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TOVS SATELLITE SOUNDINGS
OF THE
ERICA IOP-2 CYCLONE

by

John J. Pereira

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Thesis Advisor Carlyle H. Wash

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TOVS Satellite Soundings of the ERICA IOP-2 Cyclone

by

John J. Pereira
Captain, United States Air Force
B.S., The Pennsylvania State University, 1983

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Author: ______________________
John J. Pereira

Approved by: ______________________
Carlyle H. Wash, Thesis Advisor

____
Wendell A. Nuss, Second Reader

____
Robert J. Renard, Chairman,
Department of Meteorology

ABSTRACT

Satellite soundings from the TIROS-N Operational Vertical Sounder (TOVS) are used to study the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) Intensive Observation Period-2 (IOP-2), 13-14 Dec 88. TOVS data are compared with dropwindsondes and coastal rawinsondes, and Spectral Grid Model (SGM) analyses of stability, geopotential height, and temperature. The impact of the first guess on the TOVS retrieval is studied by comparing four first-guess methods: 1) regression without surface data; 2) regression with surface data; 3) climatology with surface data; and 4) SGM analyses with surface data. Ship reports and moored and drifting buoys were objectively analyzed to obtain the surface data for the first guess. The retrievals with 6-h old SGM analyses as a first guess best captured the low level structure of the in situ soundings. The TOVS stability analyses defined the rapid cyclogenesis environment, in advance of the developing cyclone. The TOVS height and temperature analyses successfully described the structure of the developing cyclone, in reasonable agreement with experimental data and synoptic-scale analyses.

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I. INTRODUCTION

Historically, accurate weather forecasts have been limited by the availability and accuracy of observations. Even with increases in computer speed and the finer resolution of current numerical models, forecasts are still limited by the amount and quality of observed data. Over large data-sparse areas, such as oceanic regions, important atmospheric properties, such as temperature, pressure, humidity, and wind velocity, are not adequately measured. These limited data come from coastal rawinsondes, ship and buoy reports, and aircraft observations. An additional concern is that the middle part of the troposphere (about 500 mb) is infrequently sampled by these data, although considered by meteorologists to be a key level for weather forecasting.

One observation source that is capable of retrieving global temperature and moisture profiles is satellite soundings. Satellite-derived measurements of temperature, geopotential height, and ozone have been available since the 1970's. Their use in initializing numerical forecasts has been steadily increasing. Over the data-sparse southern hemisphere, satellite soundings are a primary observation source for NMC's current global forecast models (Dey 1989).

Satellite soundings are important for military applications as well. In wartime when some data sources may not be available, satellite soundings can give forecasters a dynamical perspective of the atmosphere over a much larger region than would be available from a partial rawinsonde network. Particularly over the oceans, satellite sounding data could be especially valuable for military operations. The U.S. Navy plans to implement real-time satellite sounding retrievals with the third phase of their Tactical Environmental Support System (TESS-3) in the 1990's. They will collect data from the NOAA polar-orbiting satellites to use as a nowcasting aid at sea and coastal locations. These data will include profiles of temperature and moisture from the Tiros-N Operational Vertical Sounder (TOVS) onboard the NOAA satellites. The software available for retrieving TOVS soundings, during the early development phase of TESS-3, was used in this thesis research.

The purpose of this thesis is to evaluate the accuracy and synoptic utility of TOVS soundings over a coastal and oceanic environment during a rapid cyclogenesis event. Data from the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA), conducted from December 1988 to February 1989, will be used for the evaluation. Research will concentrate on Intensive Observation Period-2 (IOP-2), 13-14 December 1988.

In this study, TOVS soundings for IOP-2 will be compared with coastal rawinsondes and aircraft dropwindsondes. TOVS geopotential height and temperature plots and TOVS potential temperature cross sections will be studied in significant regions of the ERICA cyclones. Of particular interest is the determination if TOVS soundings can describe regions of low static stability observed by dropwindsondes and coastal rawinsondes available during ERICA. Emphasis will be placed on synoptic evaluation of the TOVS soundings and associated horizontal fields rather than computing error statistics (such as rms differences).

The TOVS-derived soundings were prepared from the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) version of the Simultaneous Physical Retrieval TOVS Export Package, version 4.0, March 1988, developed by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) at the University of Wisconsin (Smith et al. 1985). All software was run on a microVAX III in the Interactive Digital Environmental Analysis (IDEA) Laboratory at the Naval Postgraduate School (NPS).

The thesis is organized in the following manner: Chapter 2 discusses different sounding methods and their advantages and disadvantages; Chapter 3 describes the results of various TOVS retrieval methods; Chapter 4 gives a background on ERICA IOP-2 and a more detailed description of the software used to produce the TOVS soundings for this thesis; and Chapter 5 describes the results of this study. All figures discussed in the thesis appear in Appendix A.

II. SOUNDING METHODS

A. THE TOVS PACKAGE

The TOVS consists of three sensors that measure the emitted radiance at the top of the atmosphere. They are: the second version of the High-resolution Infrared Radiation Sounder (HIRS), the Microwave Sounding Unit (MSU), and the Stratospheric Sounding Unit (SSU). The HIRS contains 20 (19 infrared and one visible) channels to determine temperature, water vapor concentration, cloud height and amount, and ozone concentration in the troposphere and lower stratosphere. The MSU contains four channels in the cloud-penetrating microwave spectrum to supplement the HIRS over cloudy regions. The SSU contains three channels to determine the temperature profile of the upper stratosphere. Fig. 1 (NOAA 1981) gives the physical characteristics of each of the wavelength bands of the 27 TOVS channels. Each channel is sensitive to a different wavelength and is dependent on the absorption characteristics of CO_2, H_2O, O_2, O_3, and N_2O in the visible, infrared, and microwave spectral regions. Radiance measurements are made by the three sensors and converted into temperature, ozone, and moisture profiles by various retrieval methods.

For each channel, the level of peak energy contribution in the atmosphere comes from the vertical layers indicated by the peak of the weighting function, or the change of atmospheric transmittance with height. The weighting function weights the blackbody radiance from the atmosphere, so it is sensitive to changes in atmospheric temperature for a particular layer. The TOVS weighting functions for all 27 channels, giving the layer of peak energy contribution, are shown in Fig. 2 (NOAA 1981).

B. STATISTICAL RETRIEVALS

Various methods have been devised to retrieve the TOVS radiance measurements and convert them into soundings of temperature, moisture, and ozone. Smith et al. (1979) describe a statistical approach. A database of climatological temperature profiles (training data set) based on latitude and surface type (land or ocean) is used as a first guess for the final retrieved temperature and moisture soundings. The training data set is needed to derive regression coefficients for converting the observed radiances to temperature and water vapor. It also gives the retrieval method a physically reasonable temperature profile that could have produced the observed radiance values. The regression coefficients are updated weekly

The horizontal resolution of temperature and moisture soundings from the statistical retrieval method is determined from interpolated HIRS and MSU scan spots, or fields of view (FOV's). Each FOV is about 25 km in diameter. Radiance values are limb corrected so all FOV's can be treated as if they were at nadir. A 9 X 7 FOV array is used to prepare one TOVS sounding with a horizontal resolution of about 250 km.

The statistical method requires such a large FOV array because it requires clear-column radiances to determine the most accurate temperature and moisture profiles. TOVS soundings are based mostly on infrared wavelengths since 20 of the 24 sounding channels are from the HIRS. Therefore, the soundings are very sensitive to clouds. Channels that saturate when the atmosphere is too cloudy are avoided in the final temperature retrieval because they would produce temperatures that are too cold. A sounding is considered to be clear if at least four FOV's are clear. If fewer than four clear FOV's are found, the retrieval tries to determine clear-column radiances from partly cloudy scan spots by determining the differences in cloud amount of adjacent pairs. If at least four adjacent pairs are found in which cloud differences can be discerned, the sounding is judged to be partly cloudy. If fewer than four adjacent pairs are found, the sounding is determined to be cloudy, and the temperature retrieval is attempted with the MSU and stratospheric levels of the HIRS only.

The retrieval then produces vertical profiles of temperature, water vapor, mixing ratio, geopotential thickness, and total ozone concentration using regression methods. This statistical retrieval method was used operationally by NOAA from 1979 to 1989 for NOAA satellite soundings.

C. PHYSICAL RETRIEVALS

Another approach for temperature and moisture retrieval solves the radiative transfer equation (RTE) for brightness temperatures from the observed radiances. The so-called "physical retrieval method" described by Smith et al. (1983) accounts for terrain elevation, surface emissivity, and surface temperature in solving the RTE. The physical retrieval uses a 3X3 array of interpolated HIRS and MSU scan spots for each sounding. As in the statistical retrieval, each FOV is checked for cloud contamination. Each 9-FOV box gives a sounding with a horizontal resolution of about 75 km.

Unlike the statistical retrieval method, a statistical set of coincident rawinsonde profiles is not needed. Instead, first-guess temperature and moisture profiles must be specified by one of three options: a climatological profile, a regression estimate from the observed radiances in the MSU channels and stratospheric HIRS channels, or profiles produced by a numerical forecast model. The final temperature profile is determined by an iterative formula that requires first-guess temperature and brightness temperature profiles, weighting functions for 15 mandatory levels in the troposphere and stratosphere interpolated from all the HIRS and MSU channels, and the calculated brightness temperatures from the RTE solution.

The weighting functions required by the iterative formula are derived from calculated transmittances. The transmittances are derived statistically using a set of regression coefficients that relate atmospheric absorption characteristics to temperature and moisture. The coefficients are generated for each of six equally spaced scan angles, alleviating the need to limb-correct the radiance measurements. They are constant for each satellite, but can be changed if the satellite characteristics change (ie. sensor temperature change, etc.).

The iterative formula is solved for temperature at 15 mandatory levels. Iteration stops when the difference between the brightness temperature and guess brightness temperature from the previous step is less than .05 K. Total ozone concentration is also calculated with an iterative formula, using the observed radiance of the ozone-sensitive HIRS channel (CH 9) as a first guess. The water vapor profile is calculated using a mean relative humidity solution (described by Smith et al. 1983) from the observed radiances in the HIRS water vapor channels, and the final temperature estimates from the iterative solution.

D. SIMULTANEOUS RETRIEVAL

A more recent version of the physical retrieval method, described by Smith et al. (1985), solves for surface skin temperature, temperature profiles, and water vapor profiles simultaneously. The interdependence of the three parameters is taken into account and the importance of the first guess is reduced. The radiative transfer equation is solved in perturbation form, with respect to a mean atmospheric state. The solution for temperature and moisture perturbations requires a matrix inversion by least squares method. Weighting functions, as described in the physical retrieval method, serve as the basis functions for the matrix inversion.

The simultaneous physical retrieval method is more computationally efficient than the iterative physical method. Instead of an iterative formula, a two-step method is employed for solving the perturbation form of the RTE. In the first step, the first-guess profiles of temperature, moisture, and skin temperature with their corresponding weighting functions, are used to solve for brightness temperatures at each pressure level.

The same types of first-guess options are available as in the iterative physical retrieval method. The regression estimate uses HIRS CH's 1-3 (stratospheric channels), MSU CH's 2-4, and HIRS CH's 11 and 12 (sensitive to water vapor), along with an estimate of the surface skin temperature from the warmest window channel. The RTE is then solved once more for surface skin temperature, and temperature and moisture profiles, using all channels determined to be free of clouds. The method for retrieving ozone concentration is the same as that described for the physical (iterative) method.

The problem of determining cloud-free areas and retrieving profiles in cloudy regions is the most limiting factor in retrieving accurate profiles of temperature and moisture. In the simultaneous retrieval method, cloud contamination is determined by comparing the observed channel radiances with the first-guess skin temperature, the visible reflectance from HIRS CH 20, and the radiance values of the three HIRS window channels (8, 18, and 19). Once the cloud contaminated channels are found, cloud amount and height are specified by using absorption characteristics of CO_2 in adjacent channels and the CO_2 slicing technique (Smith et al. 1985).

A more recent version of the simultaneous retrieval method, described by Huang and Smith (1986), improves upon the retrieval of temperature and water vapor profiles in cloudy regions. This later version includes the simultaneous retrieval of cloud amount and cloud top temperature in the inverse matrix solution of the perturbation form of the RTE. Although the later version was not available for this thesis, it will be available for incorporation into TESS-3. Preliminary results from the latest method are described in Chapter 3.

E. COMPARISONS BETWEEN THE RETRIEVAL METHODS

The simultaneous and iterative physical retrieval methods, described earlier in this chapter, were designed to be portable. They have been sent to many different users around the world. The latest version, the Simultaneous Physical Retrieval TOVS Export Package (Smith et al. 1985), version 4.0, was sent to NOARL in March 1988.

The advantages of physical retrievals over statistical methods are that the RTE is solved in the retrieval and, thus, physical processes are used throughout. Also, the data do not need to be limb corrected (a possible source of error). Visible channel reflectance (from HIRS CH 20) is accounted for in the calculation of surface temperature. And finally, cloud contamination of the HIRS channels is accounted for to allow maximum use of the HIRS channels in a cloudy atmosphere.

Disadvantages of physical retrievals are that the transmittance coefficients are constant and assumed to be accurate. Poor quality soundings will result if the coefficients are not accurate and operational processing of the TOVS data may have to stop until the coefficients are corrected. Statistical retrievals avoid the transmittance calculation problem because of the continuous updating of regression coefficients using radiosonde observations.

III. BACKGROUND

This chapter describes several studies that evaluated the ability of TOVS soundings to describe significant synoptic and mesoscale features defined by in situ data. These investigations illustrate that TOVS soundings provide an excellent supplement to radiosonde data in analyzing a variety of meteorological phenomena.

A. STATISTICAL RETRIEVAL STUDY

Smith et al. (1979) evaluated the statistical retrieval method by compositing TOVS soundings and radiosonde reports over N. America (Fig. 3). They found that TOVS soundings were within about 2°C of the radiosonde observations. The largest differences in the satellite and radiosonde observations were at the surface and tropopause, where the vertical resolution of the TOVS is not fine enough to resolve inversions in the temperature profile.

In the same paper, Smith et al. also evaluated the ability of the TOVS statistical retrieval method to describe the environment of an intense storm over Texas in March 1979. They related TOVS 300 mb geopotential heights to a satellite image of the storm and plotted rawinsonde winds observed 9 h before and 3 h after the satellite pass on a TOVS 500 mb geopotential height analysis (not shown). The TOVS 500 mb and 300 mb analyses showed a trough over Texas between the rawinsonde report times. This trough led to heavy snowfall on the Texas-Oklahoma border. The rawinsonde reports before and after the satellite pass did not clearly delineate the storm; however, the 300 mb rawinsonde winds did show a wind shift between observation times, supporting the development of the trough.

Smith et al. also evaluated operational TOVS 1000-500 mb thicknesses over the Northern Hemisphere. NMC 1000-500 mb thickness analyses were compared with and without TOVS data. The plots were strikingly similar (Fig. 4). The largest differences were associated with the more intense troughs over the eastern North Pacific Ocean and eastern Europe on the TOVS analysis. In summary, the study showed that TOVS data have a strong positive influence on global and local forecasting.

B. PHYSICAL RETRIEVAL STUDY

Smith et al. (1983) used the Physical Retrieval TOVS Export Package to explore the Alpine Experiment (ALPEX) data in Europe during March 1982. They compared TOVS geopotential thickness analyses with thickness analyses produced from radiosonde data by the European Center for Medium-range Weather Forecasting (ECMWF). A regression first-guess with surface data was used to retrieve the TOVS temperature and geopotential height profiles. The TOVS thickness analyses were prepared using a Barnes objective analysis with a 75 km grid spacing, while the ECMWF analyses were based on optimal interpolation with a spatial resolution of 200 km. Smith et al. found that the TOVS 1000-500 mb thickness analysis resolved a higher amplitude ridge between England and Spain, and a deeper trough over the Mediterranean Sea (Fig. 5) for one of the ALPEX cases. This difference was partly due to the coarser horizontal resolution of the ECMWF analysis. However, in the low stratosphere the situation was reversed. The 300-100 mb TOVS thickness analysis (not shown) revealed a weaker horizontal gradient than the ECMWF analysis. The ECMWF analysis showed a stronger trough and ridge in these upper levels. The cause of the poorer 300-100 mb TOVS analysis was attributed to coarser TOVS vertical resolution in the upper levels.

This study also looked at the impact of the first guess and surface temperature options in the physical retrieval by comparing standard deviations between TOVS and radiosonde profiles for four different cases. The cases were: 1.) regression first-guess with surface temperature, 2.) climatology first-guess with surface temperature, 3.) regression first-guess without surface temperature, and 4.) climatology first-guess without surface temperature. The greatest impact of using the surface data was below 700 mb. When surface data were included in the retrievals, the 1000-700 mb error was significantly less (1-2°C for the regression first-guess option and 1-2.5°C for the climatology first-guess option). Without surface data, the error increased to 2-3°C from 1000-700 mb for the regression first-guess option and 2.5-4.5°C for the climatology first-guess option. In conclusion, this physical retrieval study showed results similar to the statistical retrieval study. TOVS data gave physically reasonable estimates of atmospheric structure when compared with "ground truth" radiosonde data.

C. SIMULTANEOUS RETRIEVAL STUDY

Smith et al. (1985) applied the simultaneous retrieval method to the same ALPEX data set. Objective analyses of temperature and dewpoint, derived from radiosonde observations at 1200 UTC 4 March and 0000 UTC 5 March 1982, were compared with TOVS analyses at 850, 700, 500, and 300 mb.

This study first compared two first-guess options of the simultaneous retrieval method: regression and climatology. Smith et al. found that the two first-guess methods gave similar results for all levels except 300 mb. The regression first-guess retrievals were slightly better at all levels, except 300 mb, when compared with the ECMWF analyses. However, in all cases, the differences were generally within 3°C of the ECMWF analyses. The largest differences were found over the radiosonde data-void areas. Also, both analyses revealed the rapid intensification of a trough over western Europe between 1200 UTC 4 March and 0000 UTC 5 March 1982. The first guess did not have a major impact on the temperature retrievals in this study.

Next, the simultaneous retrieval method was compared with the physical (iterative) retrieval method. The temperature profiles derived by the simultaneous retrieval were more accurate than the physical retrieval method by .5°C at nearly all levels up to 250 mb (Fig. 6). The RMS difference for the simultaneous retrieval method with a regression first-guess was generally the same as that with a climatology first-guess from 1000-500 mb. The difference between the two was significant only between 300-500 mb and at 200 mb, showing an improvement of 0.5-1.0°C for the regression first-guess. Smith et al. stated that the coefficients used for the regression first-guess helped the retrieval method derive a more accurate tropopause structure.

However, the greatest difference found between the two methods was in the dewpoint results. Smith et al. found a significant improvement in the dewpoint analyses using the simultaneous method. The simultaneous method also resolved larger and more meteorologically consistent dewpoint gradients.

Finally, the study explored the impact of surface data on the first guess in the simultaneous retrieval method. The greatest effect of surface data on the retrieval was from 1000-700 mb (Fig. 7). Near the surface, the error decreased by half when surface data were used. In summary, this study showed that the simultaneous retrieval was an improvement over previous retrievals. It gave better results than the physical retrieval and was more efficient. The investigation emphasized that TOVS soundings are useful and provide an excellent supplement to other data sources.

D. SIMULTANEOUS RETRIEVAL WITH CLOUD PARAMETERS

Huang and Smith (1986) revised the simultaneous retrieval method to include cloud amount and cloud top temperature in the matrix inversion solution of the RTE. In a 2-step simultaneous method, the CO_2 slicing method (Smith et al. 1985) is performed after the temperature and dewpoint retrieval to determine cloud parameters (height, amount, and temperature).

The study compared TOVS temperature retrievals with and without cloud parameters during ALPEX. The soundings improved during all comparisons of clear, moderately cloudy, and extremely cloudy conditions, but the greatest improvements were achieved in the extremely cloudy cases. RMS differences throughout the troposphere for the extremely cloudy cases (around 2°C to start with) decreased to an average of 1.3°C with the revised simultaneous retrieval method.

E. OTHER RETRIEVAL STUDIES

1. Goddard Laboratory for Atmospheres (GLA) physical retrieval

Other groups besides the University of Wisconsin CIMSS have made progress using TOVS. Susskind et al. (1984) described a physical retrieval method developed at the GLA. The retrieval method is iterative and produces soundings with a resolution of about 125 km. The RMS statistics showed that the GLA physical retrievals were much better than the operational soundings for a First GARP Global Experiment (FGGE) data set. The largest errors were at the surface (2.8 K), decreasing up to 700 mb (2.2 K), and remaining the same throughout the rest of the troposphere.

The GLA retrieval also gives derived sea-surface temperature fields, fractional cloud coverage, cloud top pressure, cloud top temperature, surface emissivity, and sea ice extent by interpreting the radiance observations of all HIRS and MSU channels. Retrievals for all of these fields were found to be reasonably consistent with ground-truth data.

2. Dependence of the first guess on the GLA physical retrieval

Reuter et al. (1988) investigated the dependence of first-guess data on the GLA physically-based retrievals. Their study, like Smith et al., used the ALPEX data (1200 UTC 4 March 1982 - 0000 UTC 5 March 1982). The retrieval used for the study modified the Susskind et al. (1984) physical retrieval by improving the moisture retrieval algorithm. In addition, experiments were conducted to improve the first guess if determined to be poor. Susskind and Pursch found that the thickness fields showed a low first-guess dependence. This result agrees with the Smith et al. (1985) study. However, the precipitable water fields did show a stronger first-guess dependence, especially close to the surface.

3. Using a forecast model-output first-guess to improve TOVS soundings

Daniels et al. (1989) described a study to improve the NESDIS operational temperature and moisture retrievals by inputting NMC's Medium Range Forecast Model 6-h forecast as a first guess instead of the (then current) operational method of using a data set of radiosonde temperature and moisture retrievals and satellite radiance measurements as a first guess. Their results showed a significant improvement over the operational method.

4. Simultaneous retrieval over Australia

Le Marshall et al. (1989) studied the accuracy of the simultaneous retrieval method (Smith et al. 1985) over Australia. The retrievals used either a statistical retrieval-based or a model forecast first-guess for temperature and moisture profiles. The retrieval method has been operational since late 1987. The study compared TOVS retrievals over the Australian region with NMC analyses.

TOVS potential temperature cross sections, 1000-500 mb thickness analyses, ozone concentrations, temperature profiles, and temperature analyses were compared with in situ data. The largest RMS difference between TOVS and NMC temperature profiles occurred at the surface and tropopause (2.5 K). The study found a high correlation between TOVS and NMC 500 mb temperatures over Australia. TOVS potential temperature cross sections and 1000-500 mb thicknesses were also very similar to the NMC analyses. Overall, the TOVS analyses compared extremely well with the NMC model data.

The above studies have shown that atmospheric structure can be accurately described by TOVS data. TOVS structure supplements in situ data sources, such as radiosondes, by detection of mesoscale features (both temporally and spatially) within the radiosonde network. TOVS data, using the Simultaneous Retrieval Method with a variety of first-guess options, and with and without surface data, will now be applied to the ERICA data set.

IV. ERICA: BACKGROUND AND DATA DESCRIPTION

A. ERICA BACKGROUND

As indicated in the previous chapter, the rapid cyclogenesis event investigated in this study is IOP-2 (13-14 December 1988). Some preliminary research has already been completed on this case. Chalfant (1989) showed that the early cyclogenesis period was characterized by multiple surface centers. The eventual rapid deepener formed as a wave along a pressure trough east of Cape Hatteras at about 1800 UTC 13 December 1988. It rapidly intensified over the next 12-24 hours, deepening more than 30 mb from 0000-1200 UTC 14 December, as it tracked slowly eastward. Chalfant found that NMC's Spectral Grid Model (SGM) was unable to accurately predict details of the development of this cyclone during IOP-2. However, longer range forecasts (48-h) were successful in capturing the magnitude of the deepening. Miller (1990) showed that the Naval Operational Regional Analysis and Prediction System (NORAPS) forecasts for IOP-2, were quite sensitive to the initial analyzed fields. Miller's study also showed that NORAPS had difficulty resolving the multiple surface centers present in the early IOP-2 period. Additional data now available for further research include dropwindsondes around the storm and TOVS soundings covering the whole ERICA region.

The additional mesoscale observations available during ERICA are proving critical in the diagnosis of rapid cyclogenesis. Unfortunately, those observations will not be available in a future operational environment. On the other hand, satellite soundings may be able to provide some of this key information over the data-sparse regions. If important features such as low static stability regions and short wave troughs and ridges can be accurately described by the TOVS data, this additional information can be incorporated into analysis and forecast models to more successfully predict rapid cyclogenesis.

B. DATA DESCRIPTION

The dropwindsondes and rawinsondes available during ERICA provided a useful data set to compare with the TOVS soundings. However, rawinsondes give a much better resolution than the TOVS soundings. The TOVS only contains 12 HIRS channels for determining temperature profiles in the troposphere and lower stratosphere (up to 100 mb). Recall that the TOVS weighting functions (Fig. 2) have a fairly broad vertical width of approximately 300-400 mb. This means that the radiance in each TOVS channel comes from a relatively thick layer of the atmosphere. Therefore, a point comparison between a TOVS sounding and a rawinsonde may be misleading, especially over a rapidly evolving cyclogenetic environment. So, for this study, additional comparisons were made between TOVS geopotential height and temperature fields. The ability of TOVS to physically represent the environment described by the SGM (not taking into account possible SGM errors) then can be assessed.

As mentioned earlier, a cloudy atmosphere presents the biggest challenge in retrieving an accurate satellite sounding. The problem with retrieving TOVS soundings over cloudy areas is that the HIRS channels cannot sense through clouds. Because the TOVS contains only four MSU channels, vertical resolution in cloudy regions can be expected to be poor. However, the simultaneous method tries to account for this problem by using all HIRS channels sensing above the cloudy layer and determining a "reasonable" profile below the top of the cloud and adjusting it with the MSU-determined profile. Unfortunately, if the top of the cloud is determined to be at the 700 mb level (MSU CH 2) or higher, TOVS cannot determine any structure in the critical low troposphere below 700 mb. MSU CH 1 (window channel) can penetrate through clouds, but will give an inaccurate profile in precipitating regions.

C. NOARL/NPS TOVS RETRIEVALS

The retrieval method used for this study was a version of the Simultaneous Physical Retrieval TOVS Export Package (Smith et al. 1985), version 4.0, restructured by Richardson and Haugen at NOARL. The NOARL version, redesigned in Fortran 77 format, speeds up the retrieval and allows for easier upgrades. A description of the processing steps in the NOARL version follows.

The retrieval process begins with a check of the warmest HIRS CH 8 (IR 11 μm window channel) brightness temperatures (T_b) in a 9-FOV box. Recall that each HIRS FOV is about 26 km in diameter, so the resultant resolution of an individual sounding (with MSU interpolated FOV's) represents about a 75 km volume. Next, the scan angle, local zenith angle, and surface elevation are determined. For this thesis, surface topography with 111 km resolution was used. Higher resolution topography (18.5 km), available in the original export package, was not available in the NOARL version. This higher resolution topography is not critical for this study since most of the area of interest is over the ocean. After the elevation is determined, the retrieval then finds all CH 8 T_b's within 3 K of the warmest FOV in the 9-FOV box. This determines which

FOV's to use throughout the retrieval process. It then averages all of the warm FOV temperatures for each HIRS tropospheric channel to represent one TOVS sounding.

The next step of the retrieval method is the most critical of all. The retrieval requires first-guess temperature and moisture profiles and 1000 mb heights for the initial solution of the RTE. Three options are available. First, it obtains climatological profiles of temperature and relative humidity (40 levels in the troposphere and stratosphere), 1000 mb heights, and a surface temperature extrapolated dry adiabatically from 1000 mb. The climatological values are based on five latitude zones, summer and winter. The retrieval interpolates between the zones and seasons depending on the date of the satellite pass. Using the hydrostatic approximation and equation of state, the retrieval also calculates a station pressure. The user can replace climatological profiles with model-generated temperature and moisture profiles, including surface temperature, dewpoint, and 1000 mb heights. Also, if a regression first-guess is chosen, the climatological temperatures are replaced with the regression estimates from HIRS CH's 1,2, and 3 (stratospheric channels) and MSU CH's 2, 3, and 4.

As mentioned in Chapter 3, Smith et al. (1985) showed that the difference between climatology and regression first-guess options was not significant, but that surface temperature and dewpoints estimates were critical in the final retrieval. If surface data are available, the retrieval method accepts the estimate as "ground truth" and weights it higher in the final retrieval. In that way, the TOVS radiance estimates of surface temperature do not contaminate good estimates of the low level atmospheric structure. User-input 1000 mb heights are also accepted as ground-truth and are not adjusted in the final retrieval. The use of model-generated temperature, moisture, and 1000 mb heights as a first guess was not discussed in Smith et al.'s study but will be used in this thesis. In addition, the regression and climatology options will also be employed in this study.

If no surface data are available, the retrieval tries to improve the initial estimates of surface temperature and dewpoint. First, it searches for the closest pressure level to the surface. If the station pressure is less than 1000 mb (high ground), it recalculates the surface temperature, dewpoint, and mixing ratio based on the maximum of HIRS CH 8 and 10 (8.3 $\mu m H_2O$), MSU CH 1 (microwave window), and the 1000 mb first-guess temperature. If a super-adiabatic lapse rate is found at the surface, it is reduced to dry-adiabatic between the surface and the closest pressure level. Finally, if the closest pressure level is not equal to 1000 mb, the retrieval extrapolates the temperature of the closest pressure level isothermally to 1000 mb.

The surface skin temperature is also required in the simultaneous retrieval method. It is derived from HIRS CH 8 or 18 (IR 4 μm window) or MSU CH 1. First, the retrieval uses the solar zenith angle to calculate visible reflectance from HIRS CH 20. If the reflectance is less than 25%, then the CH 18 T_b is used as the skin temperature . Otherwise, the maximum between CH 8 and MSU CH 1 is used, to avoid the cloud-top temperatures seen by CH 8.

The retrieval then attempts to find which HIRS tropospheric channels are too cloud-contaminated to use. It assumes a cloud level where the difference between the CH 10 T_b (900 mb H_2O,) and the guess T_b for each channel is less than 10 K, or wherever a temperature inversion is encountered. The matrix inversion is then performed to obtain temperature and moisture profiles. The weighting functions for HIRS CH 1 and MSU CH's 2-4 serve as the basis functions for temperature and HIRS CH 7 and CH 12 weighting functions serve as the basis functions for water vapor in the initial retrieval.

After the matrix inversion, the skin temperature is updated and used in a repeated matrix-inversion solution (second step). Cloud height and amount are redetermined and HIRS channels contaminated by clouds are rejected before the second step. However, the retrieval only rejects the shortwave channels (4.3 um) or the longwave channels (15 μm), but never both. The influence of HIRS channels below cloud level is reduced in the second step. Also, if the cloud height is determined to be above 430 mb, the final temperature and moisture soundings are output as "cloudy" and the second step is not performed. If the cloud height is below 430 mb, the second step is preformed to determine a new temperature and moisture profile. Cloud height and amount is again checked. If the cloud level is above 570 mb, the final retrieval is output as a "cloudy" sounding. Otherwise, the sounding is output as "clear". Geopotential heights for all mandatory levels are calculated using the hydrostatic approximation and equation of state. However, if 1000 mb heights are not available in the first guess, they should be used with caution, since a climatological 1000 mb height is used.

For this thesis, the various first-guess options were studied to determine the best combination of choices. Four first-guess options were explored. First, the retrieval was run with a regression first-guess and no surface data to determine the accuracy of TOVS data in a region where no other data sources may be available, such as in a wartime environment. Next, the impact of surface temperature on the retrievals using both climatology and regression first-guess options was studied to determine how much improvement, if any, could be made to the TOVS data. The surface data included additional marine data (buoys and ship reports) available during ERICA. The data were objectively analyzed using the Barnes analysis within the General Meteorological Analysis Package (GEMPAK) (des Jardins and Petersen 1985). Finally, SGM analyzed temperature, relative humidity, and 1000 mb height fields, valid 6 h prior to each NOAA pass, were used as a first guess to compare with the other retrieval options. The retrieval process, with a regression first-guess and no surface data took about 15 min to run on a microVax III in the IDEA Lab. at NPS. The addition of surface data increased the processing time to about 30 min. The addition of SGM fields increased the processing time to nearly 1 h.

V. DATA ANALYSIS

A. 0644 UTC 13 DECEMBER 1988

1. Overview

The analysis of IOP-2 starts with an evaluation of TOVS data from the NOAA-11 pass just off the east coast of the U.S. at 0644 UTC 13 December 1988. The initial IOP-2 cyclone was developing off the Carolina coast at this time. The NOAA-11 pass (AVHRR, CH 4) (Fig. 8) shows multi-layered cloudiness associated with the developing low extending from the North Carolina coast eastward. Scattered low clouds are present northward along the coast from North Carolina to Cape Cod, with broken to overcast low clouds off the coast of Maine. Mostly high clouds extend from the Ohio Valley northward to Hudson Bay. These clouds are in advance of the upper level trough moving eastward into the Mid-Atlantic states.

Seventeen ERICA rawinsondes and dropwindsondes were available for comparison with collocated TOVS soundings (Fig. 9). Dropwindsonde and rawinsonde 700 mb winds were also plotted (Fig. 9a). A total of 600 TOVS soundings were retrieved from each NOAA-11 pass. For each case in this study, all dropwindsondes and rawinsondes launched within 3-h of the TOVS soundings were used for comparison with the TOVS data. Dropwindsondes are named according to the aircraft type and time of launch. Those prefixed with an "A" were launched from USAF WC-130's, while those prefixed with "N" were launched from NOAA P-3's. The number codes represent the hour and nearest 10 min. they were launched. For example, A091 was launched at approximately 0910 UTC, nearly 2 1/2 h after the NOAA-11 pass at 0644 UTC. TOVS soundings prefixed with an "E" are clear, while soundings prefixed with an "F" are cloudy (see Chapter 4 for definitions of clear and cloudy TOVS soundings). Also, note that the TOVS soundings are not equally spaced, but represent the location of the warmest FOV in the 9-FOV box. So, some TOVS soundings overlap while others are separated by a distance greater than 75 km.

As discussed in the previous section, four different first-guess options were used to compare the TOVS retrieval data with the in situ data during IOP-2. They were: regression without surface temperature or dewpoint, regression with surface temperature and dewpoint, climatology with surface temperature and dewpoint, and SGM temperatures, relative humidity, and 1000 mb height fields with surface temperature and dewpoint (hereafter referred to as retrievals RN, RS, CS, and SS, respectively). The purpose of using all four methods is to understand the importance of the first-guess to the retrieval and to achieve the most accurate TOVS description of the ERICA cyclone environment.

2. TOVS sounding comparisons with dropwindsondes and rawinsondes

Three dropwindsondes, A091, A083, and A081, were launched in the cloudy baroclinic zone north and west of the initial IOP-2 cyclone. The 0600 UTC rawinsonde for Bermuda (XKF) was available east of the low center, while HAT and other coastal rawinsondes, available at the same time, were far to the west of the low. All four retrieval methods for cloudy sounding, F454, are compared to the XKF sounding. The regression with no surface (RN) and spectral with surface (SS) retrievals are presented in Fig. 10, while the regression with surface and climatology with surface retrievals are shown in Fig. 11.

The XKF temperature profile shows a stable region from 850-700 mb that separates weak easterly flow from the stronger westerlies aloft. The moisture trace indicates moist low level (1000-850 mb) and upper level (500-300 mb) conditions. The RN retrieval (Fig. 10a) failed to completely capture this stable structure, but the SS temperature retrieval (Fig. 10b) was very accurate. It resolves the stable temperature structure from 850-700 mb and agrees well with the XKF temperature trace to 200 mb. However, the moisture profiles for both methods were too moist from 1000-700 mb and too dry above 700 mb. A comparison between F454 RS and CS retrieval methods and XKF shows the RS and CS retrievals resolving the general temperature profile but unable to detect the low level inversion. All the moisture profiles indicated the low-level moisture but, in general, were poor. The XKF comparison clearly indicates the importance of the first guess to the retrieval.

TOVS soundings were also compared with coastal rawinsondes in the mostly clear atmosphere west of the IOP-2 cyclone. In general, the TOVS SS retrieval method produced accurate temperature profiles compared with the rawinsondes, as found with XKF. For example, HAT was compared with the collocated TOVS sounding, E424, in Fig. 12. The difference between the E424 RN and SS retrievals with HAT is striking. The RN retrieval misses the cold low-level layer and associated inversion from 900-750 mb. In contrast, the SS sounding does resolve the general structure of the low troposphere. However, both retrievals miss the sharp tropopause at 350 mb in the HAT sounding. Although the RS and CS retrieval methods for E424 (not shown) were not quite as accurate as the SS retrieval, they did accurately depict the low level temperature structure because of the inclusion of surface temperatures in the first guess. The moisture profile from 1000-500 mb was fairly well represented by all four retrieval methods. However, the shallow dry layer near 850 mb was not resolved. It is unlikely that this dry layer would be captured by the coarser vertical resolution of TOVS.

A comparison between other coastal rawinsondes and collocated TOVS soundings produced similar results to the HAT case. The TOVS soundings with the SS retrieval method captured most of the thermal structure measured by the rawinsondes. The RS and CS methods, although not as accurate as the SS method, were able to accurately capture the colder air from 1000-700 mb. The RN method was not successful in resolving the low level inversion. The collocated TOVS soundings using all four methods gave successful retrievals compared to rawinsondes located further inland (PIT and FNT). These soundings had a fairly constant lapse rate and were easier for TOVS to retrieve. However, the SS retrievals remained the most accurate for temperature and moisture.

Over the cloudy region associated with the initial IOP-2 cyclone, the TOVS sounding comparisons were not as successful. Dropwindsonde A081, at 35°N 74°W, was launched in the western edge of the baroclinic zone associated with the developing cyclone. It shows stable frontal structure in the low levels and wind shear similar to the XKF case (Fig. 13). The A081 sounding is saturated to 500 mb and suggests that rain is probably falling in the vicinity. TOVS sounding E426 was used for comparison with A081. The RN retrieval (not shown) failed to capture any of the temperature structure of A081. Instead, it showed a smooth temperature curve throughout the troposphere, 3°C too warm at 1000 mb and 3°C too cold at 500 mb. The RS E426 retrieval (Fig. 13a) shows a more accurate profile from 1000-800 mb than the RN method, but fails to show the inversion from 850-700 mb. The CS method (not shown) produced a profile identical to the RS method. The SS retrieval (Fig. 13b) does suggest the inversion structure from 850-700 mb. Although it is too cold above 850 mb, it represents the weak temperature inversion better than the other options. All four retrieval methods derived useful moisture profiles indicating the saturated state of the A081 profile. One other comparison (not shown) was made between A081 and a collocated TOVS retrieval. E427, a cloudy sounding just southeast of A081 (see Fig. 9), was quite similar to A081. The SS retrieval resolved the weak inversion, while the other retrieval methods produced smooth temperature profiles.

The remaining overwater dropwindsondes, A091 and A083 (not shown), were located closer to the surface low. Both were saturated up to 500 mb, indicating precipitation in the region. They also showed a stronger stable region in the low troposphere, similar to the XKF sounding. The collocated TOVS soundings using all four retrieval methods were too warm at 1000 mb and too cold at 500 mb. However, the SS retrievals were still the most accurate. A comparison between all four TOVS retrieval methods with the dropwindsondes and rawinsondes in the region indicated that only the SS retrievals were successful in capturing some of the structure of the cloudy atmosphere shown by the in situ data. The RN retrievals gave smooth profiles, attempting to represent the average temperature in the troposphere and lower stratosphere. The RS and CS retrievals produced more accurate temperature profiles from 1000-700 mb, but still failed to capture the thermal structure in the lower troposphere. However, even though the SS retrievals were the most accurate, only the TOVS (SS) retrieval collocated with XKF depicted all of the cloudy temperature structure shown by the rawinsonde.

The TOVS overland retrievals were much better than the overwater retrievals for this pass. However, the land area was dominated by high pressure and mostly clear skies with a constant lapse rate for most soundings. Thus, the temperature profile was considerably easier to recover from the satellite data. Over water, where cyclogenesis was occurring, the TOVS soundings were less accurate compared with the dropwindsonde measurements. Rain appeared to attenuate most of the TOVS soundings in the region, making them too cold at 500 mb. As a result, the inversion structure of the dropwindsondes was not totally resolved in the TOVS soundings. The use of SGM analyses for the first guess, even though 6 h old, improved the TOVS temperature structure considerably. The surface data were critical to TOVS resolving the boundary layer structure, particularly for the coastal rawinsondes.

3. Cross section comparisons

Another useful method in diagnosing cyclogenesis is constructing potential temperature cross sections through interesting regions of the cyclone. Significant components of the cross sections include steeply-sloped or packed isentropes and wind speed and direction changes to identify the location and strength of fronts. The TOVS data do not include actual wind information, but location and intensity of fronts and the tropopause level can be determined by the slope and packing of the isentropes.

For this first case, a cross section was constructed using HAT, A081, A083, A091, and XKF through the northern quadrant of the initial IOP-2 cyclone (Fig. 9a). Fig. 14 compares this cross section with a collocated overwater TOVS cross section using the SS retrievals. The observed cross section located along the warm front, and the packed isentropes in the region between A083 and XKF indicate the strongest part of the front. The TOVS cross section (Fig. 14b) resolves some of the frontal structure. Also, note the steeply sloped isentropes between E424 and F427, showing the cold air along the coast similar to the isentropes between HAT and A0S1. Even though the TOVS cross section isentropes are not as tightly packed as observed farther east (between F430 and F454), they still indicate the strongest area of the baroclinic zone fairly well. The tight gradient of the isentropes from 300-200 mb also resolves the location of the tropopause quite well. The TOVS tropopause corresponds to the levels of maximum winds at HAT and XKF.

4. Static stability comparisons with SGM fields

The the static stability parameter, $\frac{\Delta\theta}{\Delta p}$, described by Chalfant (1989) in a previous study of IOP-2, was evaluated for the TOVS data set. Low static stability provides a more favorable environment for upward vertical motion and cyclogenesis. During the initial stages of IOP-2, at least two cyclones were present. The first cyclone, analyzed by Chalfant to be east of Florida at this time, was forecast to rapidly develop by the NMC and NORAPS models (Miller 1990). But a second low developed to the northwest of the initial low. It was this system that rapidly deepened from 0000-1200 UTC 14 December 1988.

Chalfant found a minimum in $\frac{\Delta\theta}{\Delta p}$, 500-1000 mb, in the NMC SGM analyses off the Carolina coast for 1200 UTC 13 December (Fig. 15b). The second cyclone developed in this region during the next 12 hours. The dropwindsondes also confirmed this lower stability near the coast. The A0S1 profile was more unstable than the coastal rawinsondes to the west and the dropwindsondes to the east. Stability from the TOVS 0644 UTC data was also evaluated to determine if the areas of low static stability described by the SGM analyses were also present in the TOVS data. The TOVS stability analysis at 0644 UTC (Fig. 15a) shows lower static stability off the North Carolina coast, in the region where the eventual rapid deepener began to develop at 1800 UTC. This is in agreement with the SGM analysis that shows the lower static stability over a much broader region. Note that operational TOVS soundings would be included in the SGM analyses via the data assimilation cycle. So it is not surprising that the two analyses are similar. Also, note that the TOVS stability analysis has less meaning on the eastern edge, as the TOVS data did not extend that far east (Fig. 9).

Although both the TOVS and SGM regions of low static stability are partially confirmed by the dropwindsondes and indirectly by subsequent surface cyclogenesis, the spatial distribution and absolute magnitude is somewhat uncertain. This is partially due to the tendency of the cloudy TOVS soundings to be too warm at the surface and too cold aloft, effectively lowering the static stability. While spatial smoothing removes some of this error, a future study to determine the error distribution and its relationship to cloudy retrievals would be illuminating.

5. Height and temperature comparisons with SGM fields

One final comparison was made between TOVS and SGM geopotential heights and temperatures. Of interest was the quality of the TOVS (plus surface data) geopotential height and temperature analyses for this initial cyclogenesis period. All mandatory levels from 1000 mb to 500 mb were evaluated. Only 700 mb level comparisons will be shown, as this level proved to be the most accurate. However, the inclusion of a 1000 mb height analysis in the first guess is critical to the retrieval of accurate heights at all mandatory levels. Otherwise, less accurate climatological heights are used, which produce poor heights at all levels.

Fig. 16 compares the TOVS 700 mb height and temperature analyses at 0644 UTC with the SGM analyses at 1200 UTC. The TOVS 700 mb analyses (Fig. 16a) show the weak trough associated with the first cyclone off the North Carolina coast. The height analysis also shows general ridging over New England. The TOVS analyses are in general agreement with the SGM analyses, 6 h later (Fig. 16b).

In conclusion, the overall effectiveness of TOVS data at 0644 UTC was very encouraging, especially with the inclusion of SGM fields in the first guess and the use of a surface temperature analysis. The TOVS cross section using the SS retrieval method resolved the warm frontal region associated with the first IOP-2 low. The TOVS stability analysis isolated the lower static stability over the coastal waters, which was confirmed by the dropwindsonde data. The TOVS analyses did resolve the 700 mb trough associated with the developing cyclone. Because the SS retrieval method was so superior to the other methods, only the SS retrieval will be shown for comparison with the other data sources for the remainder of this thesis.

B. 1820 UTC 13 DECEMBER 1988

Twelve hours later a second NOAA pass covered the western North Atlantic at 1820 UTC. By this time, the second surface low had developed east of N. Carolina, near 37°N 72°W, in the relatively unstable air northwest of the initial low. The AVHRR imagery (Fig. 17) shows the cloudiness with both cyclones and strong convection around and south of the new low. The imagery reveals the rapid cloud growth of the second low in response to the movement of an upper level short wave trough over the coastal area.

Twenty-eight rawinsonde and dropwindsondes were collocated with the TOVS soundings from this NOAA-11 pass (Fig. 18). Dropwindsonde and rawinsonde 700 mb winds were also plotted (Fig. 18a). Five dropwindsondes (N140, N142, N144, N150, and N152) were launched at approximately 1500 UTC. Their locations are indicated on an AVHRR CH 1 subscene (Fig. 19). The evaluation of the TOVS retrievals at 1820 UTC starts with comparisons in this convective region near the old frontal zone, but ahead of the intense convection of the developing IOP-2 storm (see Fig. 19). The satellite imagery shows partly cloudy conditions in the vicinity of N150 and N144. Their locations, along with collocated TOVS soundings, E316 and E318, are displayed in Fig. 20. The only significant variation in the vertical structure shown by the dropwindsondes is a weakly stable layer from 850-700 mb by N150 and from about 680-600 mb by N144. The temperature profile for the TOVS sounding, E316, was very accurate compared with N150 (Fig. 20a). The TOVS profile was within 1°C of the dropwindsonde from 1000-500 mb, except for a slightly larger departure near 900 mb. In the comparison between N144 and E318 (Fig. 20b), E318 was not quite as successful. It was about 5°C too warm at 1000 mb, but within 2°C at 850, 700, and 500 mb. The weak inversion at 680-600 mb is not resolved by the TOVS sounding. And the large temperature discrepancy at 1000 mb may be due to inaccuracies in the surface temperature analysis used in the retrieval or because of the time difference between N144 and E318 (at least 3 h).

Two other comparisons were made further north along the frontal zone in cloudier areas. In these areas, the dropwindsonde temperature profiles, N142 and N140, showed a stronger inversion than the two previous profiles. N142 and N140 were compared with TOVS profiles, E300 and E282, respectively (Fig. 21). In both cases , the TOVS profiles were too warm from 1000-700 mb and too cold above 700 mb. Both dropwindsondes show a stable layer near 700 mb that is too shallow to be captured by the TOVS retrievals. However, the E282 temperature profile (Fig. 21b) shows some indication of attempting to represent the stable layer, but only weakly.

Other comparisons between overwater dropwindsondes and TOVS soundings showed similar results. The TOVS soundings were fairly accurate, but were the least accurate where shallow inversions existed between mandatory levels. The TOVS soundings were more accurate when the inversion layer was deeper and best described the soundings with a constant lapse rate. The TOVS moisture profiles did not compare favorably with the dropwindsondes as, in general, they were too moist.

The comparisons made between TOVS soundings and coastal rawinsondes showed less success than earlier. For example, the HAT and WAL temperature profiles were much different than their collocated TOVS profiles, E294 and E257 (Fig. 22), even though the atmosphere was mostly clear. The tropopause lowered to about 400 mb at both locations due to the strong upper level trough over the region (Refer to previous figure of HAT at 0644 UTC). The TOVS retrievals analyzed the tropopause at 300 mb, and the resulting TOVS temperature profiles were 4-8°C too warm from about 700-300 mb for both cases. The lower level temperature structure was fairly accurate though.

The coastal rawinsondes and TOVS profiles further north compared more favorably. For example, the ACY and CHH temperature profiles were very well represented by the collocated TOVS soundings, E221 and E205 (not shown). The E221 temperature profile was within 2°C accuracy of the ACY profile from 1000 mb to about 550 mb, except for a very shallow inversion layer at 700 mb shown by the ACY profile. The tropopause level of ACY was at about 350 mb, while E221 indicated a 300 mb tropopause, minimizing the upper troposphere errors. The tropopause at CHH was at 250 mb, and the E205 tropopause matched it almost perfectly. The result was an almost perfect match between the two soundings (< 1°C error), except for the layer from 1000-850 mb, where the TOVS profile was warmer.

A cross section in the region of the dropwindsondes launched at 1500 UTC (Fig. 23a), shows the frontal structure between the two surface centers. The collocated TOVS cross section (Fig. 23b) reproduced this thermal pattern. The slope of the isentropes in the two cross sections is nearly identical. Also, the packing of the TOVS low troposphere isentropes indicates the location of the front in the cross section 600-800 mb layer. The tropopause also is easily identified on the TOVS cross section.

Another TOVS cross section was constructed across the large-scale baroclinic zone associated with the developing low, from E221 (40°N 74°W), northwest of the cyclone along the New Jersey coast, southeast to E357 (33°N 67°W) in the warm sector. The cross section (Fig. 24) depicts the thermal structure of the developing cyclone. It shows steeply sloped isentropes just east of the low and more tightly packed isentropes associated with the large-scale baroclinic zone and the tropopause aloft. The weak vertical stability is also evident in the lowest 200 mb southeast of sounding E260.

TOVS static stability from the 1820 UTC 13 December pass (Fig. 25a) was compared with the SGM stability at 0000 UTC, 14 December (Fig. 25b). The TOVS stability analysis continues to indicate a stability minimum near the center of the developing cyclone. The SGM stability field shows a larger region of weak stability. Unfortunately, the dropwindsondes are east of the TOVS minimum and cannot confirm this feature in either analysis. However, this region of weak stability does correspond to the region of subsequent vigorous surface development, which is dynamically consistent.

The TOVS 700 mb temperature and height analyses for 1810 13 December are now compared to the SGM 0000 UTC 14 December analyses (Fig. 26). The TOVS height analysis successfully captured the developing trough east of North Carolina associated with the rapid cyclogenesis event. Also evident is the warm advection region located in the vicinity of the growing comma cloud (Fig. 19). The trough location is consistent with the 0000 UTC SGM analysis which shows eastward movement and continued amplification. The TOVS isotherm pattern captures the 700 mb frontal zone off the East Coast, but fails to show the characteristic "S" shape isotherm pattern of a developing disturbance.

In conclusion, the TOVS evaluation at 1820 UTC showed that the TOVS data were very useful in diagnosing the details of the IOP-2 cyclone. The collocated TOVS soundings continued to compare favorably with the dropwindsondes. However, the TOVS soundings were the least accurate in regions of strong inversions or thick cloudiness, analyzing the surface too warm and the mid levels too cold. The sounding temperatures were the most accurate at about 700 mb. The only significant limitation of the TOVS soundings was their inability to capture the lowering tropopause in the region of the upper level trough along the coast. The low level temperature profiles were successful in nearly all of the comparisons.

C. 0637 UTC 14 DECEMBER 1988

Explosive development of the extratropical cyclone was now in progress at 0637 UTC, the time of the next NOAA-11 pass. The storm's central pressure dropped about 30 mb from 0000-1200 UTC, as it moved eastward (Chalfant 1989). ERICA aircraft launched three dropwindsondes around its center near the time of this pass. Fig. 27a shows the dropwindsondes and rawinsondes launched within 3 h of the NOAA-11 pass at 0637 UTC, along with 700 mb winds. Fig. 27b shows the collocated TOVS soundings. One of the dropwindsondes, N023 (not shown), failed, only sampling the atmospheric layer from about 700-500 mb. The other two dropwindsondes, N020 and N070, were used for comparison with collocated TOVS soundings (Fig. 28).

The satellite imagery over the region (not shown) shows thick cloudiness over the area. However, the TOVS sounding, E182, collocated with N020 (Fig. 28a), produced a fairly accurate temperature profile, compared with the dropwindsonde. It was approximately 3°C too warm at the surface and missed a shallow inversion layer between

700-500 mb, but otherwise produced a useful temperature profile. The TOVS sounding, F204, collocated with N070 (Fig. 28b), produced a fairly accurate profile, but it was 3-5°C too cold throughout the lower and mid troposphere. This cloudy TOVS sounding is cold likely due to the effects of precipitation attenuation of the MSU channels.

Other comparisons between rawinsondes and TOVS soundings for this time period (not shown) produced similar results to the previous time periods. The TOVS temperature profiles were generally within 2-3°C of the rawinsonde profiles at all the mandatory levels in the troposphere. The largest errors were at 1000 mb and the tropopause. Unfortunately, no conclusions can be made about their accuracy near an explosively developing cyclone, because only two comparisons could be made. However, additional insight can be gained by comparing TOVS cross sections and objective analyses over a larger area.

A cross section of the 0637 UTC TOVS soundings (Fig. 29) was constructed through the warm front of the rapidly developing cyclone, from F143 (41°N 67°W) north of the low center near Cape Cod, southeast to E321 (30°N 63°W) in the warm sector. The cross section shows steeply sloped isentropes ahead of the warm front, but misses the location of surface front near E244, according to Chalfant's (1989) analysis. However, the cross section shows tighter isentropes associated with the warm front aloft. Also note the sloping tropopause and location of the jet stream clearly defined by the TOVS cross section.

The minimum stability from the TOVS analysis (Fig. 30a) was again located near the center of the cyclone. The TOVS analysis was compared with the SGM analyses at 0000 UTC, 14 December (Fig. 25b) and 1200 UTC, 14 December (Fig. 30b). Notice the similarity of the TOVS analysis to the SGM analysis at 0000 UTC. However, the TOVS analysis places the lower stability area northeast of the SGM analysis, and shows higher stability southwest, where the SGM minimum stability area is located. Recall that these two analyses are not independent because TOVS data are used in the SGM analysis. At 1200 UTC, the SGM analysis concentrates the minimum stability area into a more confined location, in the warm sector south of the position of the surface low at 1200 UTC 14 December 1988. The TOVS 0637 UTC minimum stability area is in the approximate location of the surface low at 1200 UTC. Some of these differences between the SGM and TOVS static stability analyses may be due to the retrieval problems in cloudy areas as well as differences in time of analysis. This point should be explored more thoroughly in a future study.

The TOVS 700 mb height and temperature analyses (Fig. 31a) at 0637 UTC 14 December indicates continued development of the 700 mb trough. The 0000 UTC SGM analyses (Fig. 26b) shows a strong trough developing just east of the mid-Atlantic coast. By 1200 UTC (Fig. 31b), it has developed into a cutoff low near 35°N 65°W. The TOVS analysis deepens the trough more than the 6-h earlier 0000 UTC SGM analysis. The TOVS temperature analysis looks fairly reasonable compared with the SGM analyses, but may be too cold north of the low. Still, the TOVS analysis shows strong warm advection occurring ahead of the low, consistent with vigorous cyclogenesis.

D. 1810 UTC 14 DECEMBER 1988

The analysis of IOP-2 ends with an evaluation of TOVS data at 1810 UTC 14 December 1988. The NOAA-11 AVHRR imagery (not shown) portrays a well-wrapped cyclone at the far eastern edge of the pass near 38°N 63°W. Many dropwindsondes were launched within 3 h of the NOAA-11 pass around the storm center. Their locations and 700 mb wind observations are depicted in Fig. 32a. Note how well the dropwindsonde winds delineate the center of the 700 mb trough. Unfortunately, the region of TOVS soundings (Fig. 32b) only extends to the cyclone center. The intense frontal zone east and north of the low is not covered by this pass.

Dropwindsondes, N171 and N203, were compared with TOVS soundings, E205 and E225, respectively (Fig. 33). In both cases, the TOVS soundings represented the dropwindsonde temperature profiles reasonably well. The TOVS soundings were colder than the dropwindsondes likely due to precipitation in the region. The SGM first-guess fields in the TOVS retrievals were extremely important for retrieving accurate TOVS profiles, as seen at all the previous times.

A cross section (Fig. 34) from E149 (44°N 63°W) north of the storm near the Nova Scotia coast, through the low to E263 (37°N 62°W) along the cold front, showed the location of the surface trough (denoted by the slope of the isentropes near E187) and a baroclinic zone north of the low. It also depicted the location of the tropopause quite well. In summary, the TOVS analyses at 1810 UTC were still very useful in describing the cyclone environment. TOVS geopotential height and temperature analyses were not presented for this case because the TOVS data covered only the western half of the cyclone circulation.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis examined the effectiveness of TOVS in describing the environment of the IOP-2 cyclogenesis event. Numerous dropwindsondes and TOVS comparisons were made to assess the ability of TOVS to retrieve temperature and moisture profiles. Emphasis was placed on the synoptic evaluation of the TOVS soundings and associated horizontal fields rather than computing error statistics. TOVS soundings were found to be effective in describing the synoptic-scale distributions of static stability and upper level height and temperature fields associated with a developing cyclone. TOVS potential temperature cross sections also successfully described the larger-scale structure of the cold frontal or warm frontal region associated with the IOP-2 cyclone, as well as the location of the tropopause.

However, a limitation in the overall effectiveness and use of TOVS soundings is that TOVS retrievals require an accurate first guess to derive accurate profiles. In the simultaneous retrieval method, surface data in the first guess proved to be crucial in the accurate retrieval of temperature from the surface to 700 mb. And, the addition of model gridded temperatures was important for retrieving vertical structure in the lower troposphere. The further addition of 1000 mb heights in the first-guess was crucial for obtaining a physically reasonable height field from the TOVS data. Finally, an important observation of this study was that the TOVS overland soundings generally were more accurate than the overwater soundings. A primary reason for this was that most of the overwater soundings were in areas associated with cyclogenesis during IOP-2. The least accurate soundings were those affected by clouds and or precipitation.

B. RECOMMENDATIONS

Further study of TOVS data should include the use of forecast fields in the first guess instead of 6-h old observations. Now that an interface is available to input model gridded data in the IDEA Lab., comparisons can easily be made between other gridded data sets, such as the NORAPS forecast fields or NGM forecasts, to compare the accuracy of the retrievals with different first-guess methods. The use of gridded data greatly enhanced the TOVS retrievals in this study, but the inclusion of surface data was also crucial. Unfortunately, the additional surface data included in the TOVS retrievals for this study will not be available operationally.

Another option to test is the use of the National Environmental Satellite Data and Information Service (NESDIS) operational gridded sea-surface temperatures derived from multi-channel NOAA AVHRR. This option was already explored by NOARL scientists (Richardson and Haugen 1989). Sea-surface temperatures were input into the simultaneous retrieval as surface skin temperatures (versus first-guess surface temperatures) during the Genesis of Atlantic Lows Experiment (GALE). Their inclusion produced more accurate overwater surface temperatures compared to a NORAPS surface analysis. Additionally, the sea-surface temperatures improved low level cold frontal structure on cross sections. However, very little difference (with and without sea-surface temperatures) was observed in the temperature profile above 1000 mb. The study concluded that the use of sea-surface temperatures in the retrieval needs to be studied further.

Several options described in the original Export package were not available for incorporation into this thesis. They include: the filtering of redundant or inaccurate TOVS retrievals before they are used in objective analyses; the derivation of geostrophic winds based on the temperature and geopotential height retrievals; and the availability of higher resolution geography in the determination of surface elevation. As discussed in the previous chapter, a study examining the error distribution of TOVS soundings in cloud vs. no-cloud retrievals would be helpful in making better use of TOVS soundings in weather forecasting. The filtering option, mentioned above, should be incorporated into such a study to determine its significance. And finally, TOVS MSU channel images might provide some useful information in determining the location of low pressure centers and frontal regions and should also be evaluated in future TOVS studies. In conclusion, TOVS data provide a useful supplement to other data sources and should be incorporated into future cyclogenesis studies.

APPENDIX A. FIGURES

HIRS Channel number	Channel central wavenumber	Central wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	668	15.00	CO_2	30 mb	*Temperature sounding.* The 15-μm band channels provide better sensitivity to the temperature of relatively cold regions of the atmosphere than can be achieved with the 4.3-μm band channels. Radiances in Channels 5, 6, and 7 are also used to calculate the heights and amounts of cloud within the HIRS field of view.
2	679	14.70	CO_2	60 mb	
3	691	14.50	CO_2	100 mb	
4	704	14.20	CO_2	400 mb	
5	716	14.00	CO_2	600 mb	
6	732	13.70	CO_2/H_2O	800 mb	
7	748	13.40	CO_2/H_2O	900 mb	
8	898	11.10	Window	Surface	*Surface temperature* and cloud detection
9	1 028	9.70	O_3	25 mb	*Total ozone* concentration.
10	1 217	8.30	H_2O	900 mb	*Water vapor sounding.* Provides water vapor corrections for CO_2 and window channels. The 6.7-μm channel is also used to detect thin cirrus cloud.
11	1 364	7.30	H_2O	700 mb	
12	1 484	6.70	H_2O	500 mb	
13	2 190	4.57	N_2O	1 000 mb	*Temperature sounding.* The 4.3-μm band channels provide better sensitivity to the temperature of relatively warm regions of the atmosphere than can be achieved with the 15-μm band channels. Also, the short-wavelength radiances are less sensitive to clouds than those for the 15-μm region.
14	2 213	4.52	N_2O	950 mb	
15	2 240	4.46	CO_2/N_2O	700 mb	
16	2 276	4.40	CO_2/N_2O	400 mb	
17	2 361	4.24	CO_2	5 mb	
18	2 512	4.00	Window	Surface	*Surface temperature.* Much less sensitive to clouds and H_2O than the 11-μm window. Used with 11-μm channel to detect cloud contamination and derive surface temperature under partly cloudy sky conditions. Simultaneous 3.7- and 4.0-μm data enable reflected solar contribution to be eliminated from observations.
19	2 671	3.70	Window	Surface	
20	14 367	0.70	Window	Cloud	*Cloud detection.* Used during the day with 4.0- and 11-μm window channels to define clear fields of view.

MSU	Frequency (GHz)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	50.31	Window	Surface	*Surface emissivity* and *cloud attenuation* determination.
2	53.73	O_2	700 mb	*Temperature sounding.* The microwave channels probe through clouds and can be used to alleviate the influence of clouds on the 4.3- and 15-μm sounding channels.
3	54.96	O_2	300 mb	
4	57.95	O_2	90 mb	

SSU	Wavelength (μm)	Principal absorbing constituents	Level of peak energy contribution	Purpose of the radiance observation
1	15.0	CO_2	15.0 mb	*Temperature sounding.* Using CO_2 gas cells and pressure modulation, the SSU observes thermal emissions from the stratosphere.
2	15.0	CO_2	4.0 mb	
3	15.0	CO_2	1.5 mb	

Fig. 1. Characteristics of TOVS sounding channels (From NOAA 1981).

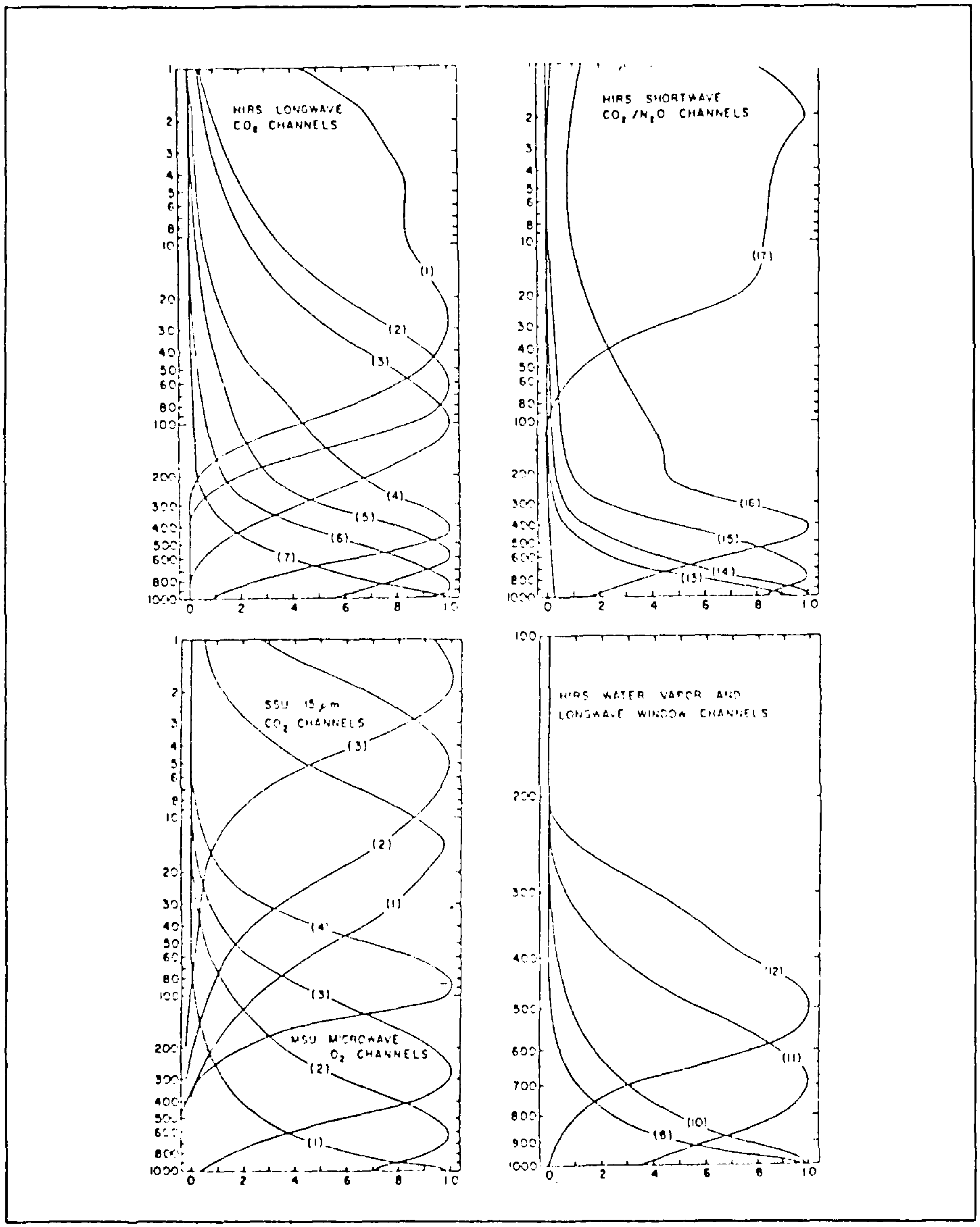


Fig. 2. TOVS weighting functions (From NOAA 1981).

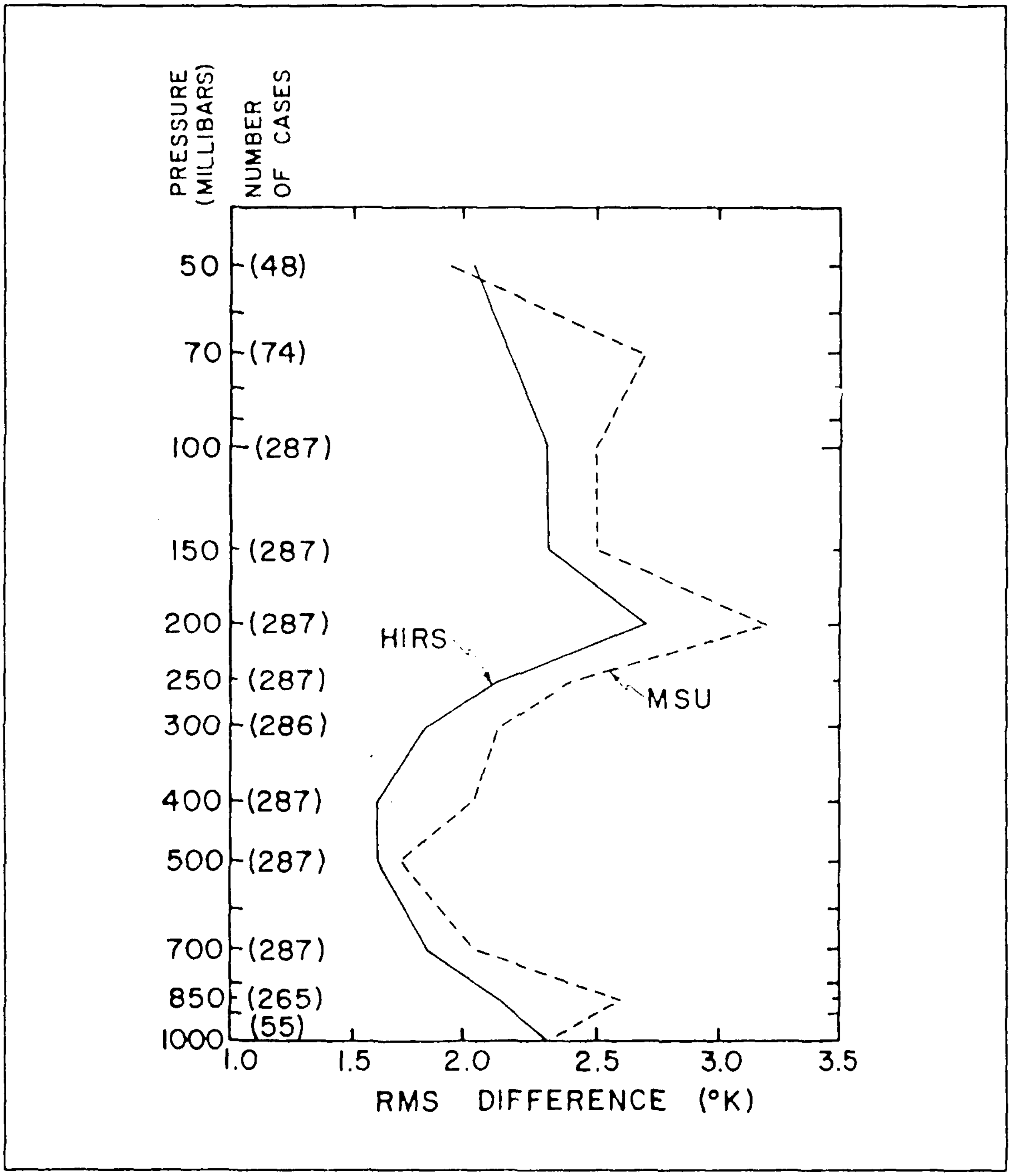


Fig. 3. TOVS and radiosonde composites. The rms difference between North American interactively derived TIROS-N soundings and radiosondes, 22 March-19 April 1979 (From Smith et al. 1979).

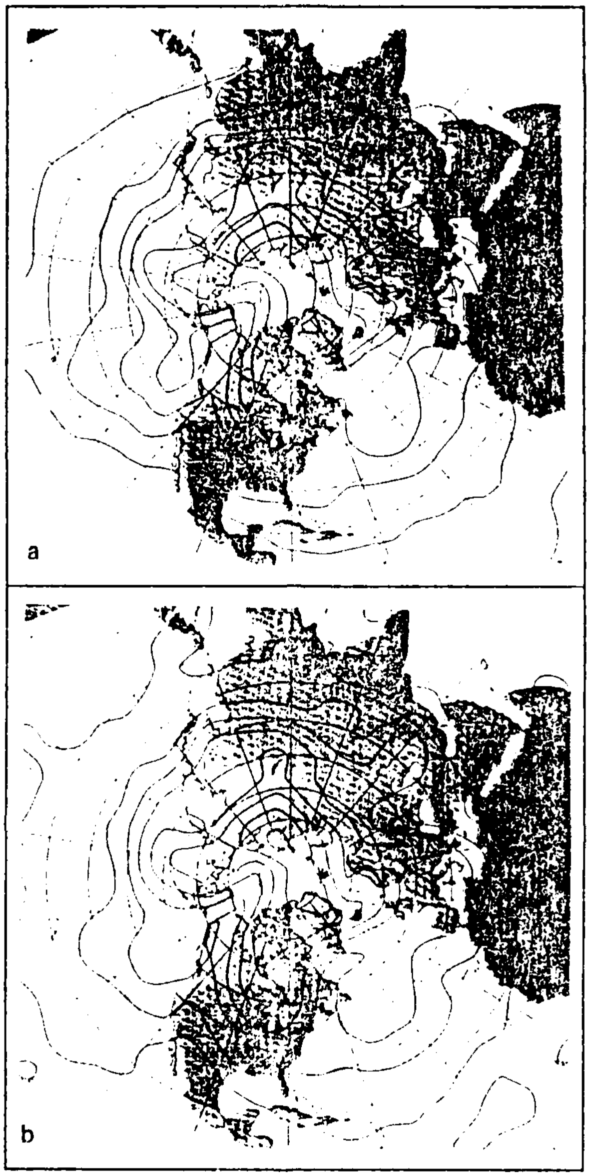


Fig. 4. Hemispheric analysis with and without TOVS data. Comparison of 1000-500 mb thickness charts obtained solely from TIROS-N sounding data on 1800 UTC 29 Apr-0600 UTC, 30 Apr (Fig. 4a, top) and from conventional data on 0000 UTC 30 Apr (Fig. 4b, bottom) (From Smith et al. 1979).

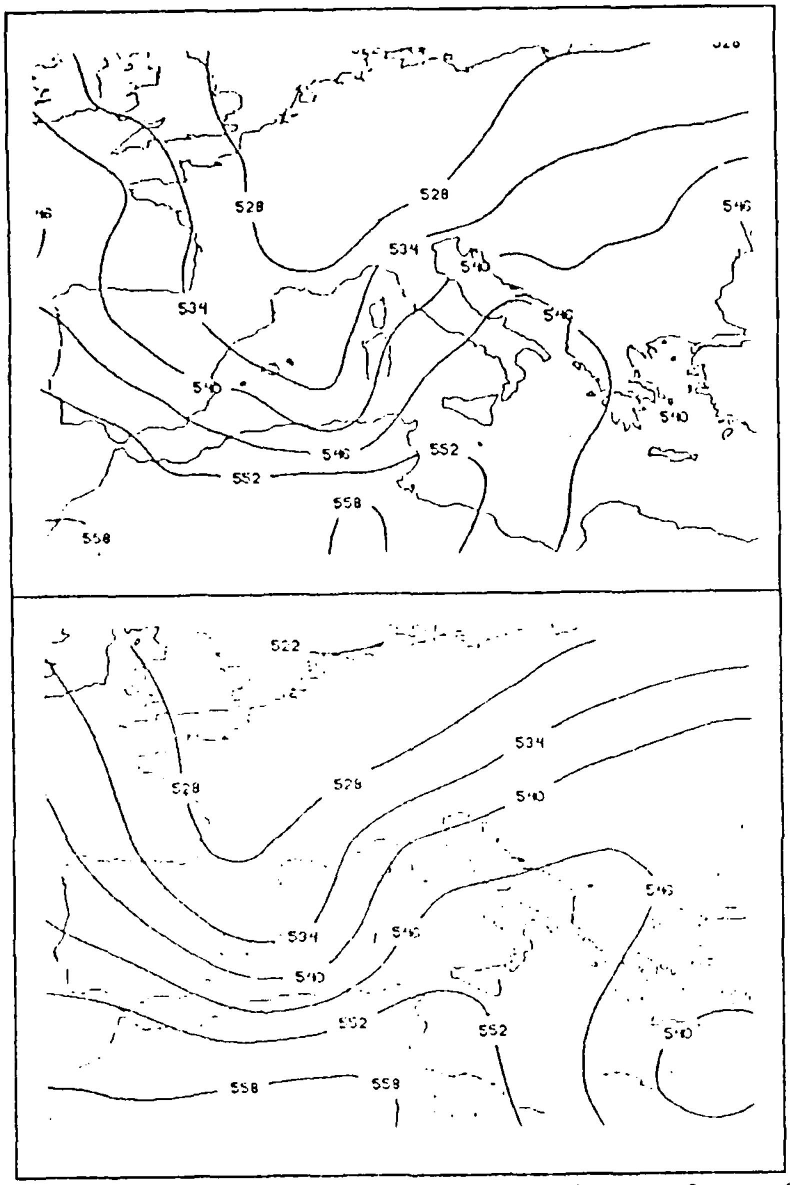


Fig. 5. Comparisons of TOVS and ECMWF 1000-500 mb thickness analyses. The TOVS analyses (Fig. 5a) shows a higher amplitude ridge between England and Spain and a deeper trough over southern Europe than the ECMWF analysis (Fig. 5b) (From Smith et al. 1983).

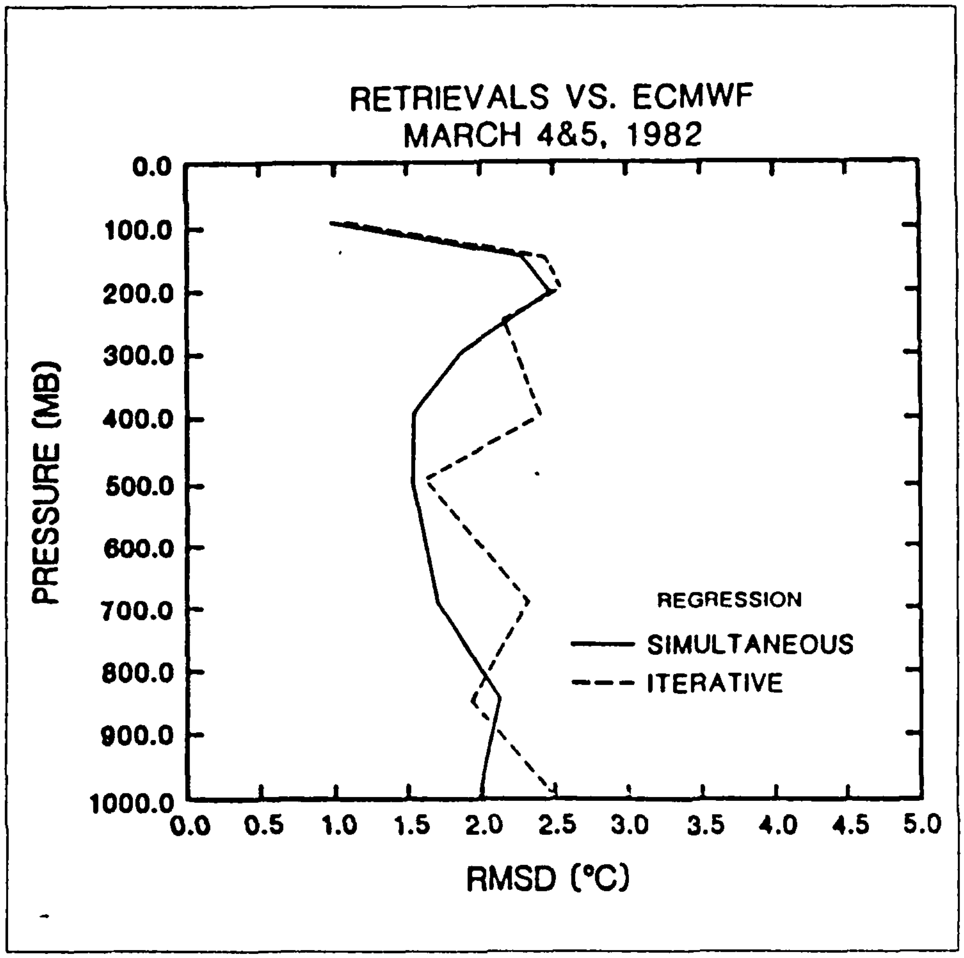


Fig. 6. RMS difference between ECMWF gridded temperature profiles, simultaneous retrievals, and physical retrievals. Data was obtained from ALPEX, 4-5 Mar 82 (From Smith et al. 1985).

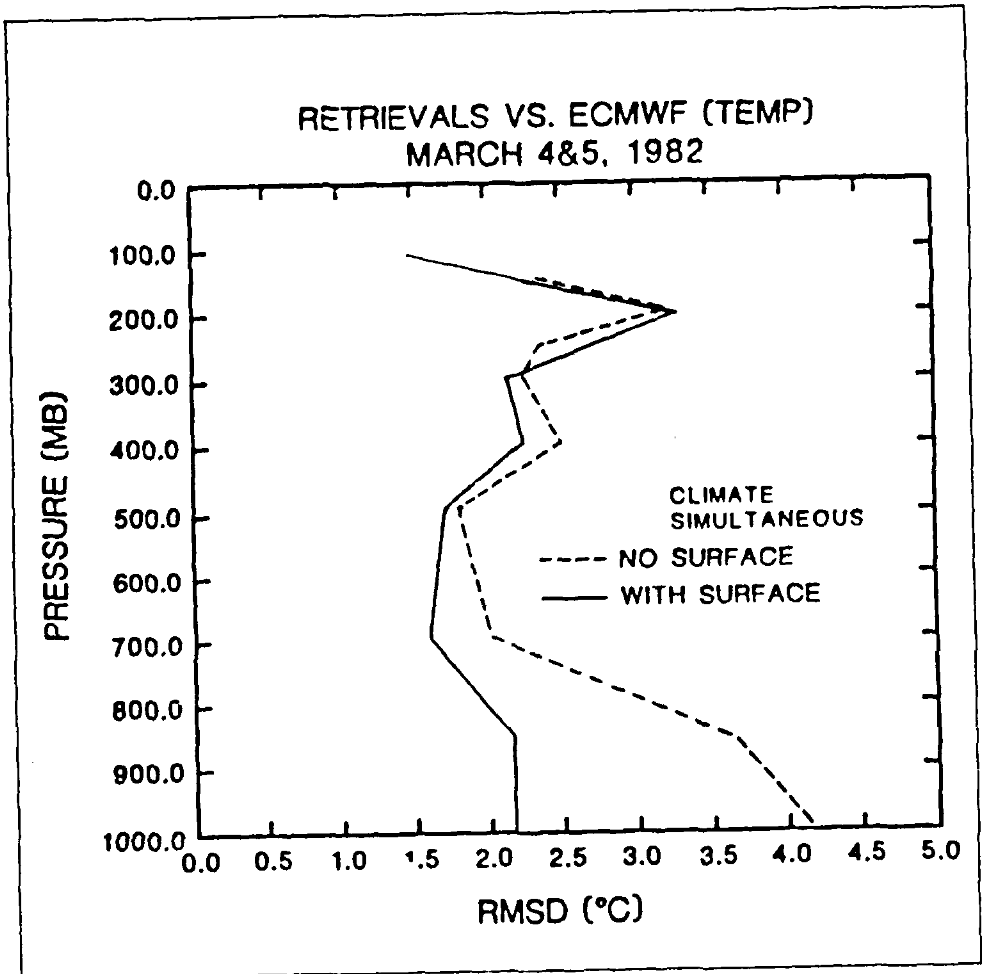


Fig. 7. RMS difference between ECMWF gridded temperature profiles and simultaneous retrievals, with and without surface data (From Smith et al. 1985).

Fig. 8. NOAA-11 AVHRR CH 4 imagery, 0644 UTC 13 December 1988.

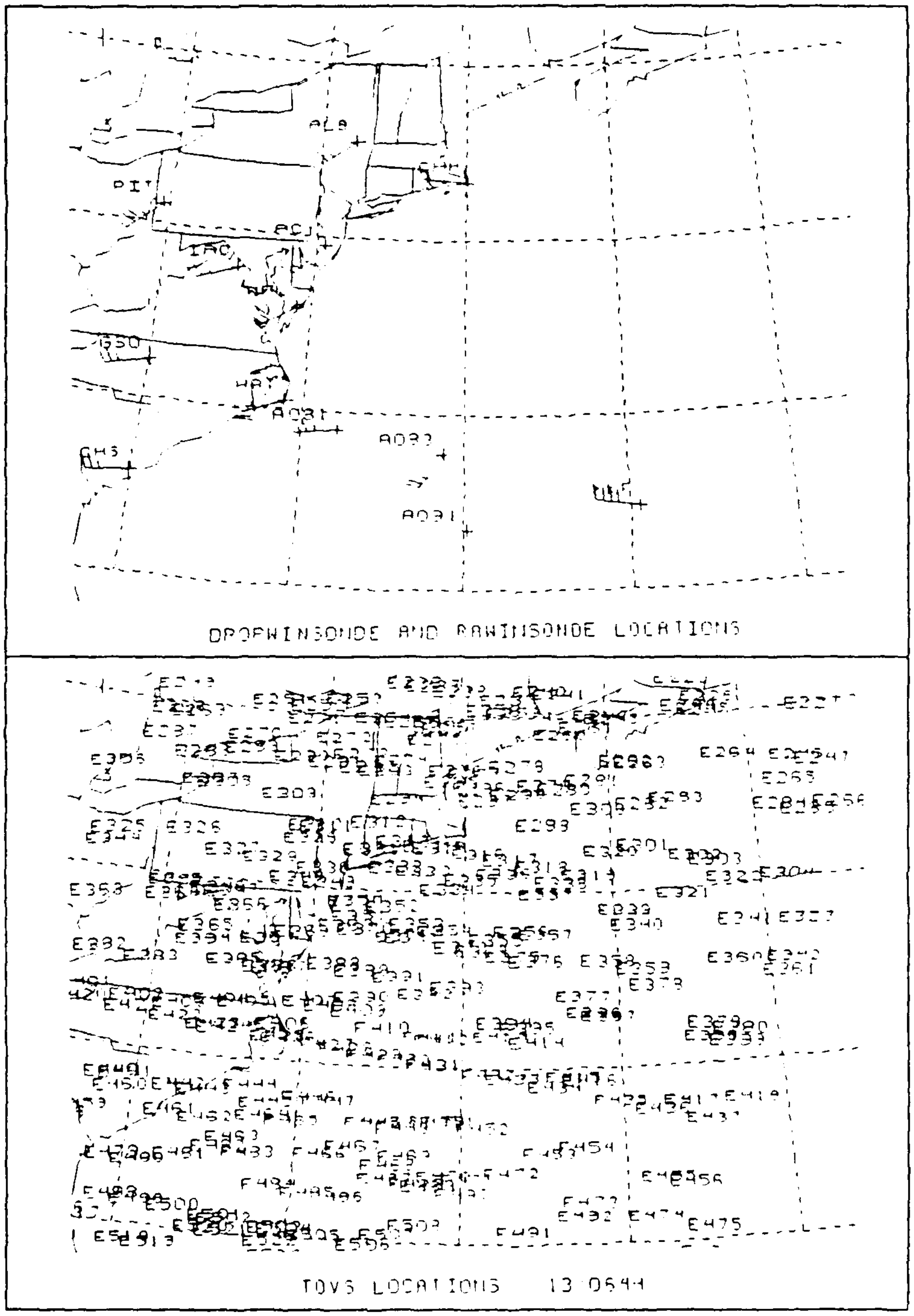


Fig. 9. Rawinsonde and dropwindsonde locations at 0600-0920 UTC and collocated TOVS soundings at 0644 UTC 13 December 1988. Fig. 9a shows rawinsonde and dropwindsonde locations. Fig. 9b shows TOVS sounding locations.

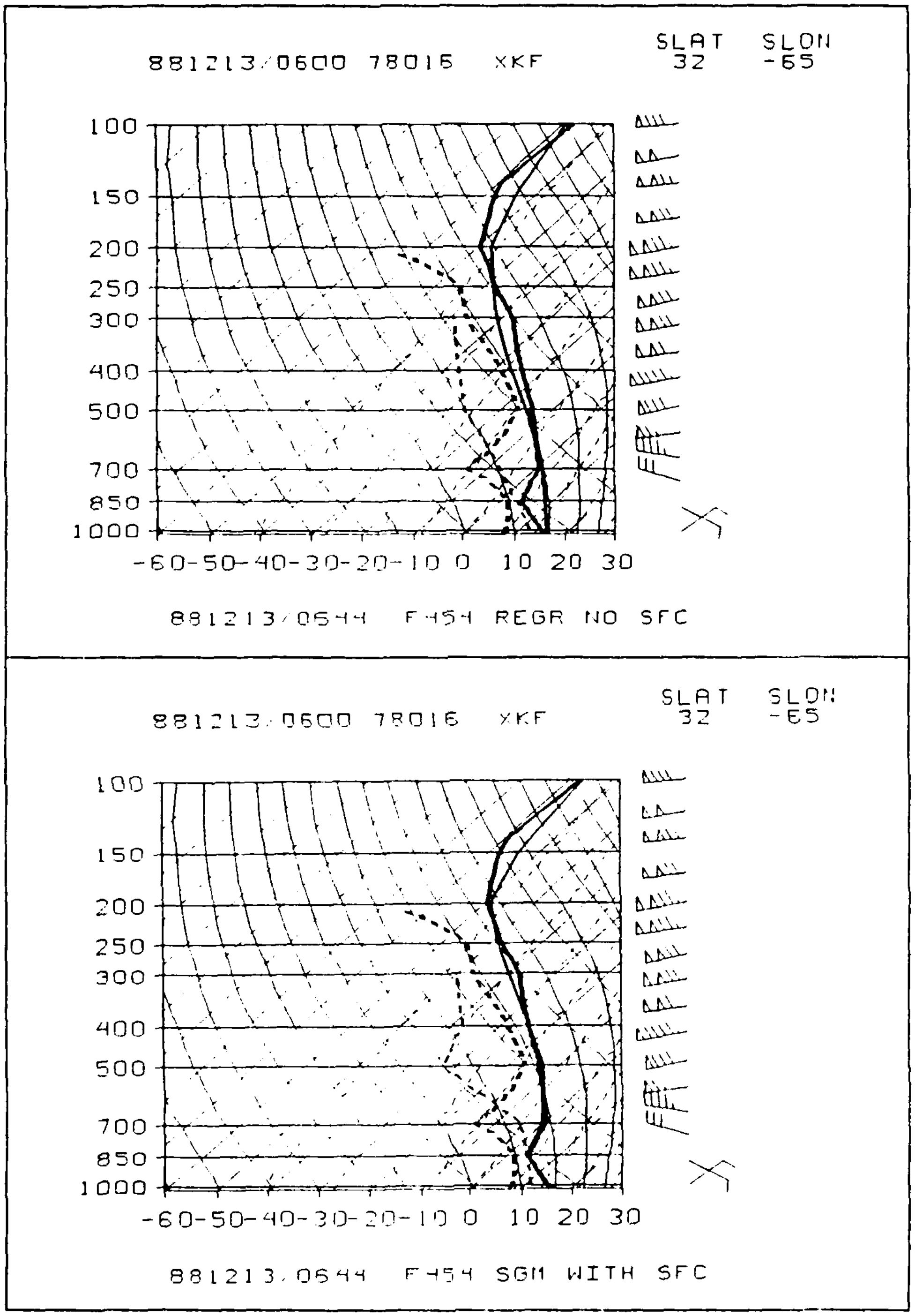
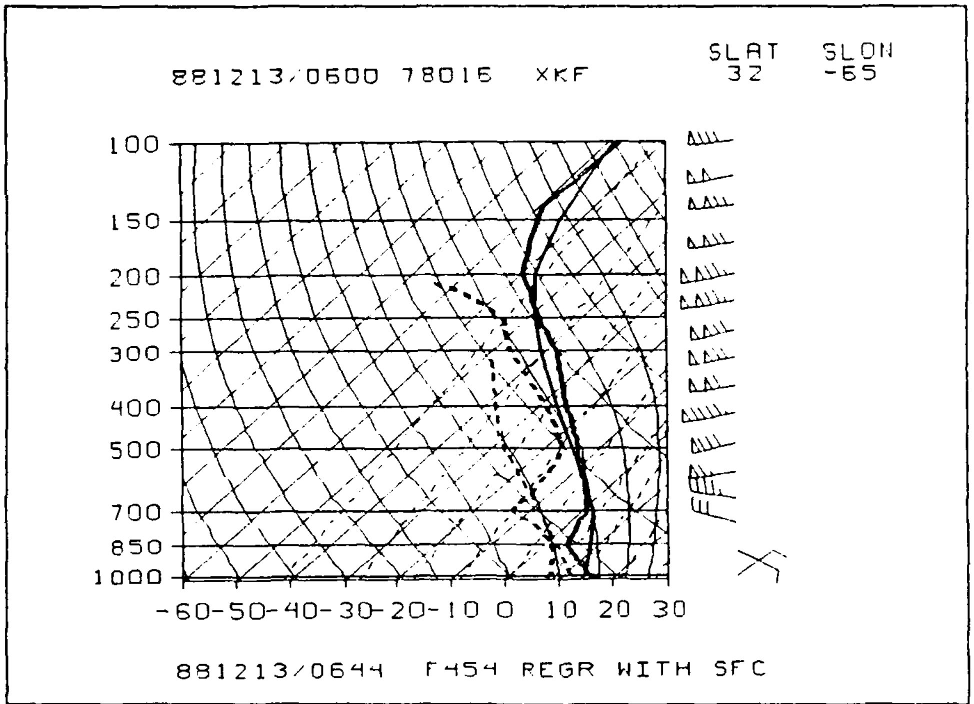


Fig. 10. Rawinsonde XKF with collocated TOVS sounding F454. Fig. 10a compares XKF with a RN TOVS retrieval. Fig. 10b compares XKF with a SS retrieval.



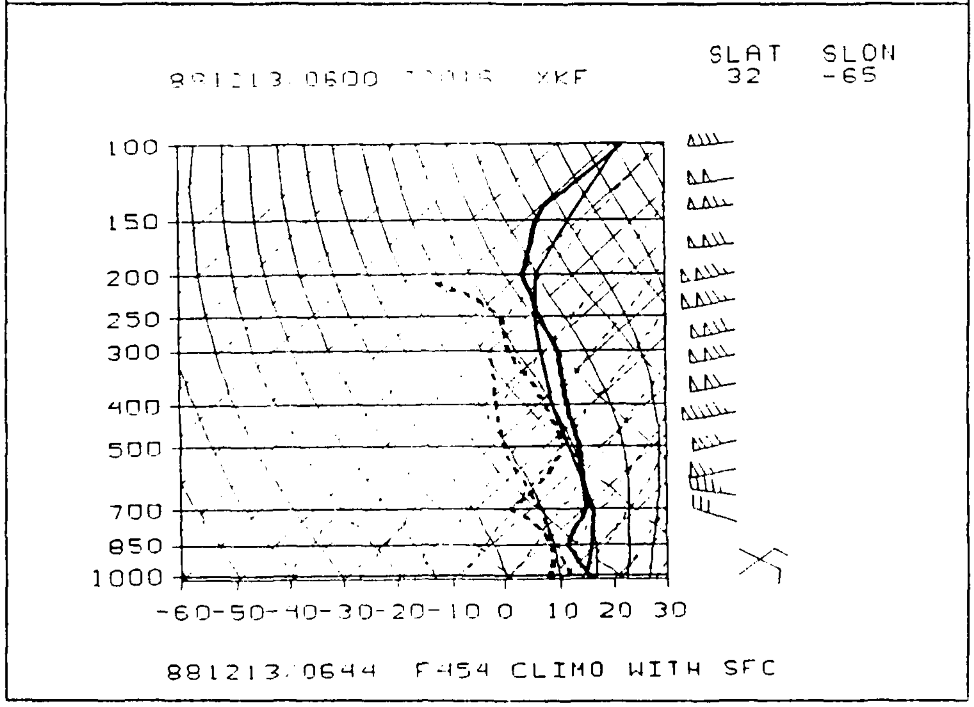


Fig. 11. Same as Fig. 10 except F454 used a regression first-guess with surface data and a climatology first-guess with surface data. Fig. 11a compares XKF with a RS retrieval. Fig. 11b compares XKF with a CS retrieval.

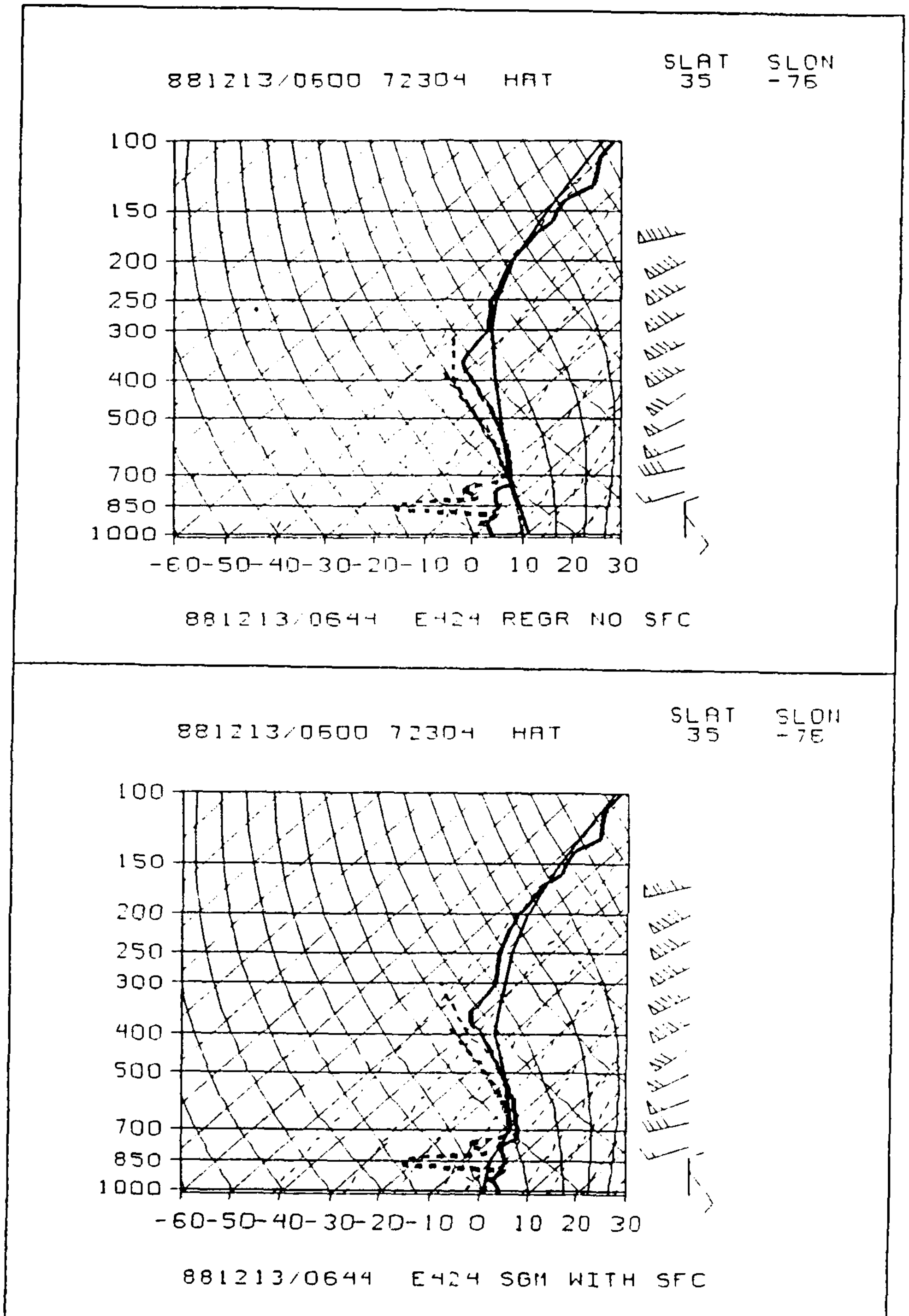


Fig. 12. Same as Fig. 10 except for HAT with E424. Fig. 12a compares HAT with a RN TOVS retrieval. Fig. 12b compares HAT with a SS retrieval.

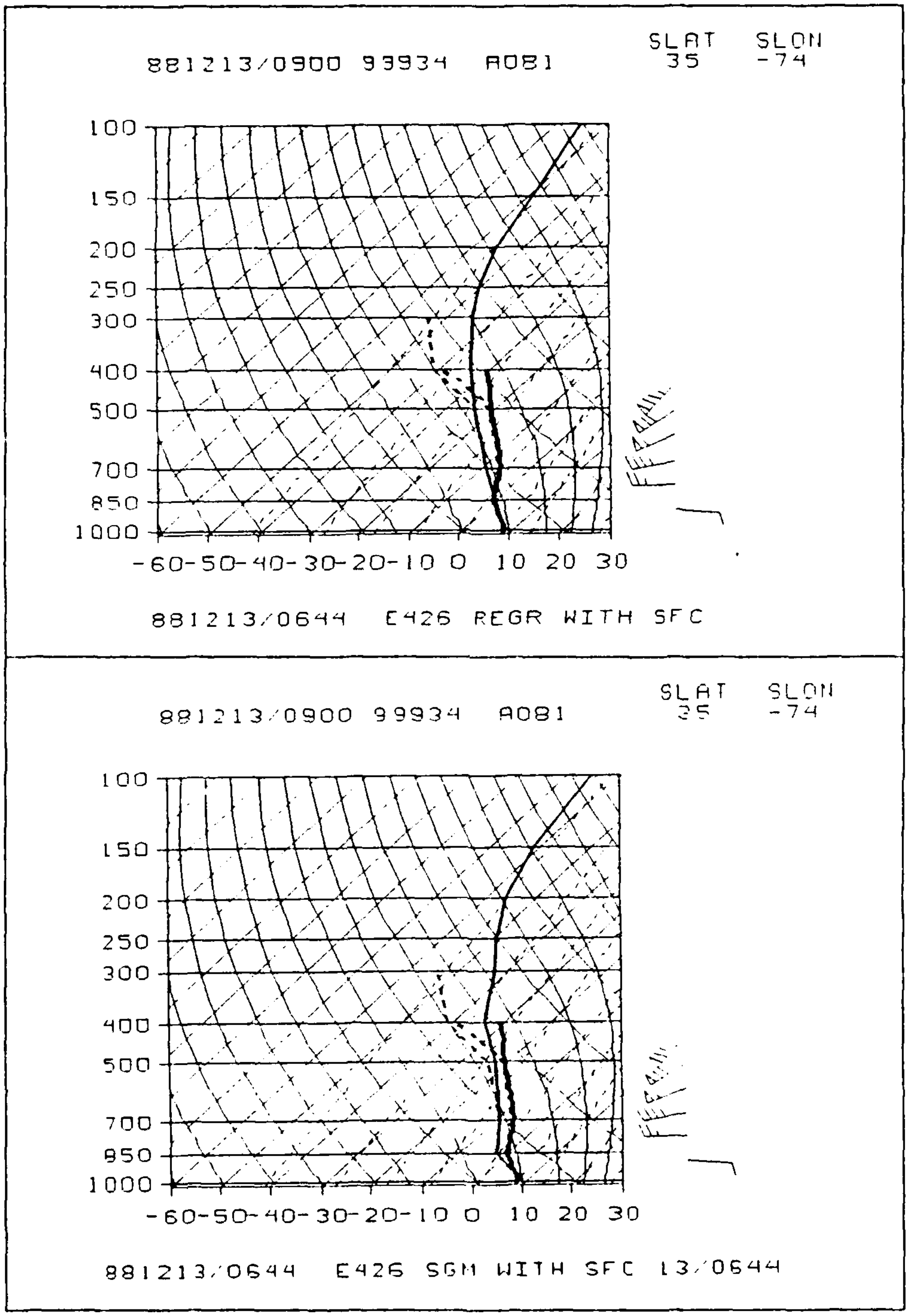


Fig. 13. Dropwindsonde A081 with collocated TOVS sounding E426. Fig. 13a compares A081 with a RS TOVS retrieval. Fig. 13b compares A081 with a SS retrieval.

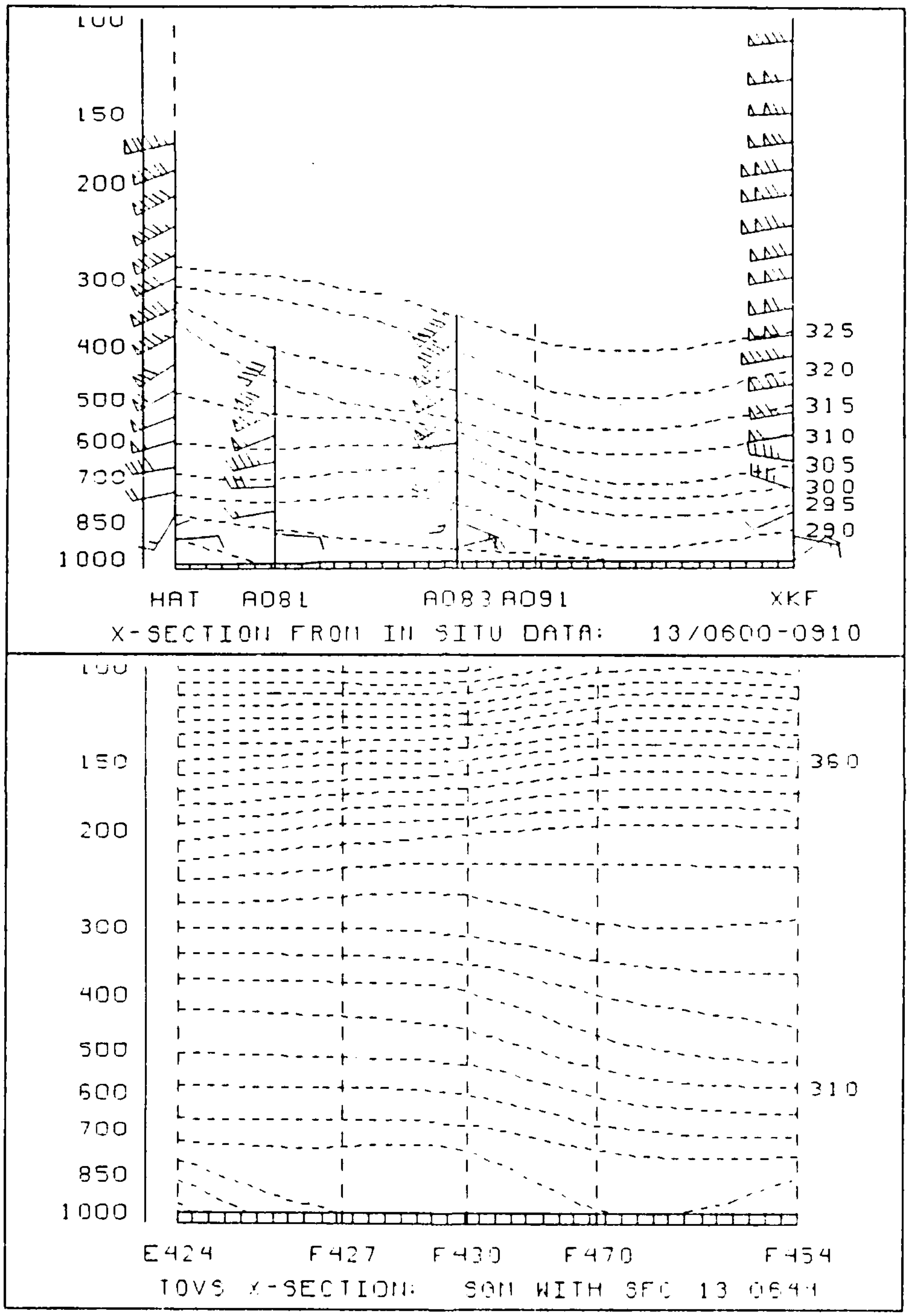


Fig. 14. Cross section through rawinsondes and overwater dropwindsondes, and collocated TOVS cross section. Fig. 14a shows the cross section with the in situ data. Fig. 14b shows the cross section with the collocated TOVS soundings.

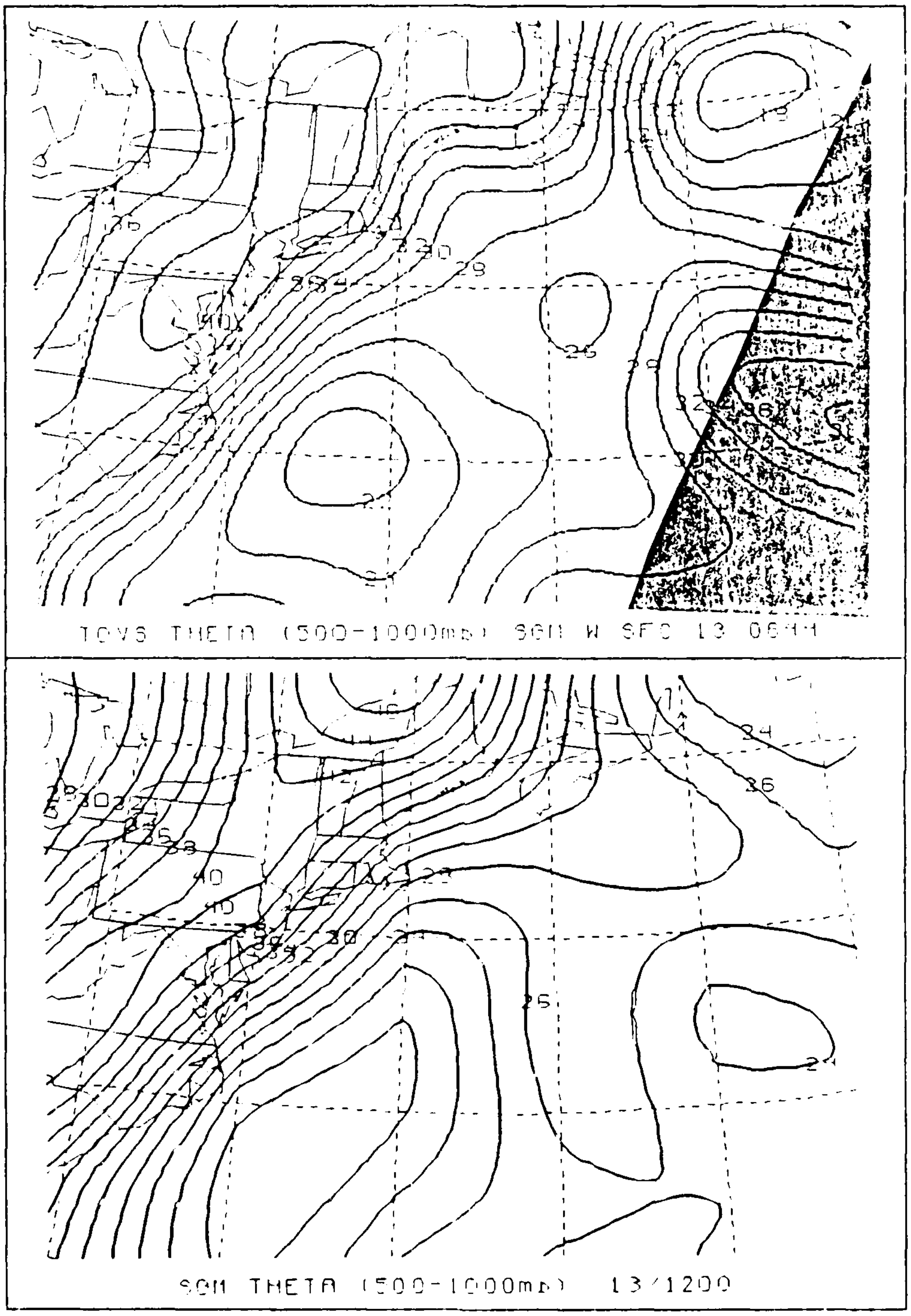


Fig. 15. Comparison between TOVS static stability analysis and the NMC operational analysis from the SGM 6 h later. Fig. 15a shows the TOVS static stability analysis at 0644 UTC 13 December 1988. Fig. 15b shows the NMC analysis at 1200 UTC 13 December 1988.

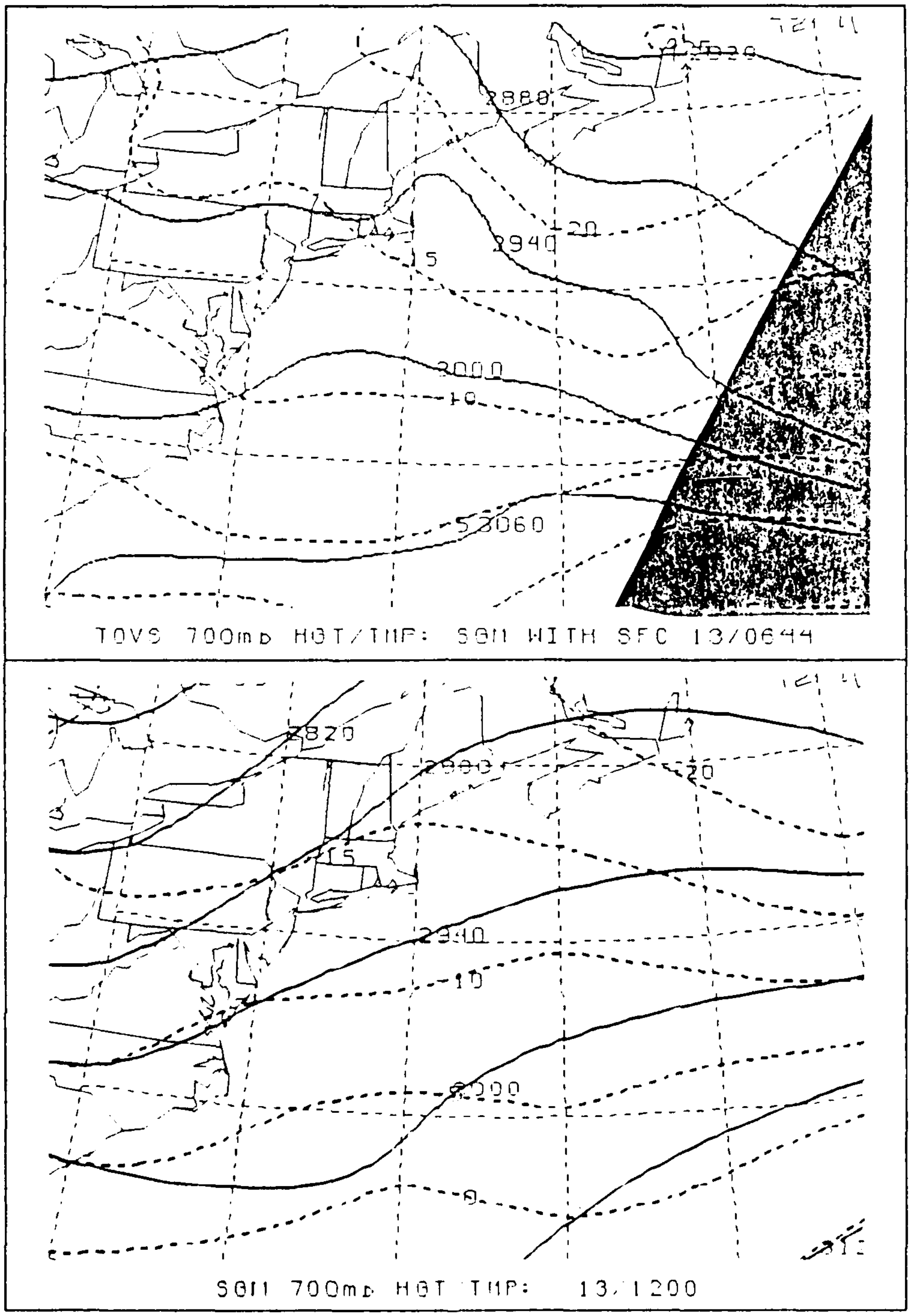


Fig. 16. Comparison between TOVS 700 mb height and temperature analyses and the NMC operational analyses from the SGM 6 h later. Fig. 16a shows the TOVS analyses at 0644 UTC 13 December 1988. Fig. 16b shows the NMC analyses at 1200 UTC 13 December 1988.

Fig. 17. Same as Fig. 8 except for AVHRR CH 1, at 1820 UTC 13 December 1988.

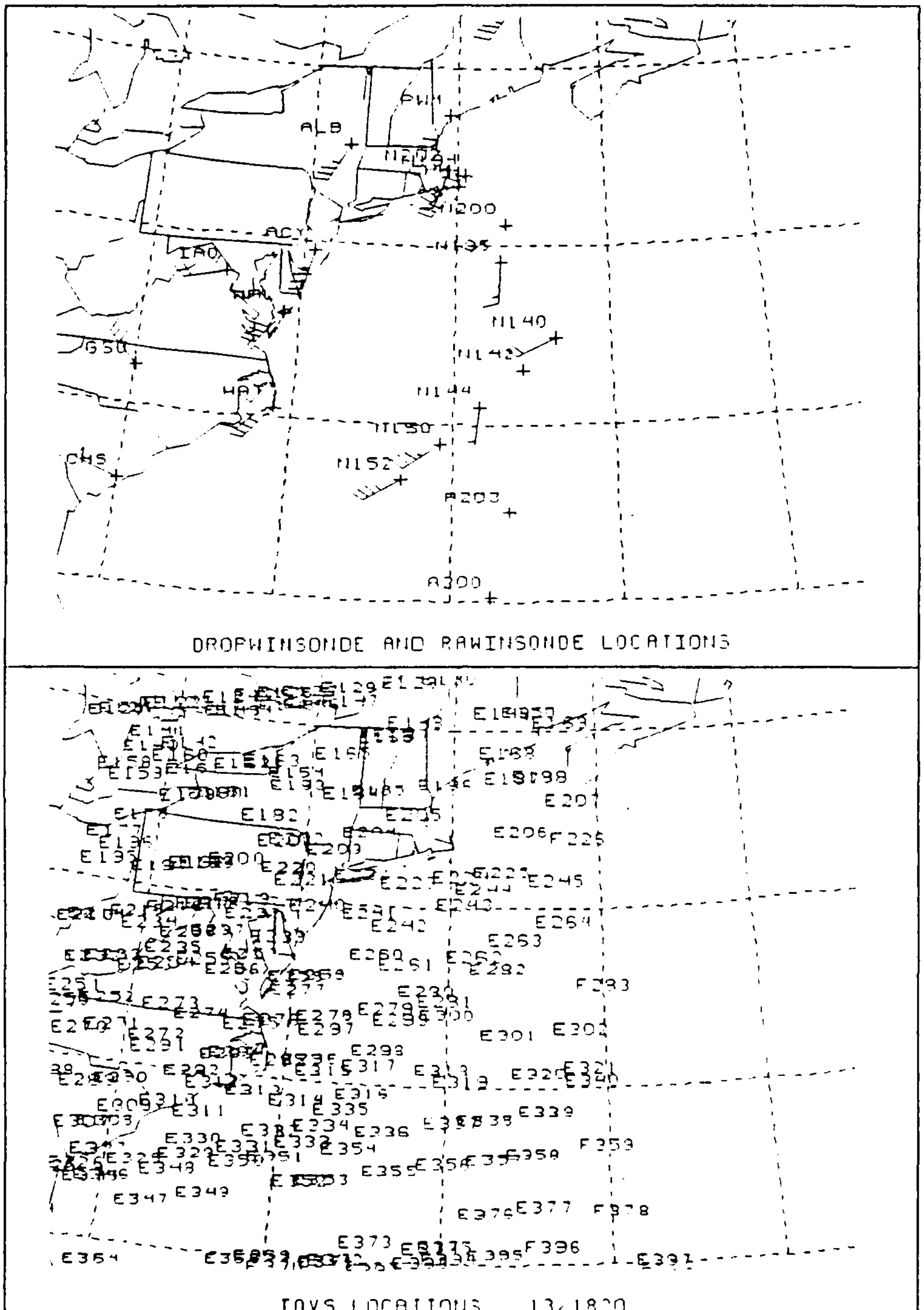


Fig. 18. Rawinsonde and dropwindsonde locations at 1500-2100 UTC and collocated TOVS soundings at 1820 UTC 13 December 1988. Fig. 18a shows rawinsonde and dropwindsonde locations. Fig. 18b shows TOVS sounding locations.

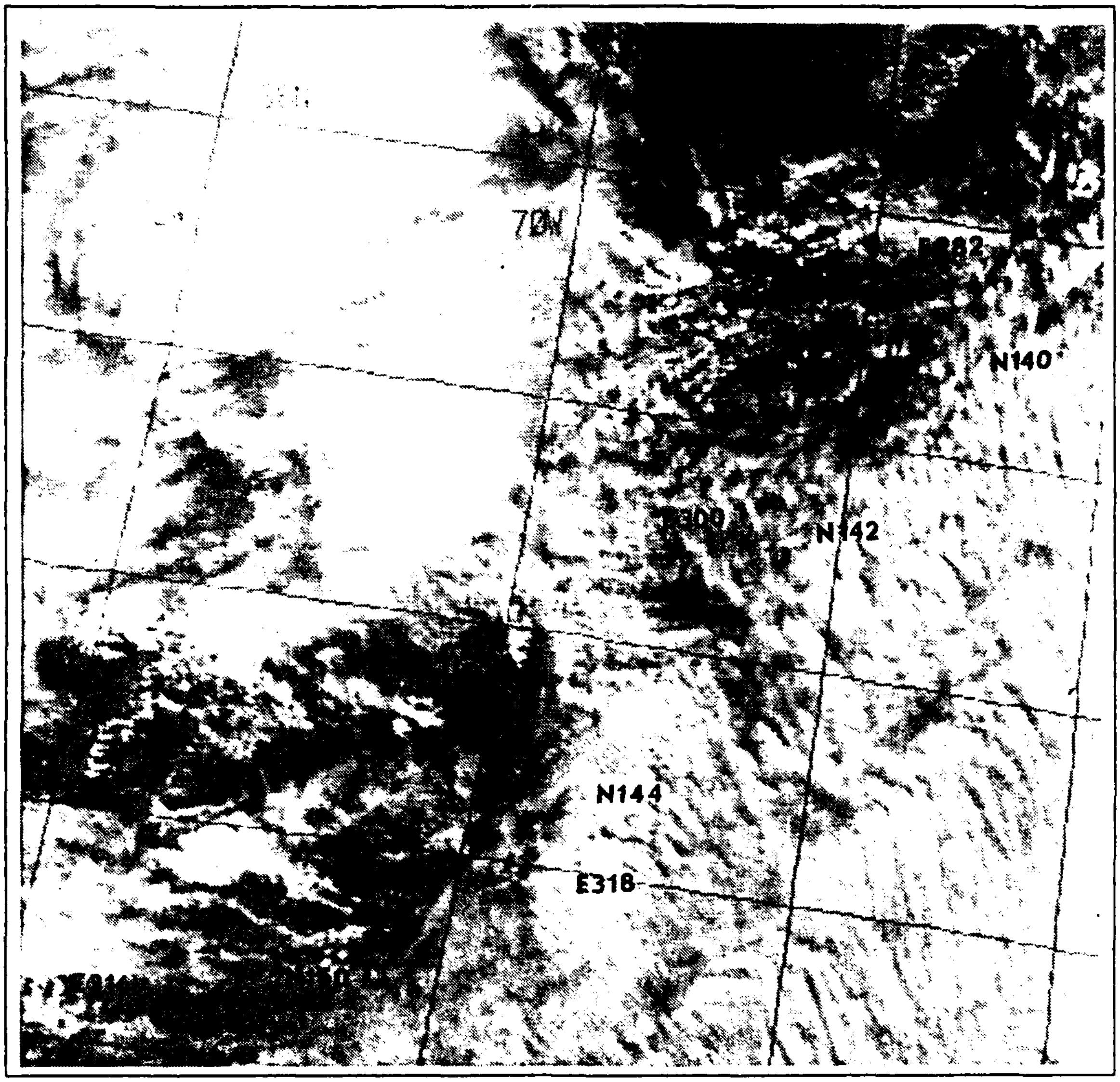
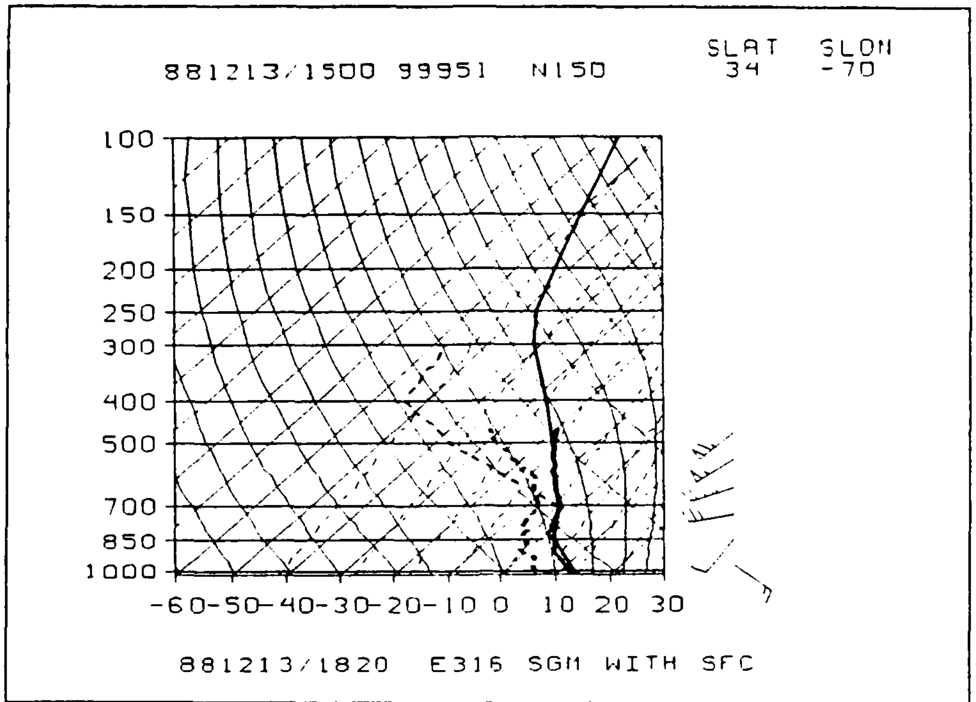


Fig. 19. NOAA-11 AVHRR CH 1 subscene of the ERICA region at 1820 UTC.



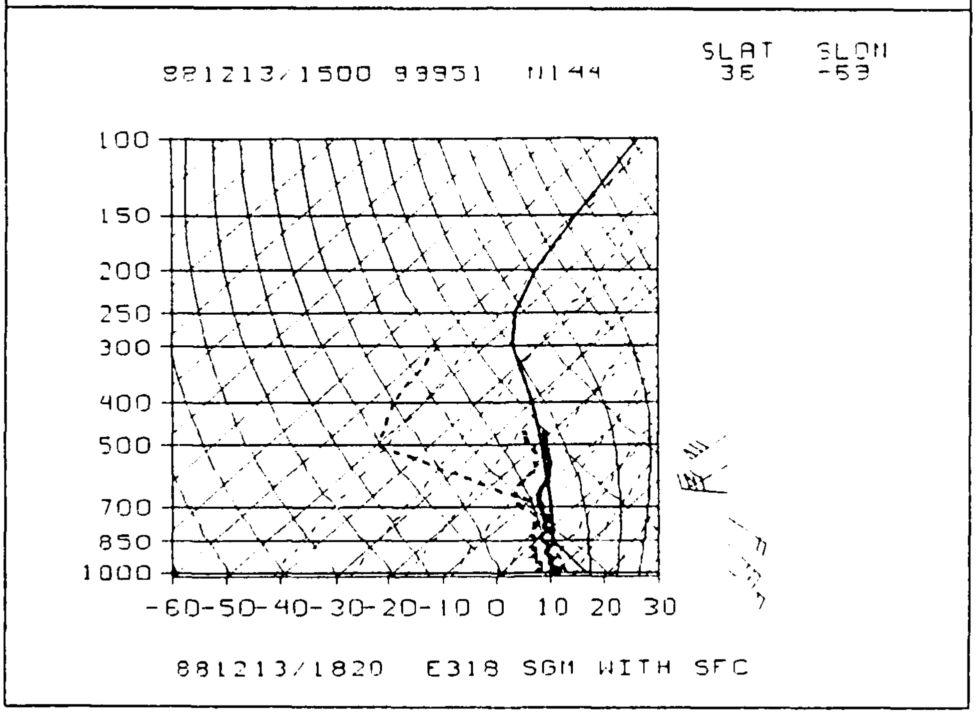


Fig. 20. Dropwindsondes N150 and N144 with collocated TOVS profiles E316 and E318. Fig. 20a shows the difference between N150 and E316. Fig. 20b shows N144 and E318.

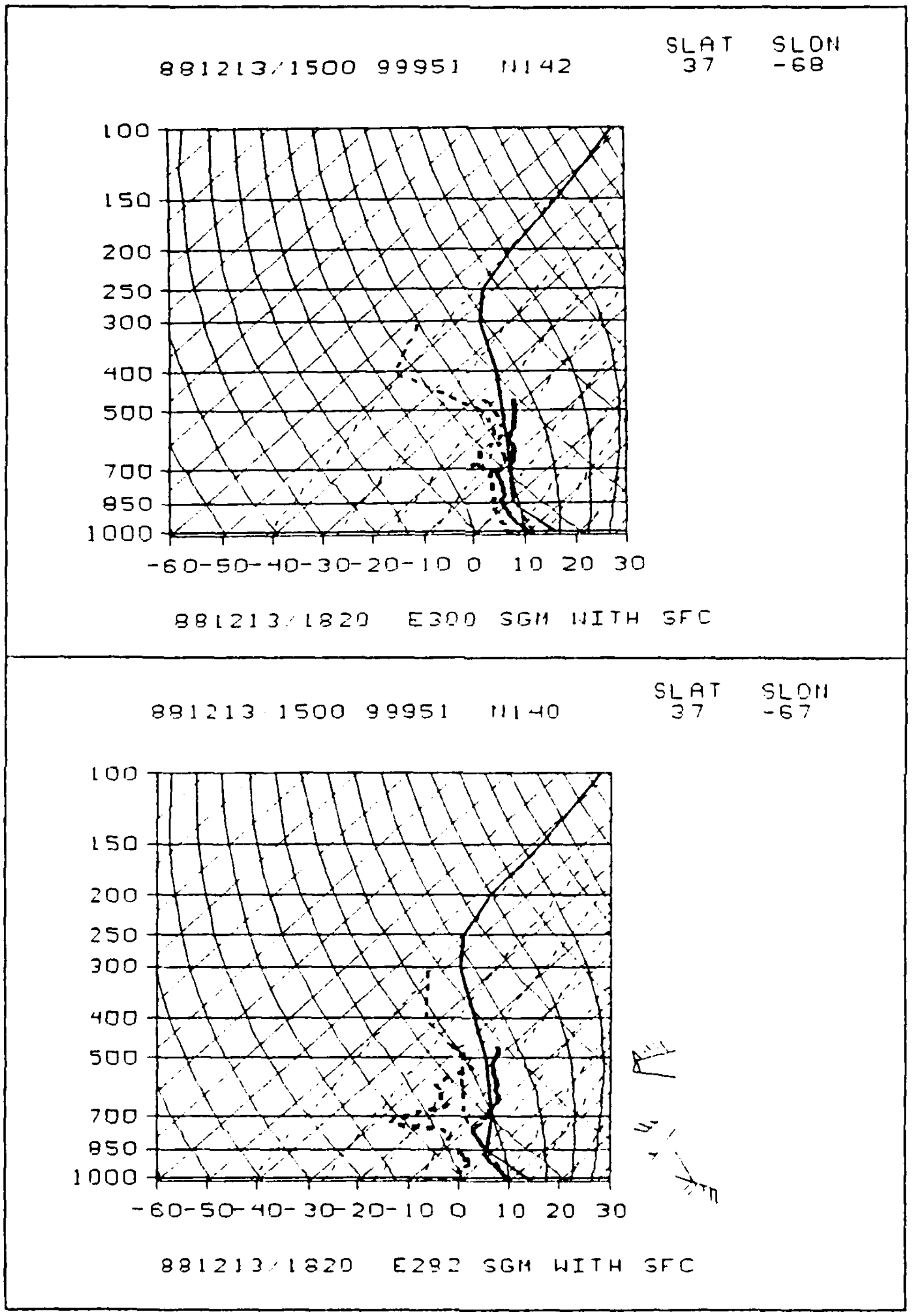


Fig. 21. Dropwindsondes N142 and N140 with collocated TOVS profiles E300 and E282. Fig. 21a shows the difference between N142 and E300. Fig. 21b shows N140 and E282.

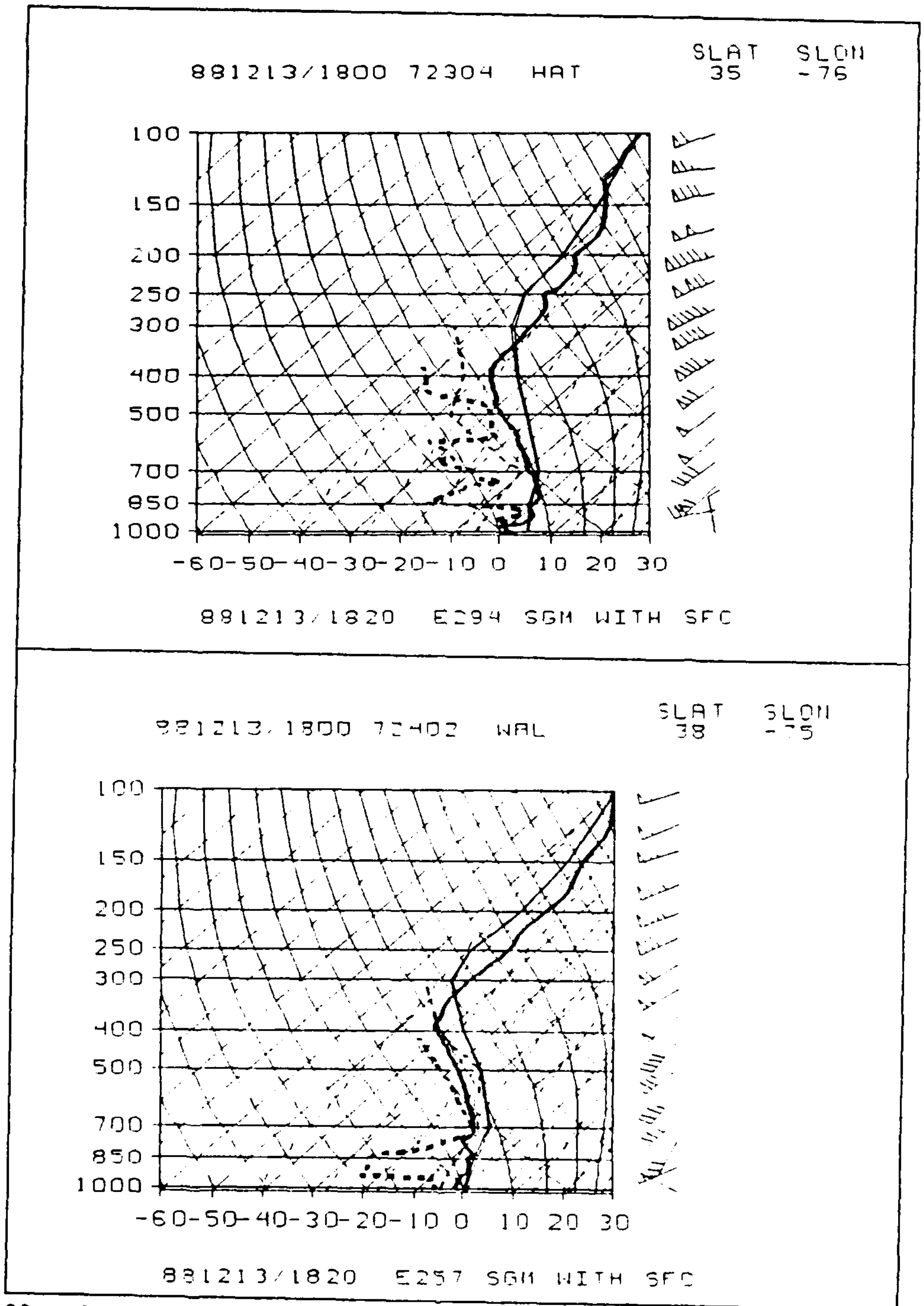


Fig. 22. Rawinsondes HAT and WAL with collocated TOVS profiles E294 and E257. Fig. 22a shows the difference between HAT and E294. Fig. 22b shows WAL and E257.

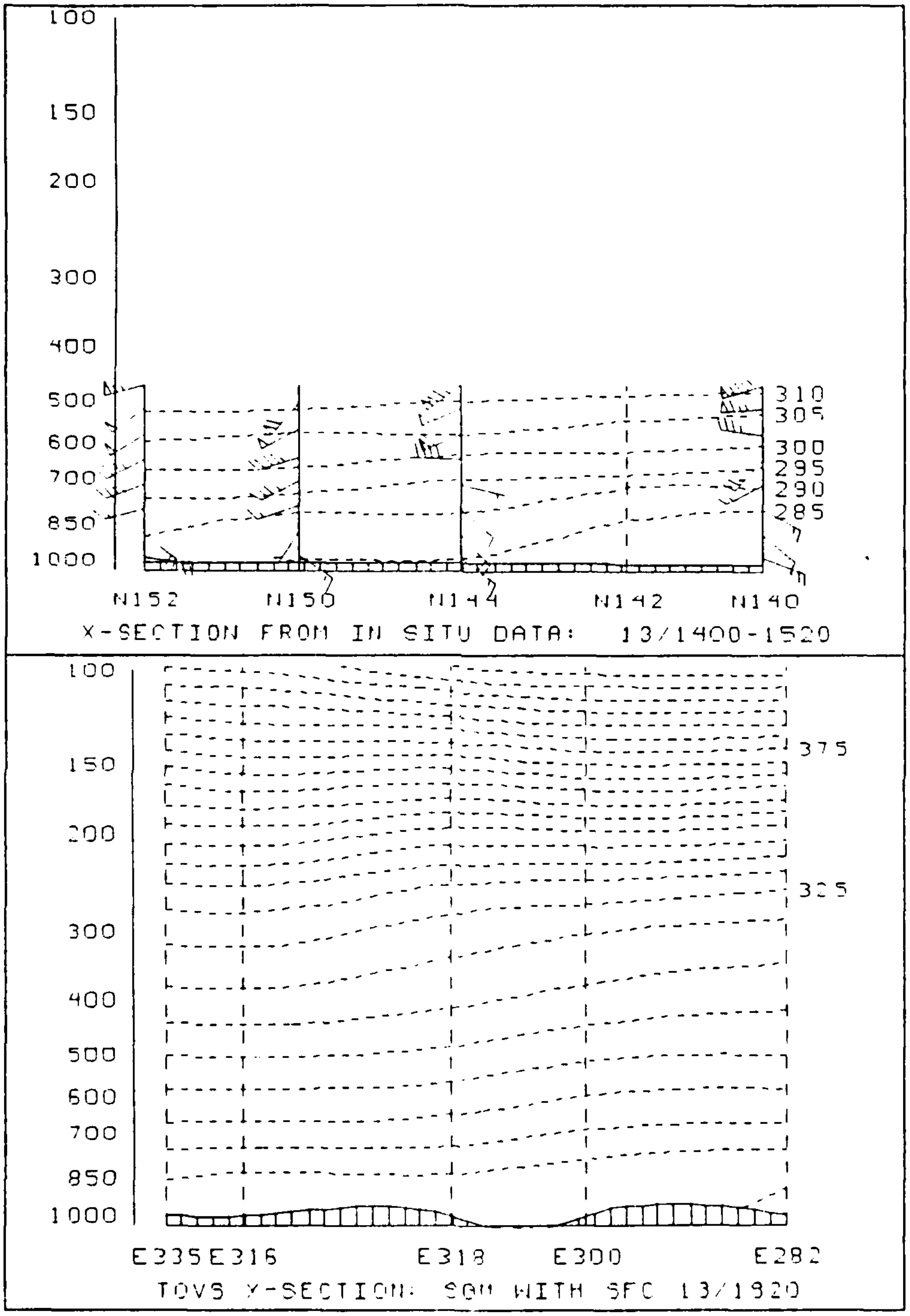


Fig. 23. Dropwindsonde and TOVS cross sections at 1820 UTC. Fig. 23a shows a cross section through the dropwindsondes at 1500 UTC. Fig. 23b shows a cross section through the collocated TOVS soundings.

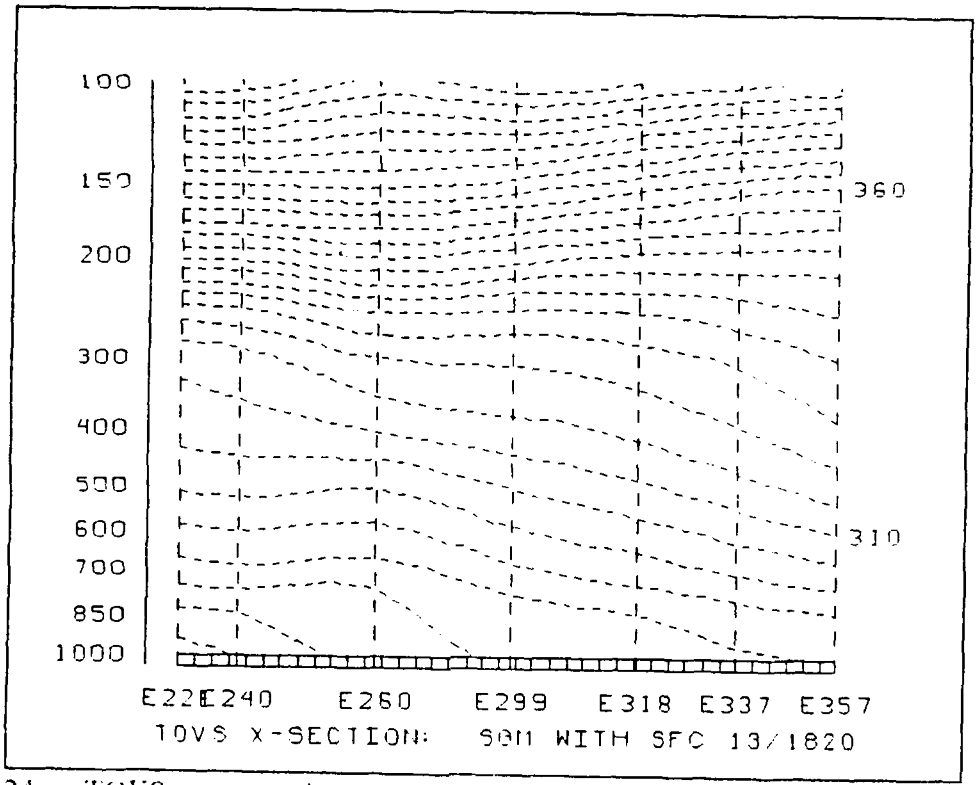
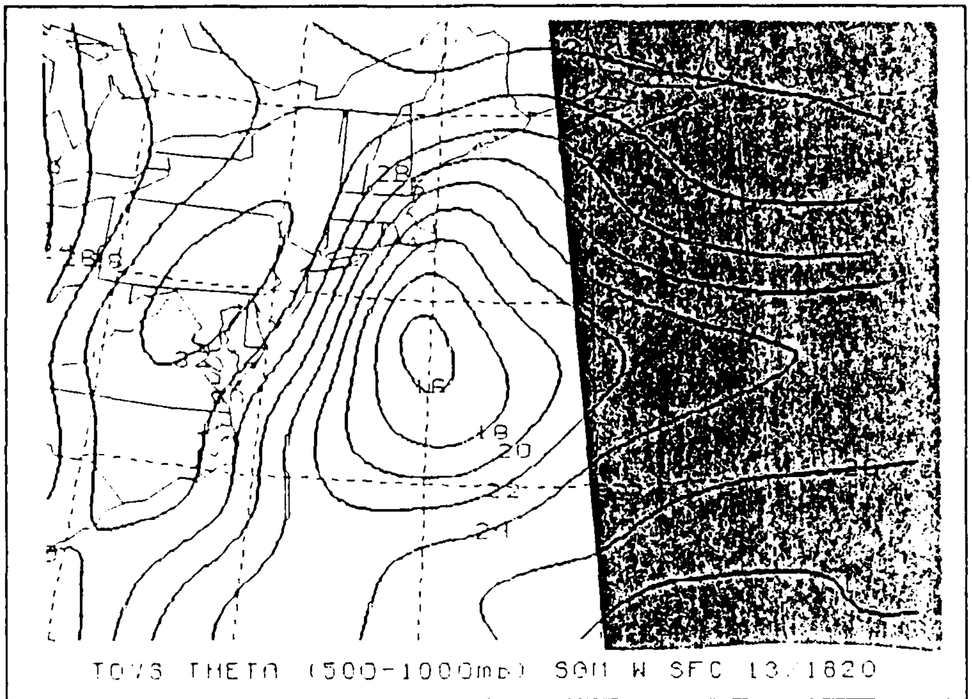


Fig. 24. TOVS cross section over developing cyclone at 1820 UTC. Cross section extends from E221 (40°N 74°W) to E357 (33°N 68°W).



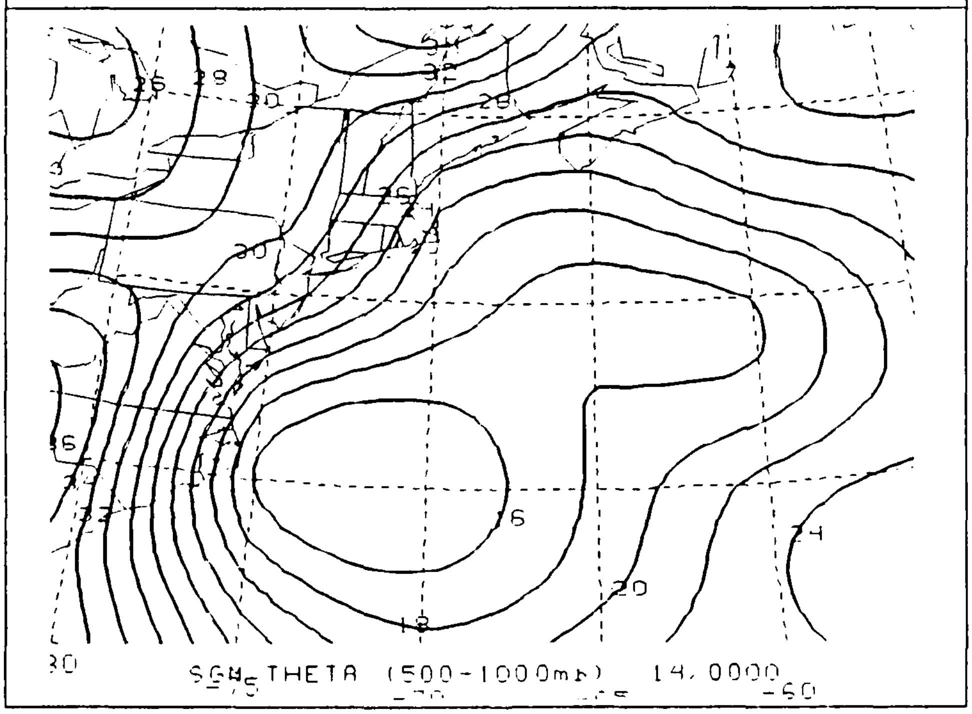


Fig. 25. Same as Fig. 15 except for TOVS data at 1820 UTC 13 December 1988 and NMC data at 0000 UTC 14 December 1988. Fig. 25a shows the TOVS stability analysis. Fig. 25b shows the SGM stability analysis.

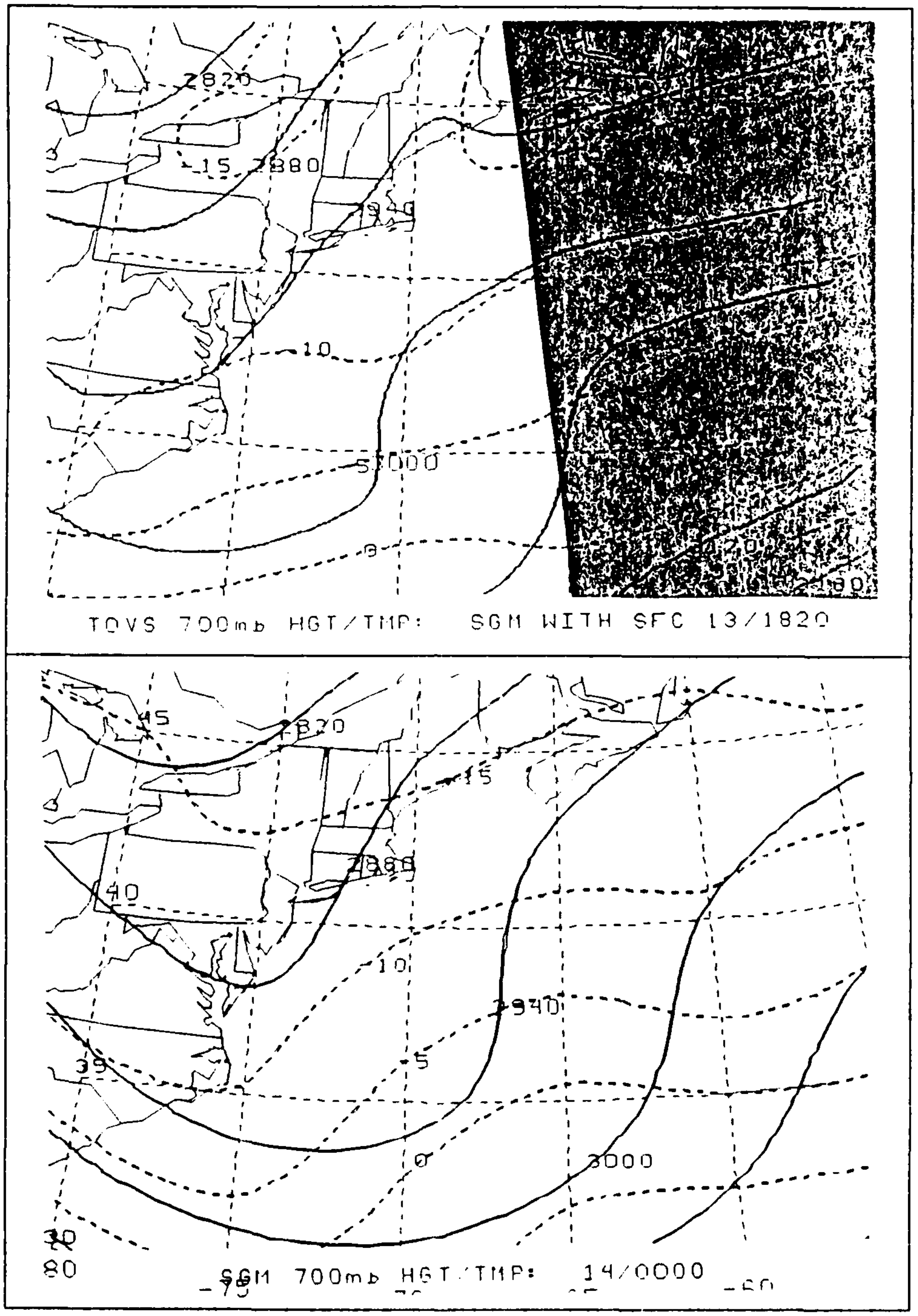


Fig. 26. Same as Fig. 16 except for TOVS data at 1820 UTC 13 December 1988 and NMC data at 0000 UTC 14 December 1988. Fig. 26a shows the TOVS 700 mb analyses. Fig. 26b shows the SGM 700 mb analyses.

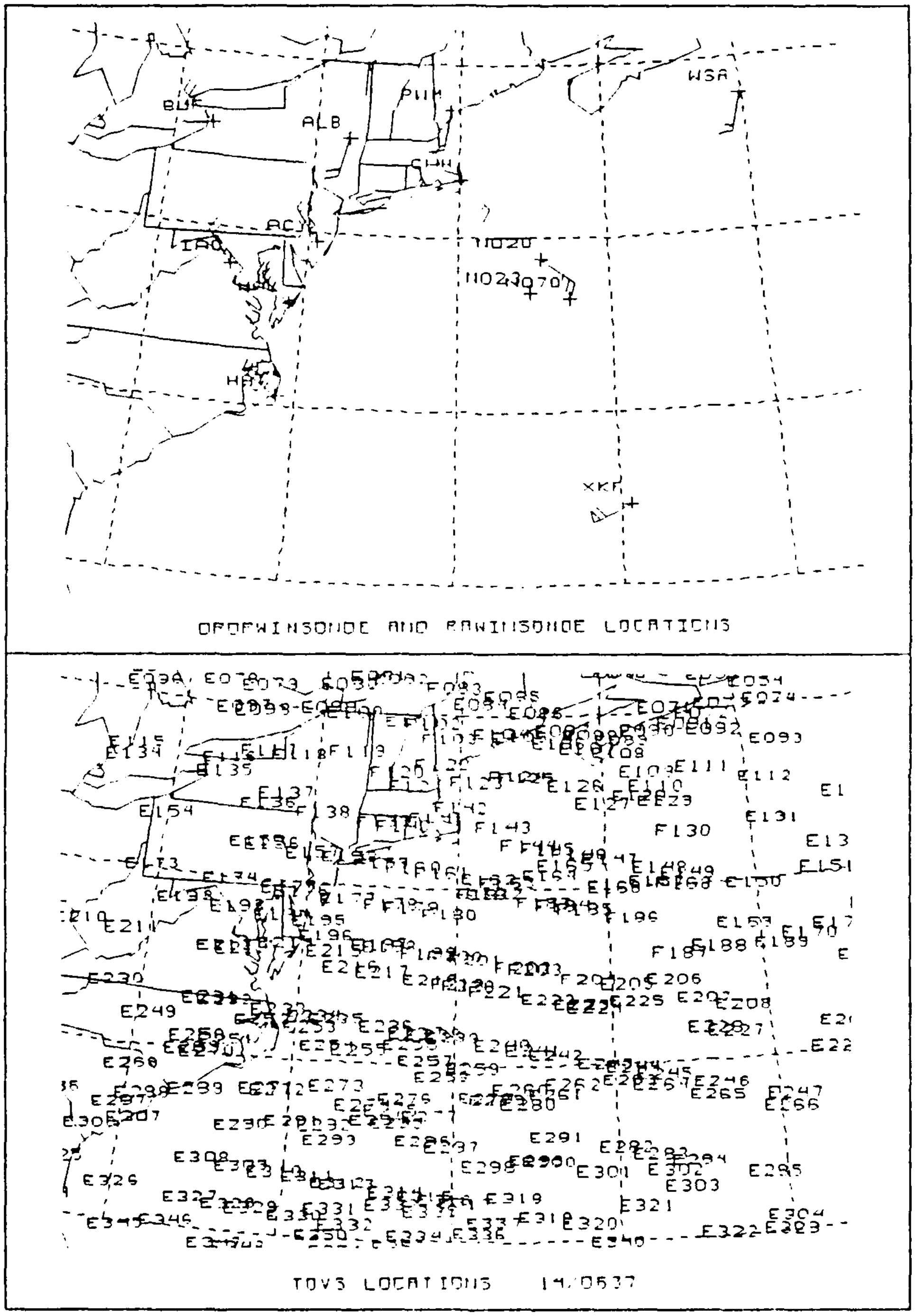
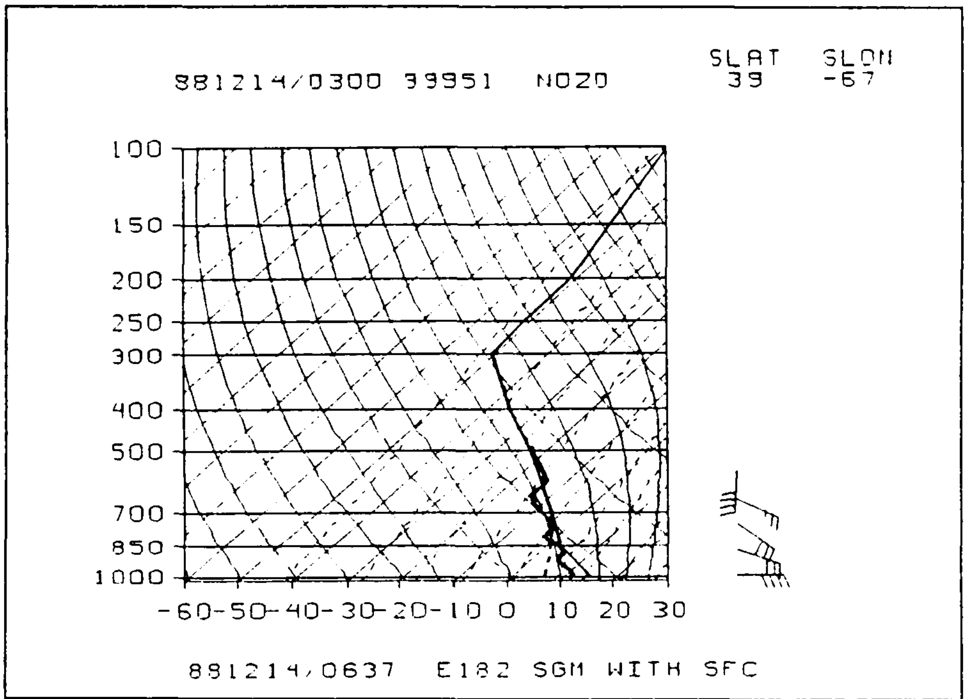


Fig. 27. Rawinsonde and dropwindsonde locations at 0300-0900 UTC and collocated TOVS soundings at 0637 UTC 14 December 1988. Fig. 27a shows rawinsonde and dropwindsonde locations. Fig. 27b shows TOVS sounding locations.



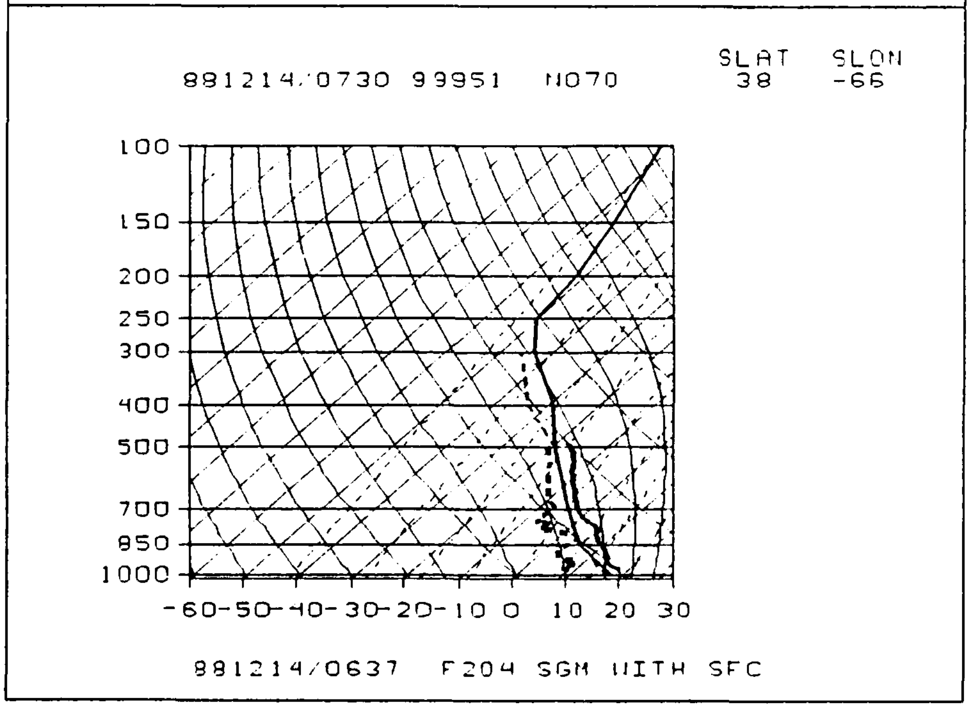


Fig. 28. Dropwindsondes N020 and N070 with collocated TOVS profiles E182 and F204. Fig. 28a shows the difference between N020 and E182. Fig. 28b shows N070 and F204.

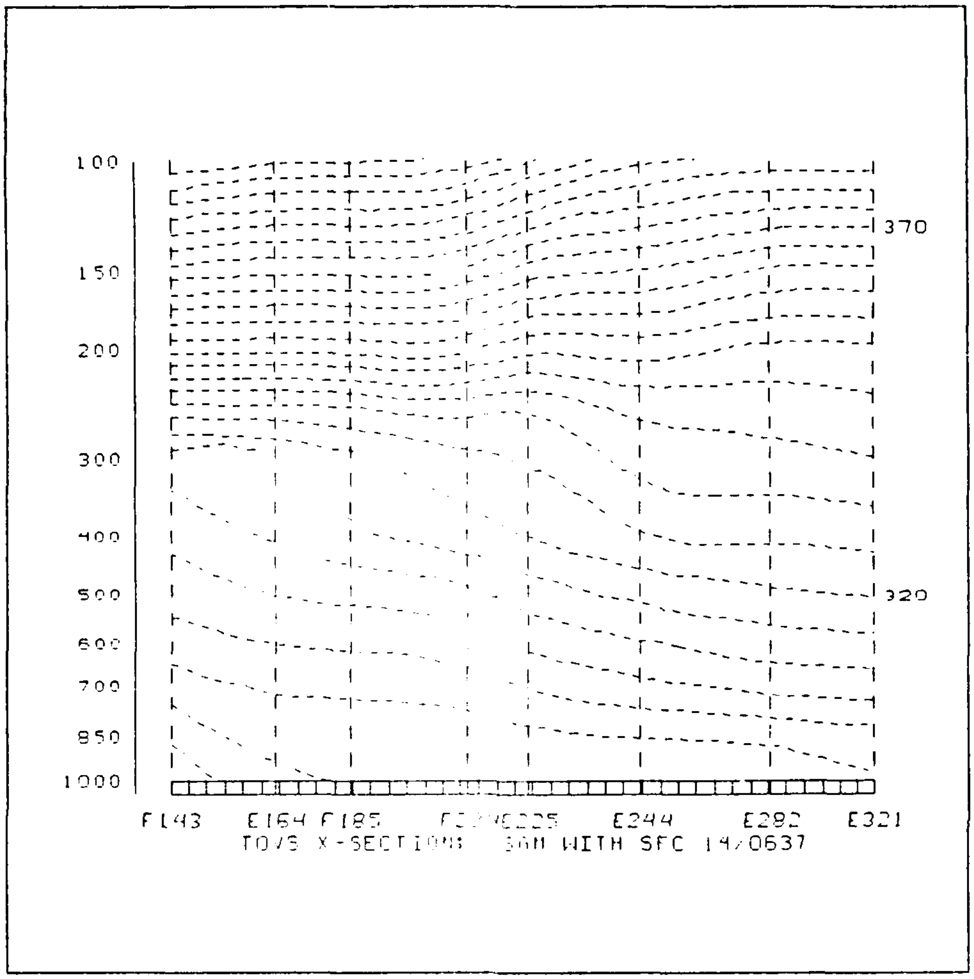


Fig. 29. TOVS cross section over developing cyclone at 0637 UTC 14 December 1988. Cross section extends from E143 (41°N 67°W) to E321 (30°N 63°W).

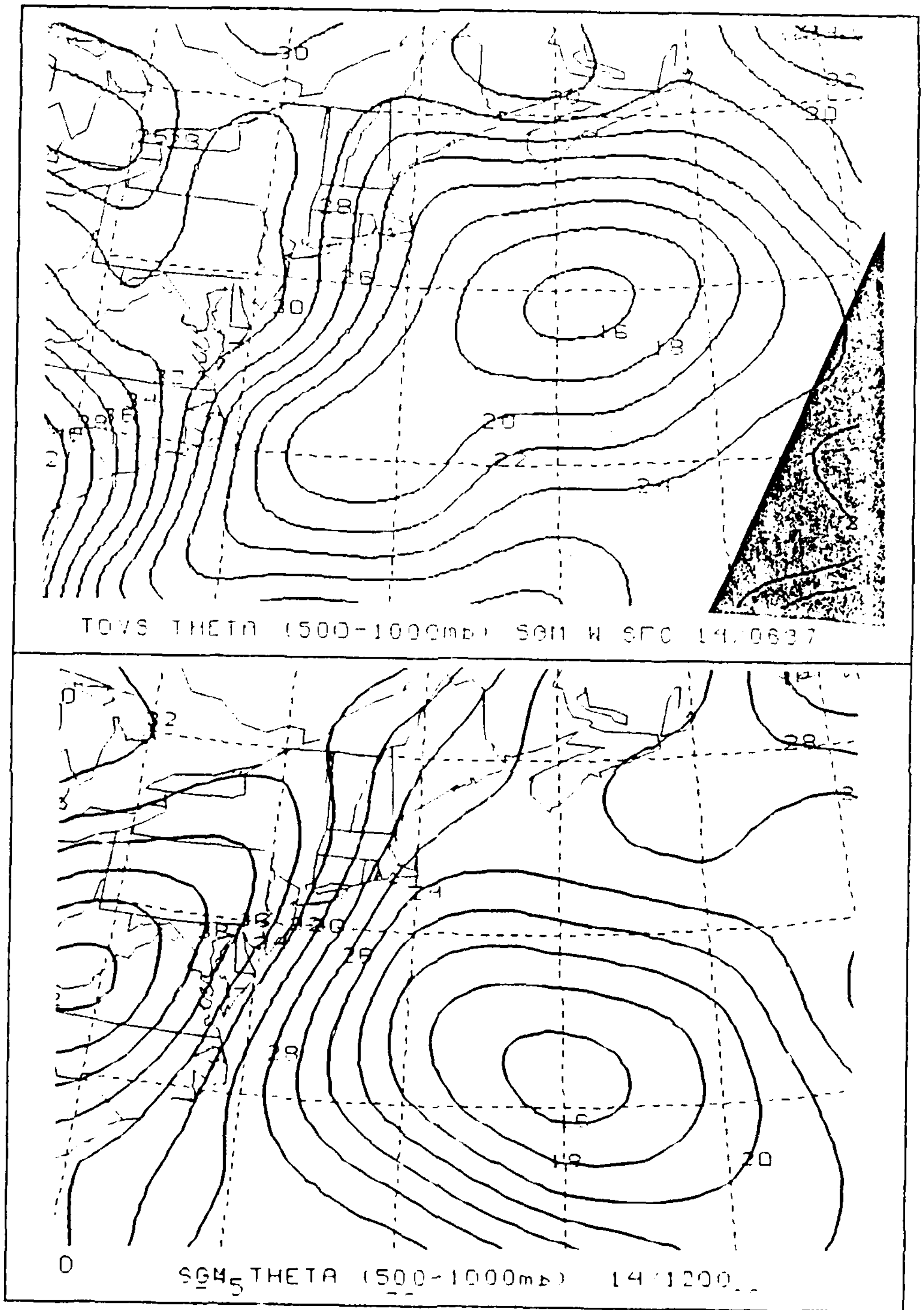


Fig. 30. Same as Fig. 15 except for TOVS data at 0637 UTC 14 December 1988 and NMC data at 1200 UTC 14 December 1988. Fig. 30a shows the TOVS stability analysis. Fig. 30b shows the SGM stability analysis.

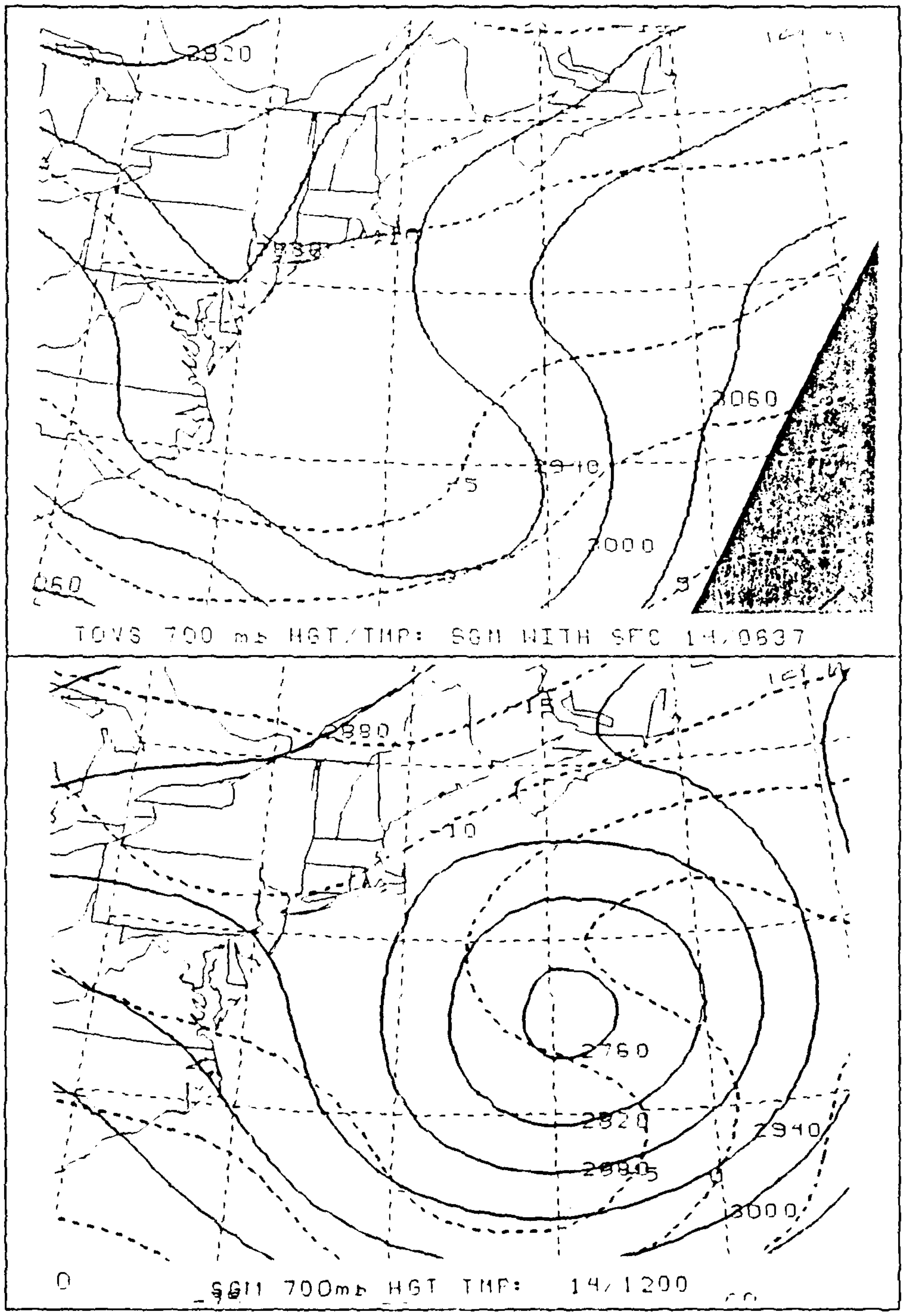


Fig. 31. Same as Fig. 16 except for TOVS data at 0637 UTC 14 December 1988 and NMC data at 1200 UTC 14 December 1988. Fig 31a shows the TOVS 700 mb analyses. Fig. 31b shows the SGM 700 mb analyses.

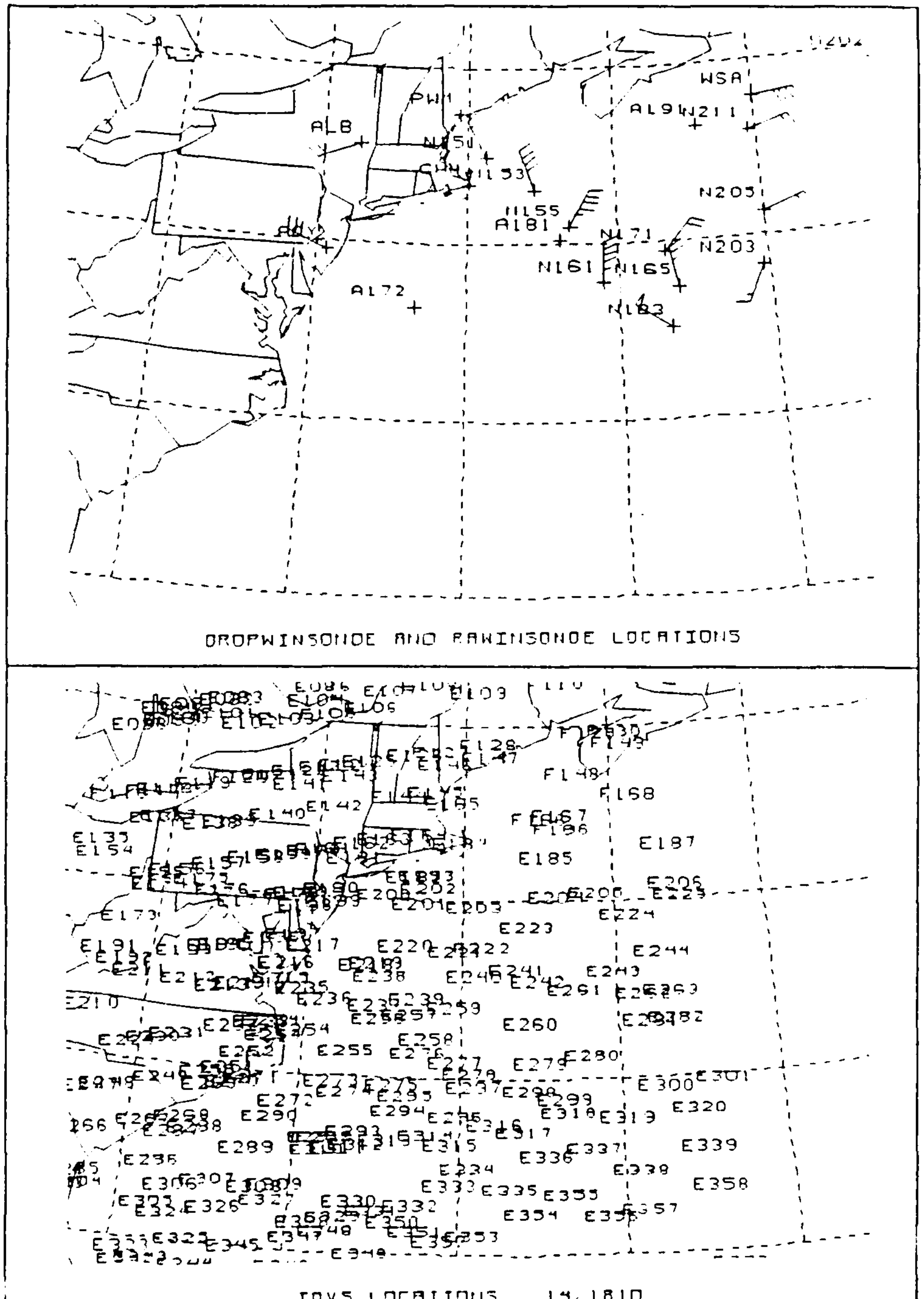


Fig. 32. Rawinsonde and dropwindsonde locations at 1500-2100 UTC and collocated TOVS soundings at 1810 UTC 14 December 1988. Fig. 32a shows rawinsonde and dropwindsonde locations. Fig. 32b shows TOVS sounding locations.

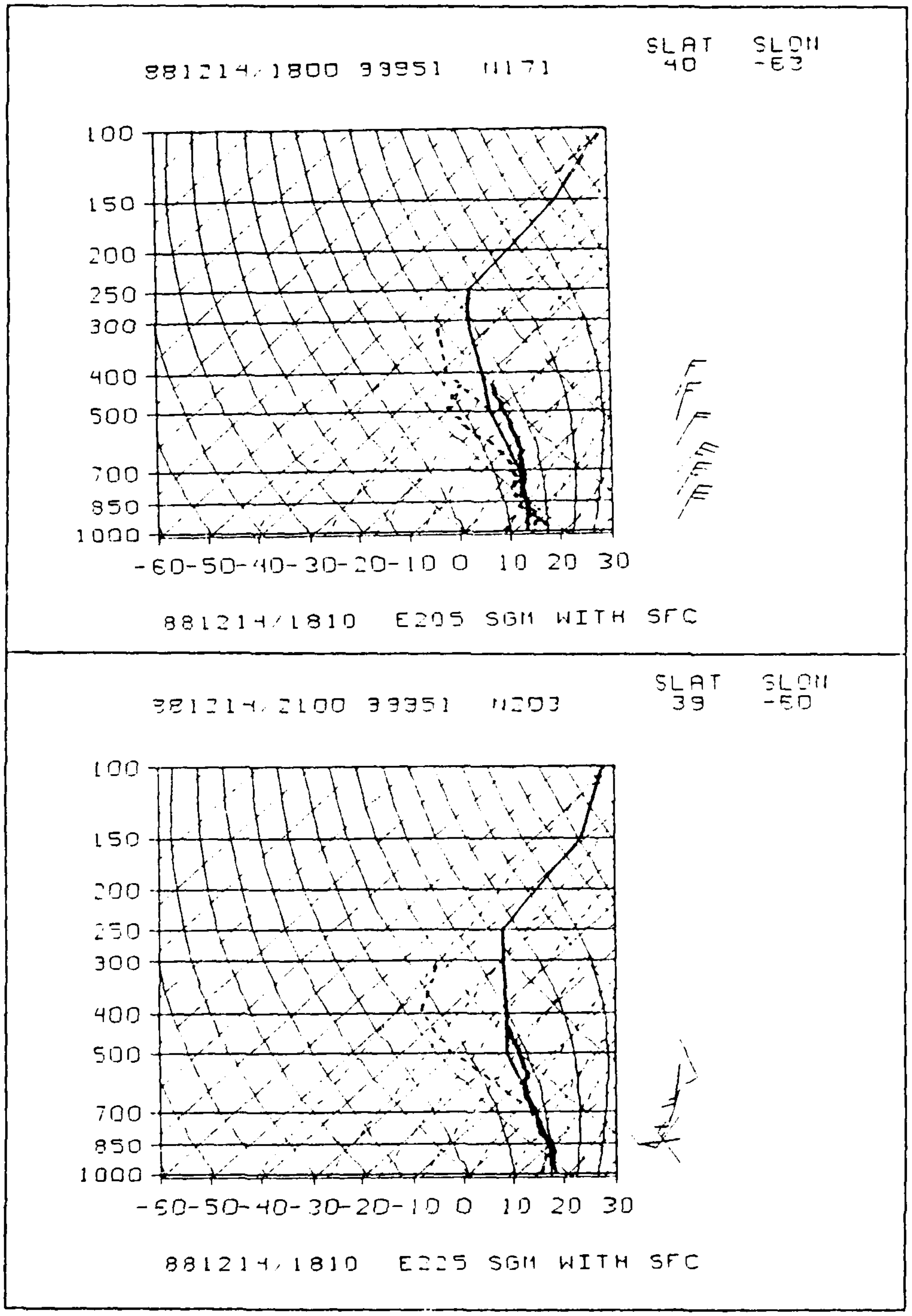


Fig. 33. Dropwindsondes N171 and N203 with collocated TOVS profiles E205 and E225. Fig. 33a shows the difference between N171 and E205. Fig. 33b shows N203 and E225.

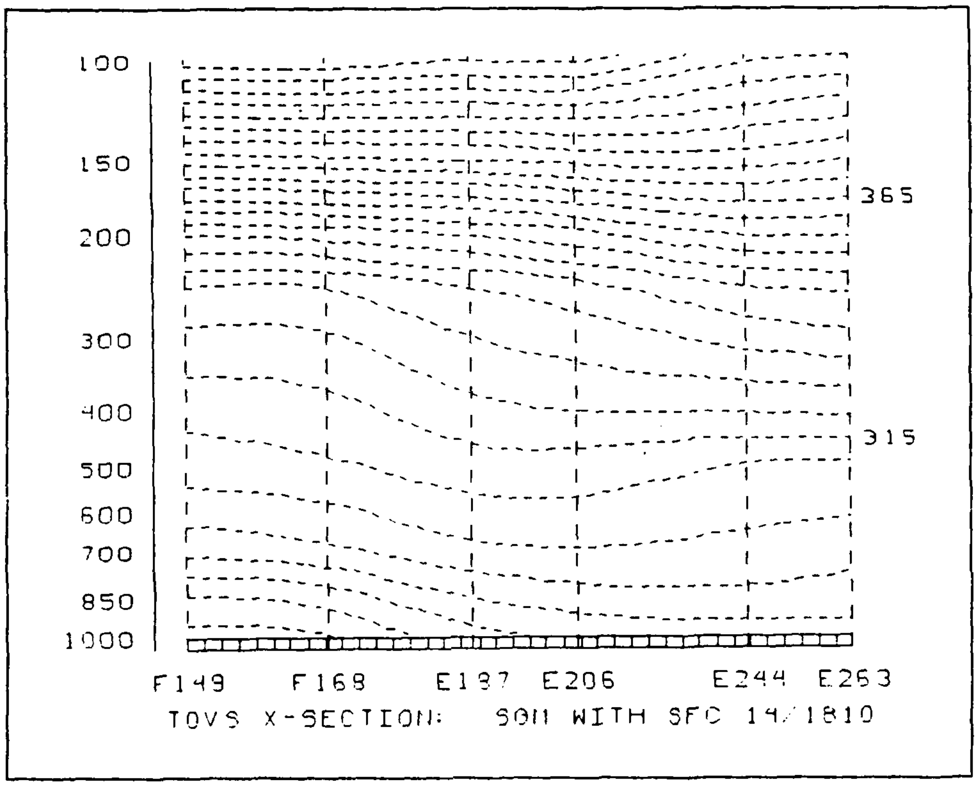


Fig. 34. TOVS cross section over developing cyclone at 1810 UTC 14 December 1988. Cross section extends from F149 (44°N 63°W) to E263 (37°N 62°W).

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Naval Postgraduate School
Monterey, CA 93943-5000

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Code 4380
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