mb (DDC sounding) can produce similarly moist (bright) signals. By contrast, the lack of nearly saturated conditions above approximately 700 mb consistently yields a distinctly dry (dark) signal as noted at Little Rock and near the jet streak axis at Sault Saint Marie (Figures 6e,f).

The ability to monitor situations where narrow bands of dry air are detected above regions of low-level moisture yielding the potential for convective instability could provide an important tool to operational forecasters. One such technique involves superimposing the mid-level dryness signal from 6.7μ image over conventional visible imagery and noting where the dry air overlays regions of warm low-level clouds. Using the image analysis capabilities of the Goddard Space Flight Center (GSFC) Atmospheric and Oceanic Image Processing System (AOIPS), this procedure has been successfully applied to monitor the progression of a band of prefrontal convection associated with a January Gulf Coast extratropical cyclone development (10). In this July case, however, the rapid thunderstorm growth in eastern Iowa and weaker showers in Kansas and Oklahoma developed in a situation of little if any pre-existing cloud cover. To obtain an estimate of the low-level water vapor content in clear areas such as this, Chesters, et al, (11) have developed a "split-window" technique for combining radiance information from two VAS window channels in a manner which is adaptable for real-time operations.

As shown in Figure 5, the 11.2 and 12.7 micron window channels of the VAS each have their largest sensitivity at the earth's surface. However, not only do the two channels observe slightly differing depths of the atmosphere, but, more importantly, the 12.7 micron channel observations are significantly more attenuated by atmospheric water vapor. In the "split-window" technique, a simple physical model is used to simulate the radiation transfer through the boundary layer involving three unknowns: (1) surface (skin) temperature, (2) an average air temperature for the layer from 1000 to 700 mb, and (3) integrated moisture. When the air temperature over the cloud free area is estimated using radiosonde observations imbedded within the area of interest, fields of estimated low-level moisture can be obtained directly using the physical algorithm (11).

A time sequence of images of low-level precipitable water obtained using this method, with an average layer temperature representative for the southeastern two thirds of the United States, is shown in the right hand column of Figure 7. Solid black areas on the images are either regions of obvious cloud cover which have been eliminated from the computations or areas in which the boundary layer air temperature is much colder than the estimate made for the central United States, so accurate precipitable water estimates cannot be made. In itself the continuity of the various water vapor features observed over the United States throughout the period speaks for the stability of the technique. For example, the moist (bright) area initially located along the Arkansas-Oklahoma border drifts slowly northward during the day, in agreement with the observed low-level flow. North of this maximum, the dry (dark) region centered over Nebraska and Kansas remains relatively stationary. In support of these observations, radiosonde reports of 850 mb dewpoints in the dry area averaged less than 10C and in the moist area near 18C. Further quantitative verifications are made in Chesters, et al, (11).

Other smaller scale features on the moisture imagery, however, cannot be directly verified since they occur between conventional radiosonde observation points. Consider, for example, the evolution of the moisture in Kansas and Oklahoma into two distinct bands and the tongue of dry air initially extending across northern Missouri into west-central Illinois. While direct verification using the operational radiosonde network is impossible, the time continuity and spatial progression of these features agree with the orientation of the low-level flow and the subsequent development of precipitation (or lack of it). Further subjective evidence for the presence of the dry feature extending from Missouri can be drawn from the fact that the thunderstorms initially drifting southeastward over Iowa dissipated and changed direction to move outside the perimeter of the low-level moisture minimum as they entered Illinois after 1800 GMT.

Another mesoscale feature of particular interest was the appearance of an increasing amount of boundary layer moisture across Iowa in the wake of the morning thunderstorms. Although surface convergence was present along the entire length of the stationary surface front, severe convection was initiated only in a small area of eastern Iowa, where a superposition of low-level moisture and mid-level dryness patterns was observed by VAS. While a color combination of successive pairs of images at shorter time intervals is available in loop form using image display devices, the reader is asked to visually co-locate the various image features in Figure 7. By 2100 GMT, a maximum of mid-level dryness has drifted over the low-level moisture concentrated in eastern Iowa, indicating a local potential for convective instability which, as noted previously, was realized in the subsequent two hours. Several other outbreaks of convection were also observed along the edges of such mid-level dryness over low-level moisture interfaces after 1800 GMT along the Oklahoma border, along west-central Oklahoma and in central Arkansas. While direct verification of these mesoscale patterns is not usually possible, the persistence of the development of convection along these thermodynamically meaningful interfaces is itself convincingly supportive evidence.

5. QUANTITATIVE ASSESSMENT

In an independent effort, quantitative soundings have been derived from the middle half of the United States for this same period. Due to the case study nature of the work currently being undertaken at Goddard Laboratory for Atmospheric Sciences (GLAS), the linear regression technique applied in this case study uses co-located radiosonde/radiance observations in cloud free areas at 1200 and 2300 GMT to derive correlation matrices (12). To increase the low-level detail present in the derived soundings, surface airways data are also included in the regression procedure as statistical predictors, along with the VAS radiances. While the technique precludes an exact fit of the surface data to the lowest level of the retrieval results, a distinct improvement in the VAS-radiosonde comparison RMS statistics is noted in Figure 8. The inclusion of surface temperature and dewpoint data also stabilizes the regression technique since the surface data is a better "predictor" for the lowest part of the troposphere than any combination of VAS channels, whose broad weighting functions do not permit a distinct measurement of atmospheric structure at these levels. The net result, when surface data is included, is a more cohesive field of VAS soundings, with less point-to-point variability.

Discussion of results presented here will be limited to the last three time periods and will concentrate on the Iowa thunderstorm development. Analyses shown were generated from satellite soundings obtained at approximately 100 km intervals in cloud free regions only. These data were then interpolated to a .5 by .5 degree latitude-longitude grid using a Barnes analysis (13). The time sequences of 850 mb temperature and dewpoint analyses both show striking temporal continuity (Figures 9a, b, c, and 9f, g, h). The wedge of warm air extending from the west through Omaha on the radiosonde reports is further localized reaching eastward along the Iowa-Missouri border. A comparison with analysis of radiosonde data for 0000 GMT shows a marked increase in the detail of the thermal structure near the surface frontal zone and an almost perfect correlation at radiosonde observation points (Figure 9c).

Analyses of 850 mb retrieved dewpoints again show characteristics beyond the resolution limits of the conventional radiosonde network. As in the qualitative low-level moisture imagery, a moisture maximum can be traced eastward moving across Iowa during the 5 hour period shown, while a second maximum is intruding into southwestern Missouri and eastern Kansas from Oklahoma. These two high moisture regions are punctuated by a band of drier low-level air extending southeastward from Nebraska through central Missouri. Comparisons with 0000 GMT radiosonde analyses (Figure 9j) again illustrate the increased horizontal resolution present using the spatially and temporally more frequent VAS observations in addition to conventional radiosonde data. Not only had the mesoscale structures within the 2300 GMT VAS temperature analyses accurately delineated the location of the front within Iowa with colder temperatures to the north and warmer temperatures to the southwest, but the dewpoint analysis had also isolated a distinct moisture maximum in southeastern to east-central Iowa, in the location of the sudden convective development. Additionally, this moisture maximum, the band of lower dewpoints across Missouri, and the second moisture regime extending northeast from northeast Oklahoma into central Kansas all agree well with the low-level water vapor images presented earlier.

It was expected that the limited vertical resolution of the VAS weighting functions would limit the retrieval of both horizontal and vertical gradients in pre-convective environments (8). To test the vertical temperature and moisture variability resolvable in the VAS retrievals in this case, a vertical cross-section of retrieved equivalent potential temperature along 41 degrees north latitude (across Iowa) for 2100 GMT, just prior to the thunderstorm development, is shown in Figure 10. Not only does the highest low-level moisture potential appear at the proper location, but the vertical gradient is also maximized in this area. While the vertical gradients are much weaker than would be expected from radiosonde observations (had they been available at this time and space scale), the cross-section is in agreement with the convective instability qualitatively inferred from the combined image overlay procedure discussed previously.

6. SUMMARY

Analyses of the VAS data from the 13 July case study indicate that the VAS offers a mesoscale data base suitable for the study of severe storms. VAS imagery depicts mesoscale moisture patterns for the upper and lower troposphere which provide structure that cannot be fully resolved (nor verified) with the conventional radiosonde data base. The technique of overlaying the 6.7 micron upper tropospheric VAS moisture channel with the VAS "split-window" low level moisture field has proven useful in delineating regions of potential convective instability (dry air over moist air) within which intense convection can rapidly develop.

The study of the 13 July case also uses a regression sounding algorithm to produce temperature and moisture profiles with 55 km horizontal resolution to quantify the information gleaned from the VAS imagery. Again regions of upper level drying overlying low level moisture can be delineated, adding coherent mesoscale structure, both in space and time, not possible with the conventional data base. Cross sections of equivalent potential temperature derived using VAS reveal that the region of convective instability, as inferred from the imagery, is indeed related to those areas where θ_e decreases significantly with height.

Since the methods used at the Goddard Space Flight Center to convert VAS radiances into meteorological parameters are heavily dependent on the use of conventional data bases, we are not advocating the substitution of VAS for radiosonde or surface reports. Rather, given our experience with VAS data, we feel that the VAS has great potential for filling the temporal and spatial data gaps which currently exist within the conventional data base, providing a means to study and better predict severe local storms. The most serious problem we have encountered so far is the effect that unresolved clouds have upon the quality of VAS soundings. Visible images should be used for cloud detection, since the 15 km IR resolution is not adequate to fully resolve developing boundary layer cumulus clouds or thin cirrus. Whenever soundings are attempted within what is assumed to be clear conditions using the VAS infrared window channels, but in reality is cloud contaminated as later revealed by visible images, the soundings tend to be too cool by up to 3°C. Ultimately, the utility of the VAS derived upper and lower tropospheric moisture and temperature patterns will be judged by their acceptance as mesoscale nowcasting and forecasting tools when the VAS data are routinely distributed as a product of the GOES system.

7. ACKNOWLEDGEMENTS

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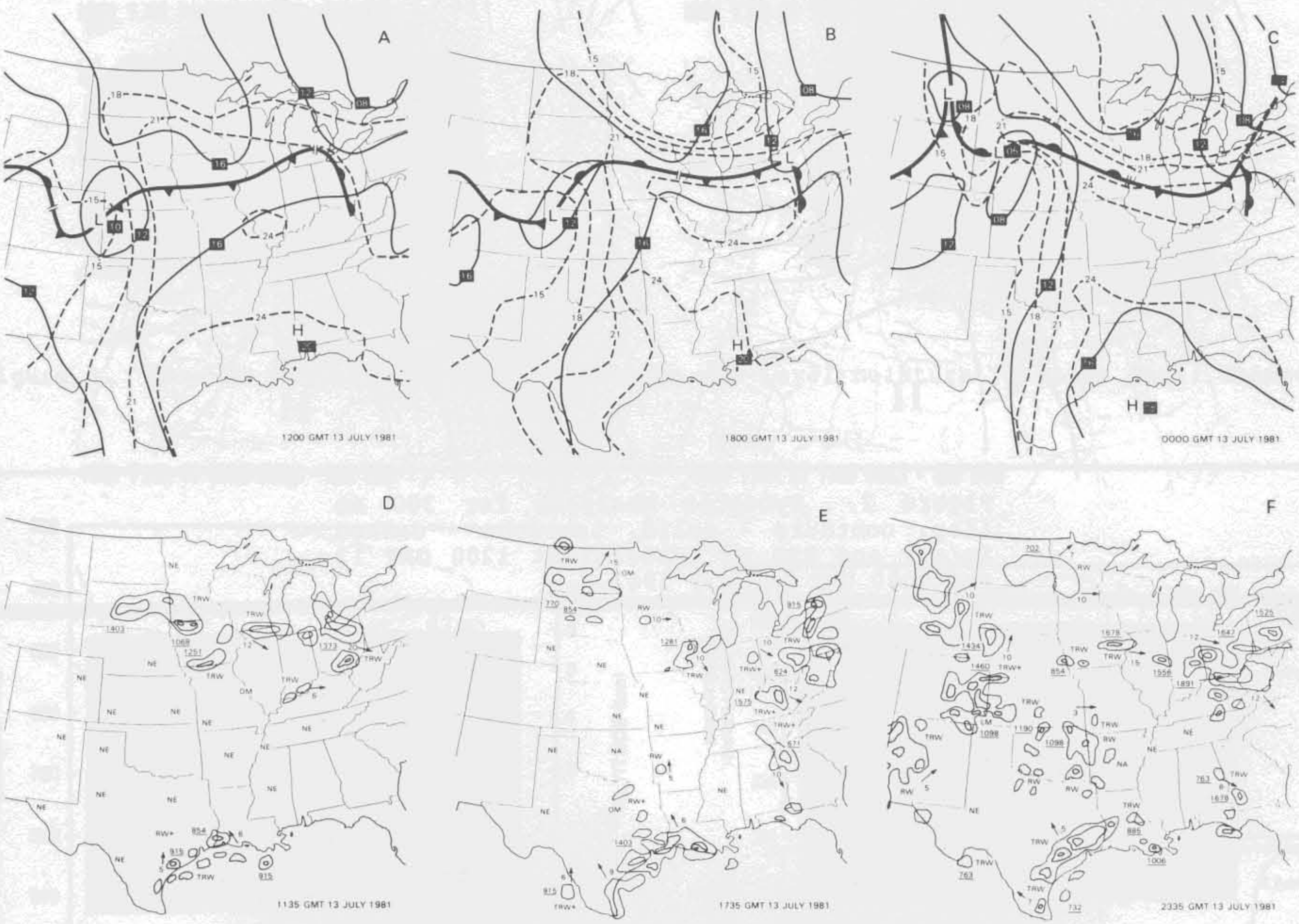

Figure 1. Surface analyses of MLS pressure (mb) and dewpoint temperature (dashed, °C at 1200 GMT, 1800 GMT and 0000 GMT and corresponding radar summaries (cloud tops in meters).

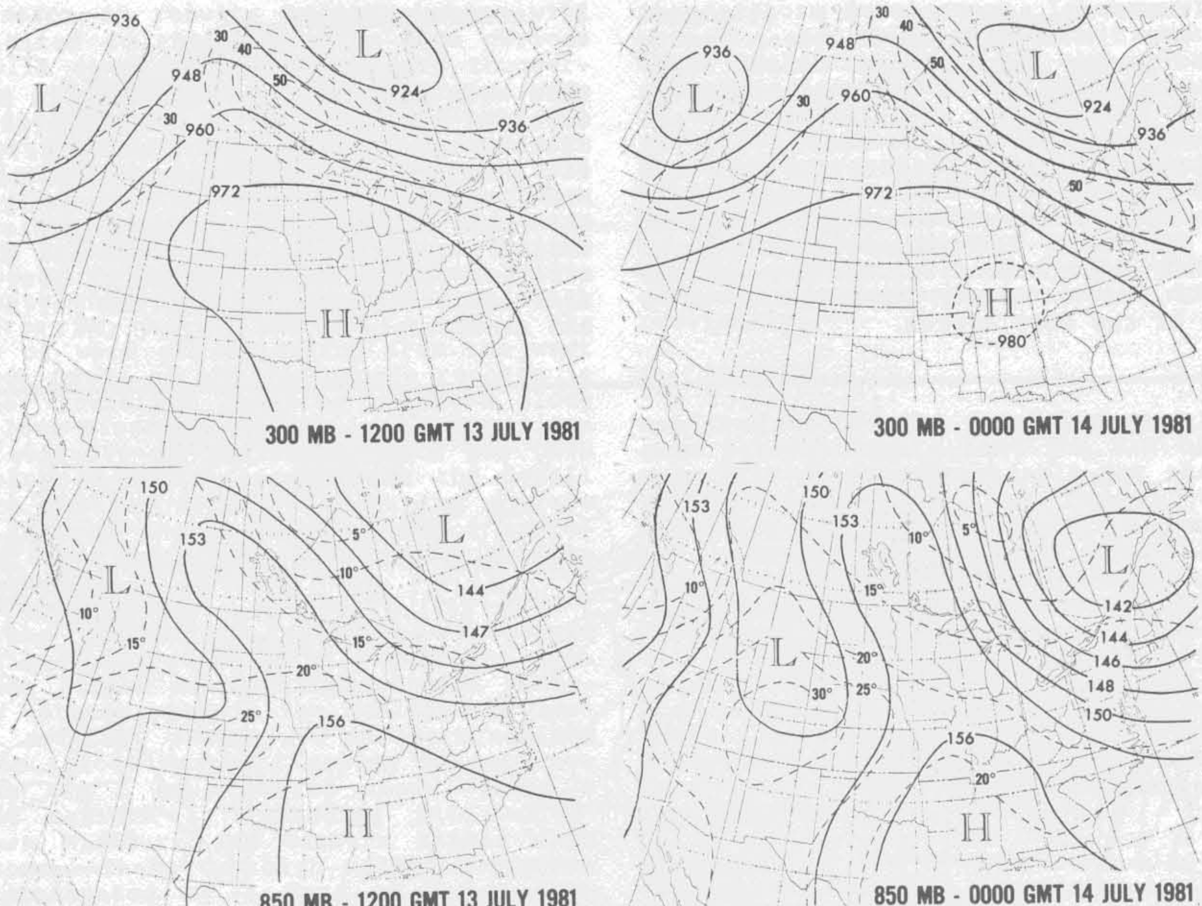

Figure 2. Synoptic analyses for 300 mb (top, contours - solid, isotachs - dashed (m/s)) and 850 mb (middle) at 1200 GMT 13 and 0000 GMT 14 July 1981.

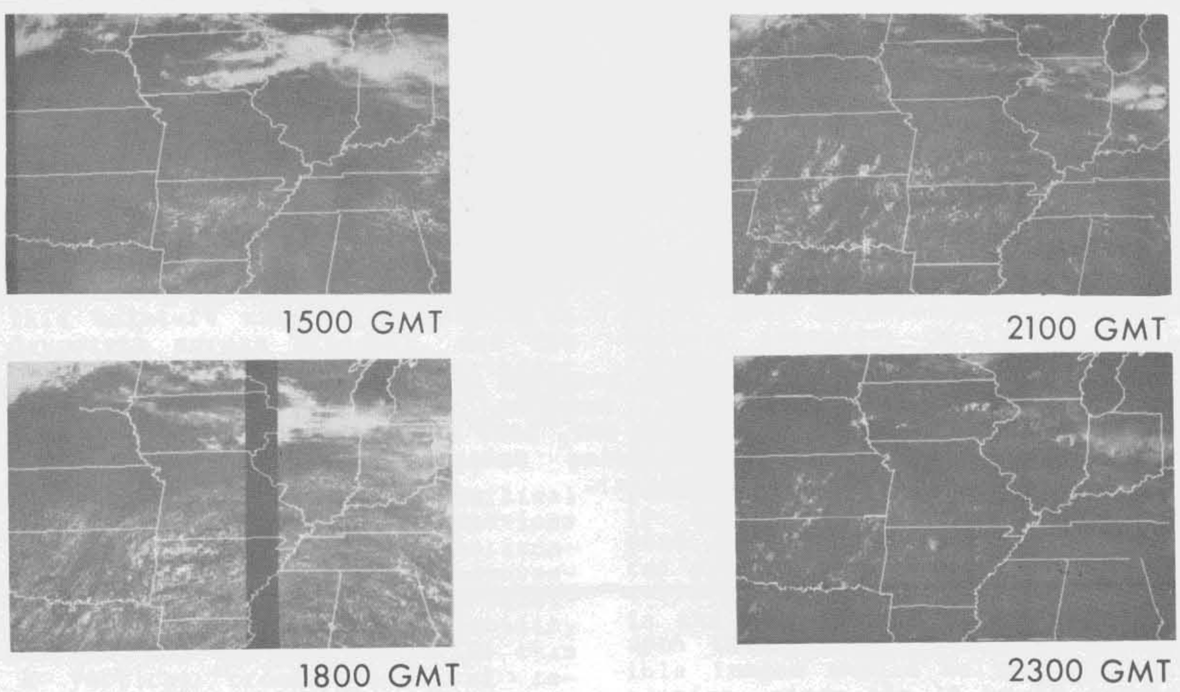

Figure 3. 1500, 1800, 2100, and 2300 GMT 4.3 micron window channel images for the eastern United States.

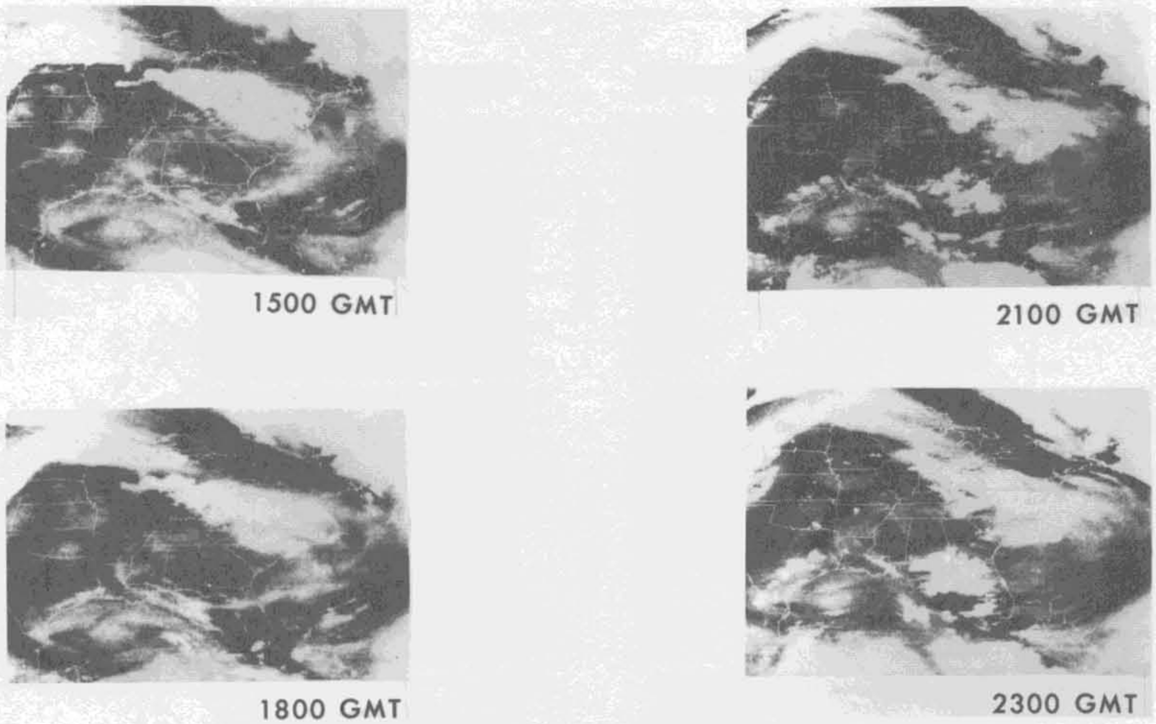

Figure 4. Same as Figure 3, except 6.7 micron mid-level moisture (dryness dark) channel.

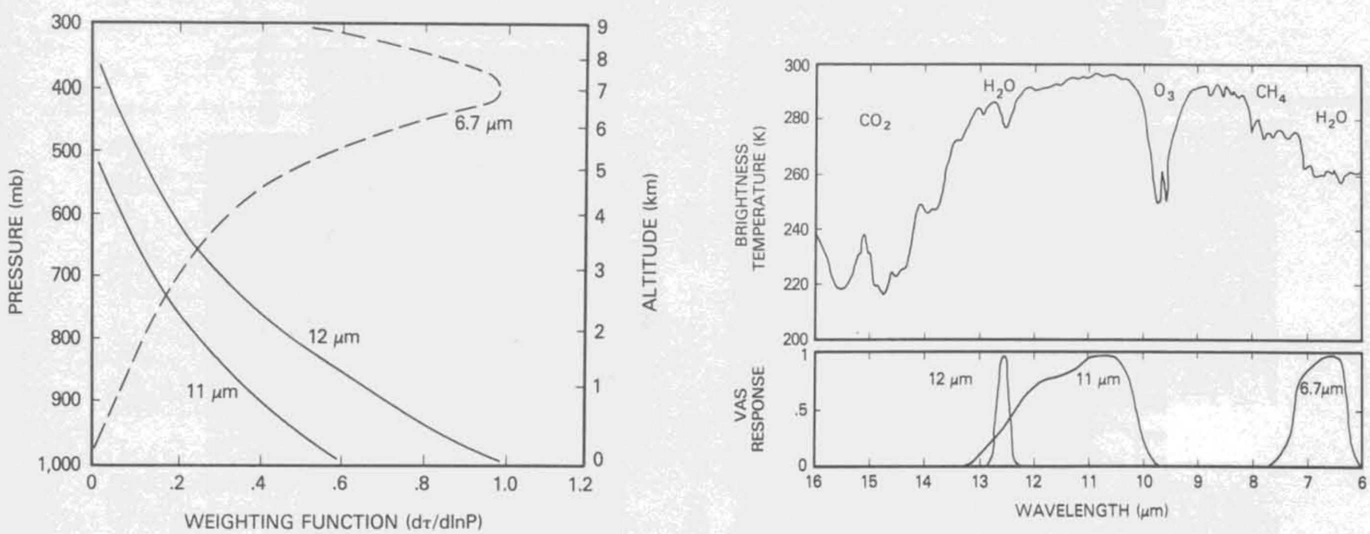

Figure 5. VAS moisture channel weighting functions (a) and absorption curves (b).

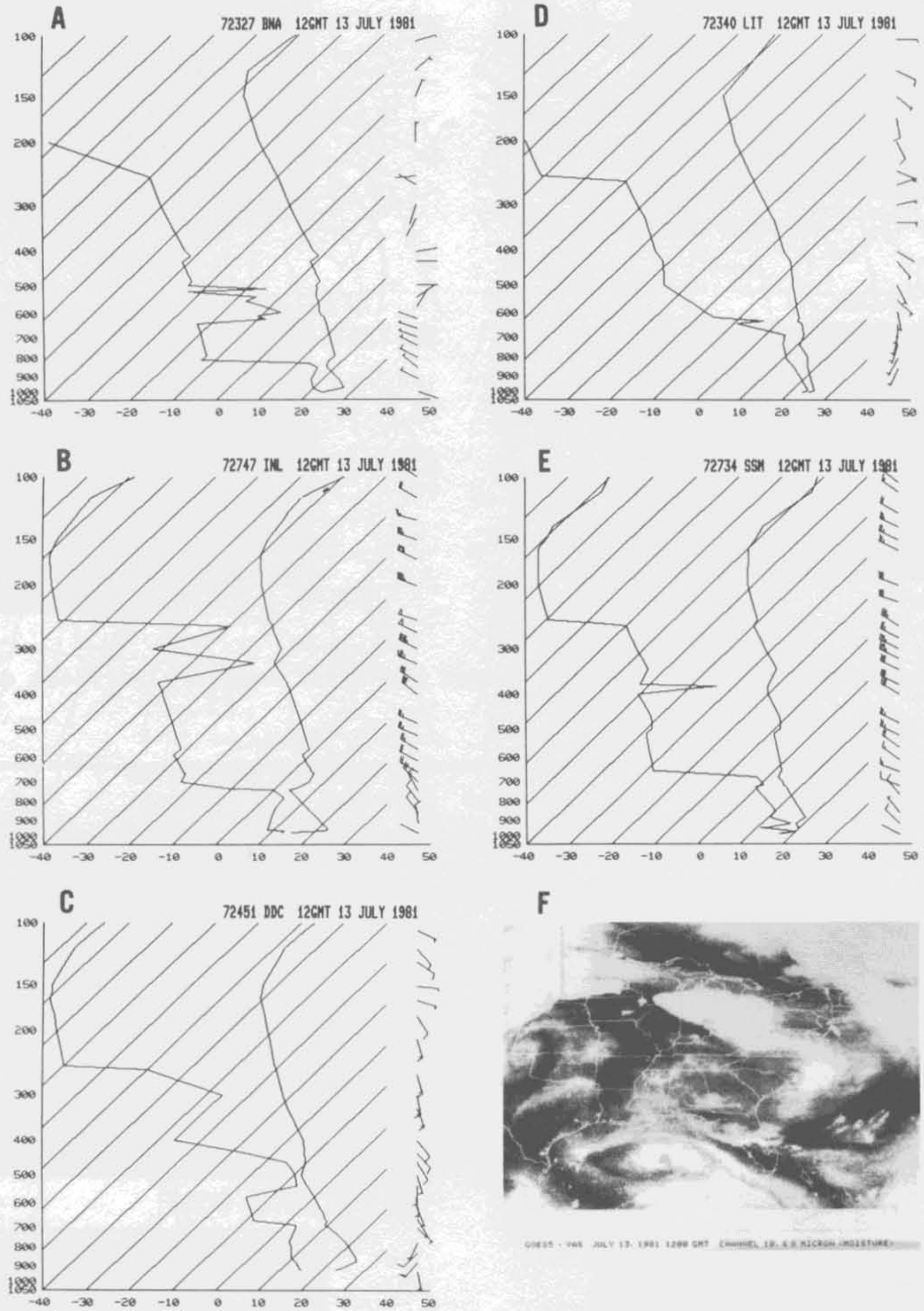

Figure 6. 1200 GMT radiosonde sounding for selected stations with: variable mid-troposphere moist layers (a, Nashville, TN, BNA; b, International Falls, MN, INL; c, Dodge City, KS, DDC), and total dryness above 700 mb (d, Little Rock, AR, LIT; e, Sault Saint Marie, MI, SSM) and 1200 GMT 6.7 micron moisture channel image (f).

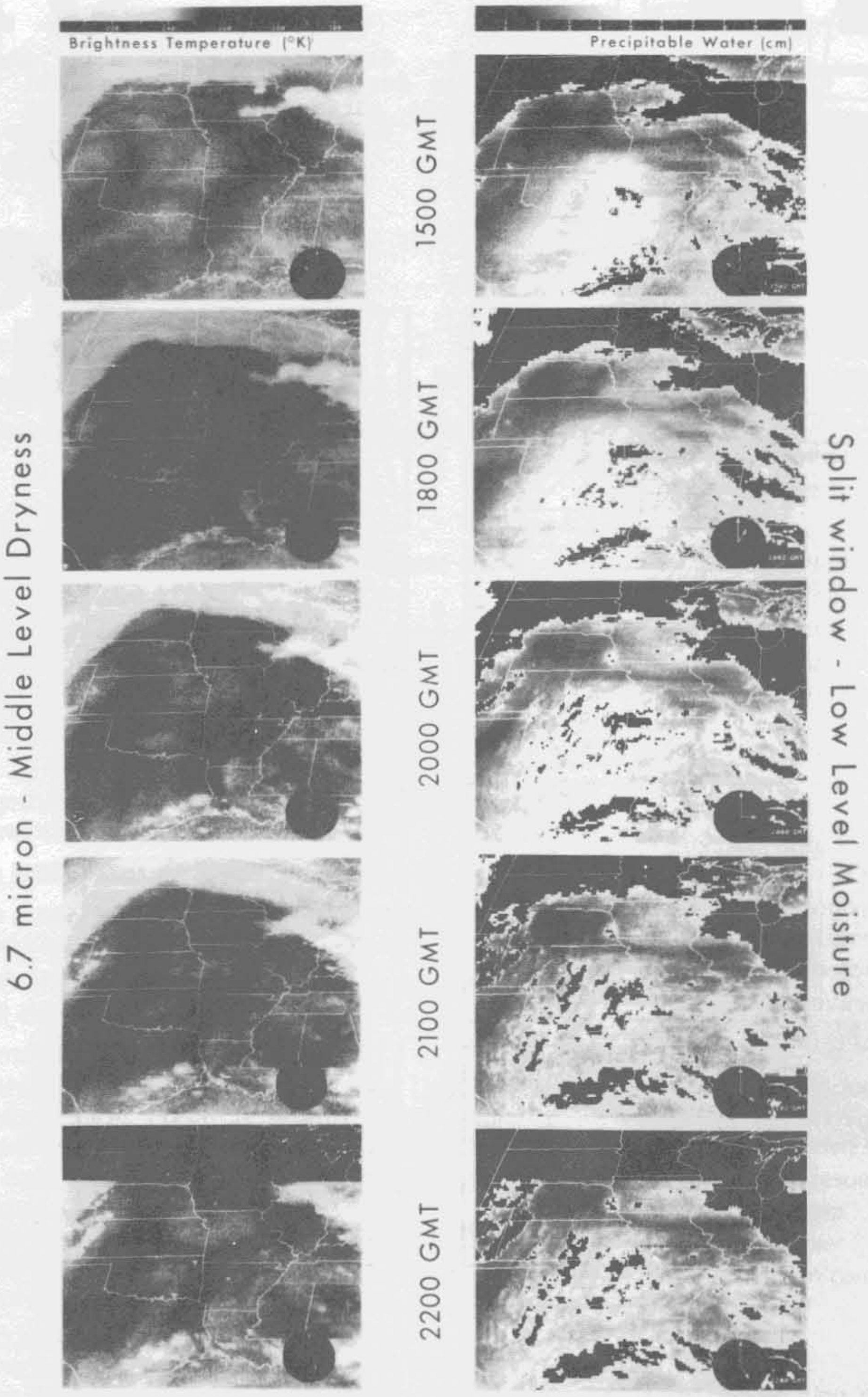

Figure 7. 1500, 1800, 2000, 2100, and 2200 GMT 6.7 micron mid-level moisture (left column-dryness dark) and 11.2/12.7 micron "split-window" low level precipitable water estimates (right column-moistness light). Clock faces show hours in C.D.T.

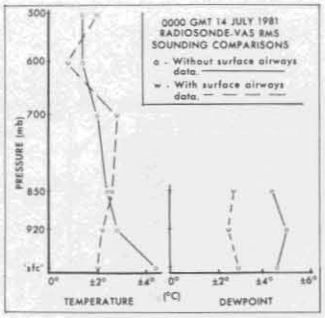

Figure 8. Statistical comparison of VAS retrievals for 2300 GMT 13 July 1981 with and without surface airways data as compared with colocated radiosonde observations.

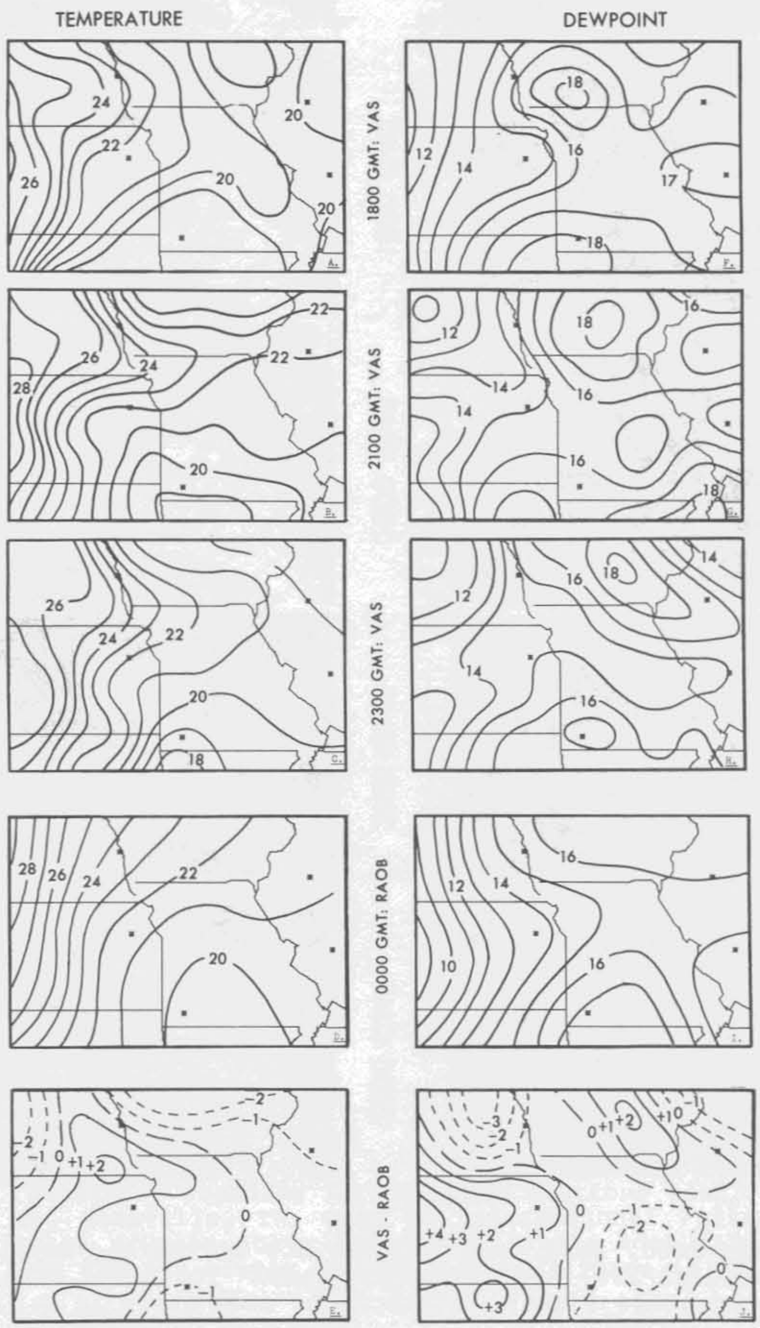

Figure 9. 1800, 2100, and 2300 GMT VAS temperature (a,b,c) and dewpoint (f,g,h) analyses, 0000 GMT radiosonde temperature (d) and dewpoint (i) analyses, and difference fields between 2300 GMT VAS and 0000 GMT radiosonde analyses (+ indicates VAS warmer).

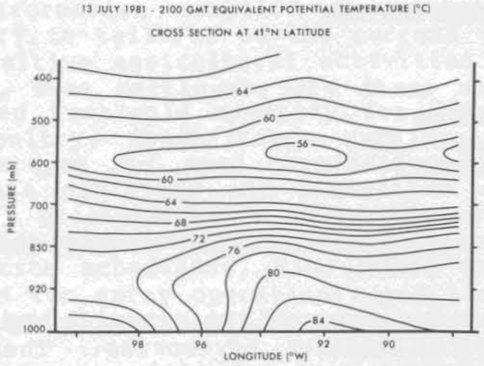

Figure 10. Vertical cross-section of equivalent potential temperature taken from VAS analyses along 41 degress north latitude (°C).

FOOTNOTES AND REFERENCES

1. Ralph A. Petersen is the Severe Storms Research Group leader for the VAS Demonstration at GLAS. His interests range from synoptic-mesoscale interactions to computer nowcasting applications.

2. Louis W. Uccellini is a group leader in the Severe Storms Branch of GLAS. His research is related primarily to jet streak dynamics and interactions.

3. Dennis Chesters is a physical scientist in the Climate and Radiation Branch of GLAS. His research involves the optimal retrieval of meteorological information from satellite radiances.

4. Anthony Mostek, a meteorologist/analyst for Computer Sciences Corporation, is the task leader for the VAS task, part of the on/off-site contract with NASA/GSFC supporting the VAS Demonstration activities as GLAS.

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