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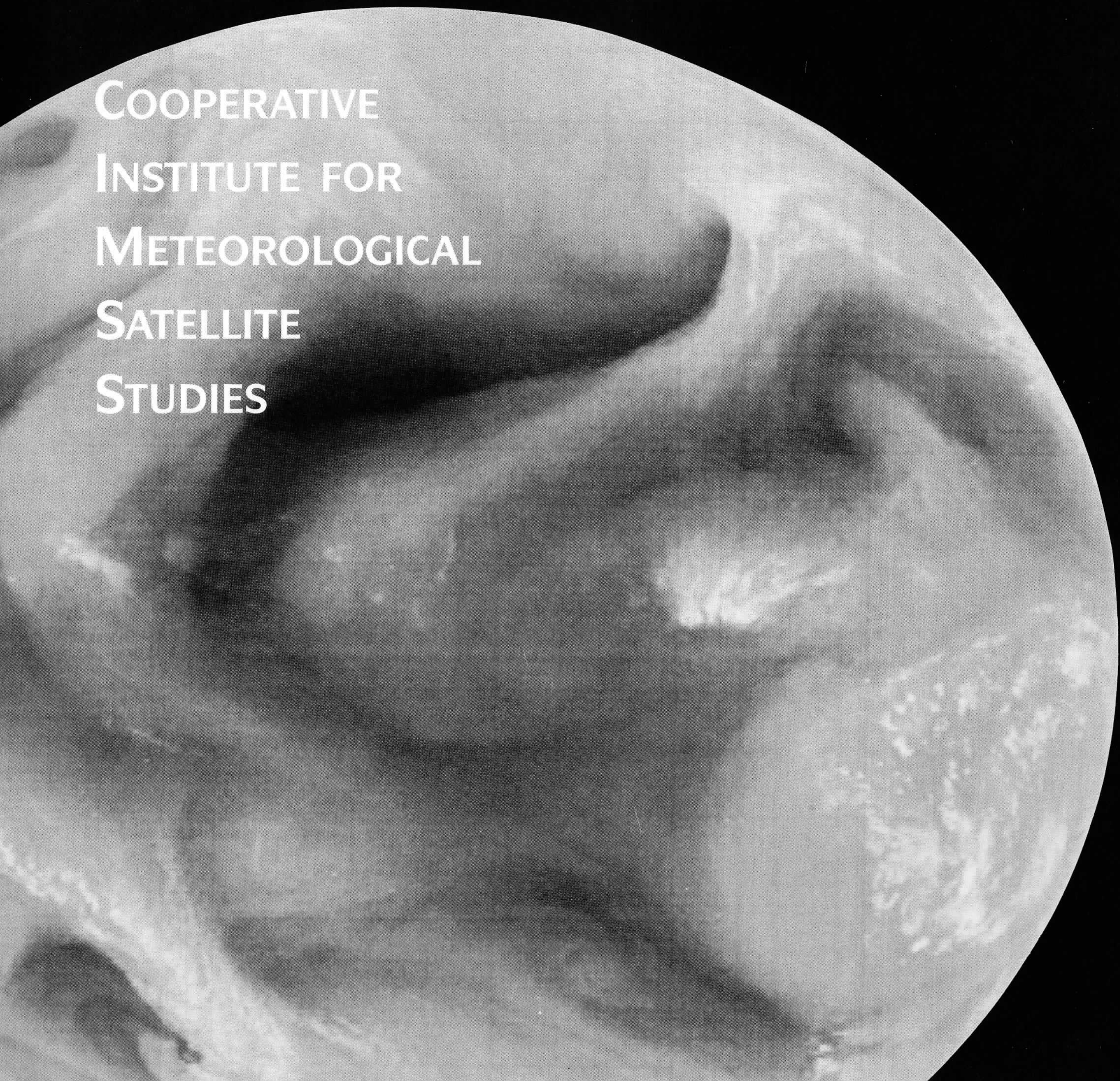
University of Wisconsin–Madison

A COMPARISON OF SATELLITE DERIVED THERMAL-GRADIENT WINDS AND RADIOSONDE WINDS AT MANDATORY ATMOSPHERIC LEVELS

A REPORT from the

COOPERATIVE INSTITUTE FOR METEOROLOGICAL SATELLITE STUDIES



A COMPARISON OF SATELLITE DERIVED THERMAL-GRADIENT WINDS AND RADIOSONDE WINDS AT MANDATORY ATMOSPHERIC LEVELS

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1. INTRODUCTION

This report summarizes the results of a comparison of atmospheric winds observed with radiosonde, and winds generated from NOAA polar orbiting weather satellite vertical temperature sounding information. The study collected these data types for 43 cases from October 1992 through March 1993 over the mid United States. The wind data for mandatory atmospheric levels were divided into speed and direction scalar components and statistical comparisons applied. A comprehensive discussion of the methods applied and the ensuing results is provided below.

A Background section discusses the data processing steps required to generate thermal-gradient winds from NOAA polar orbiting weather satellite vertical temperature sounding information. A Data section summarizes characteristics of the wind types and the procedures involved with data accumulation which are relevant to this study. The Methods section discusses steps taken to ensure quality control, prepare the data for statistical comparison, and "fine tune" the algorithms to determine the most relevant output. The Results and Conclusions section presents a summary of the findings and a discussion / interpretation of the results. Finally, a References section provides some relevant literature to this subject.

2. BACKGROUND ON TOVS THERMAL-GRADIENT WINDS

Thermal-gradient winds are generated from vertical temperature information obtained through radiative transfer calculations in the International TOVS Processing Package (ITPP). This section will provide a brief review of the satellite and instrument characteristics, the radiance data used in the calculations, the software modules of the ITPP and the formulation of the gradient wind product.

NOAA Weather Satellites

The first launch in the TIROS-N series occurred in October 1978. Currently the 11th and 12th satellites of the TIROS series are operational. The NOAA weather satellites are in sun-synchronous orbit at an inclination to the equator of 83 degrees and an altitude of 870 km. It's orbital period is 102 minutes, with a 26 degree rotation of the earth per satellite orbit. These orbital characteristics provide for almost full earth coverage from one satellite every 12 hours (there are some gaps near the equator, and overlap near the poles). With two operational satellites, a given geographical location can be viewed four times per day (two ascending and two descending passes, one from each satellite). Figure 1 shows a small window of consecutive orbits of NOAA 12 over the United States for 2 March 1993. Note the descending passes during the morning hours and the ascending passes in the evening hours.

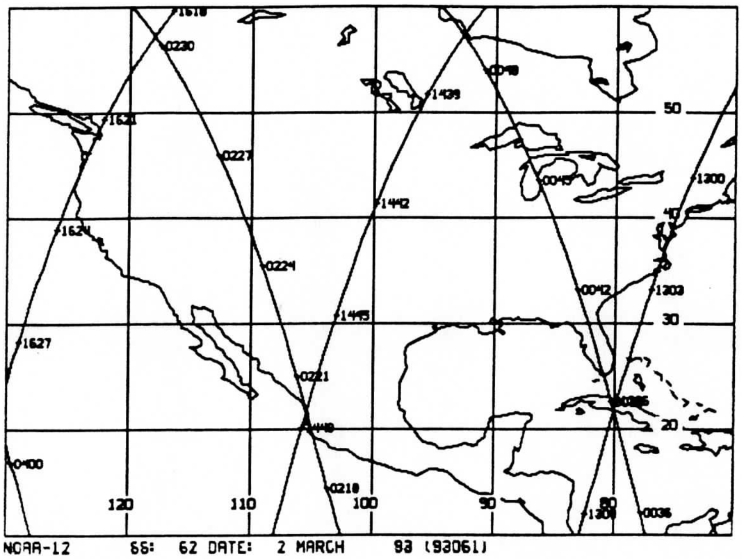

Figure 1. Solid lines indicate sub-satellite point of NOAA 12 for 2 March 1993. Time for a given location (UTC) is given every 5 minutes.

TOVS Instrument Characteristics

The NOAA Weather Satellites carry four radiometers for gathering weather-related data. The Advanced Very High Resolution Radiometer (AVHRR), used primarily as a imager, has 5 spectral channels with nadir resolution of approximately 1 km. The TIROS Operational Vertical Sounder (TOVS) contains three instruments for atmospheric vertical sounding, and other multi-spectral applications (Smith, et. al., 1978). The High resolution Infrared Sounder (HIRS/2) and the Microwave Sounding Unit (MSU) radiances are used in the International TOVS Processing Package; the Stratospheric Sounding Unit (SSU) is also included in the instrument array, but not used in the ITPP, since the measurements are essentially duplicated by HIRS/2. The HIRS/2 and MSU instruments gather radiation emission at 24 spectral intervals (20 HIRS/2 and 4 MSU). Table 1 summarizes the characteristics of these TOVS sounding channels.

There are two main absorption bands in the HIRS/2 instrument configuration used for temperature sounding; near 15 um and near 4 um. The 15 um band is free of reflected solar

Table 1: Characteristics of TOVS sounding channels

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	

radiation (which limits the 4 um band to night time use) but is not as temperature sensitive as the 4 um band. A combination of these two absorption bands (when possible) provides best results. The MSU takes advantage of an Oxygen absorption band near 50 GHz to provide vertical temperature information. Although the microwave measurement does not have as high spatial resolution (110 km at nadir vs. 25 km for HIRS/2), the thermal information provided from this spectral region is not affected by clouds or small raindrops, and thus, gives an "all sky" sounding capability. Taken together, radiances from these three absorption bands will provide vertical sounding information in almost all atmospheric conditions.

ITPP software

The International TOVS Processing Package (ITPP) was developed to provide temperature and moisture sounding information from NOAA polar orbiter weather satellite radiance measurements. The ITPP software modules format, calibrate, and navigate the data, and create files necessary to finally run a physical simultaneous retrieval algorithm to produce vertical profiles of atmospheric temperature and moisture.

The ITPP can operate on direct readout HRPT TIP data or historical 1-B format (tape) data. The three essential operations are software ingest, data preprocessing and retrieval generation. Of importance to this study is the retrieval generation technique, which is discussed in some detail below.

The ITPP retrieval algorithm is a physical simultaneous solution developed by Smith (Smith, et. al., 1985). The algorithm is an iterative technique in that it starts with an initial estimation (guess) of the surface and atmospheric temperature and moisture structure, and applies the TOVS radiances to move towards a more accurate solution. To avoid cloud induced error and excessive dependence on the first guess, an initial iteration is made using only microwave radiances, which yields an "updated" guess over the entire region under consideration. In a second algorithm pass, following several tests for cloud attenuation of HIRS/2 spectral radiances, a final temperature and moisture profile for the atmospheric volume under consideration is achieved.

For the initial or first guess, the ITPP provides a "climatology" or a statistical guess based on a regression relationship between radiosonde and calculated TOVS radiances. The use of a numerical model forecast profile is also possible in the ITPP, but the software connection must be added by the user. Given that the retrieval model iterates toward the final solution, a more detailed initial estimate will likely provide the best results, but even a course guess (such as climatology) will work successfully, particularly if surface data is provided.

The radiative transfer equation relates the radiance measured by a satellite instrument to a combination of surface and atmospheric contributions. By better defining the surface contribution, one can more accurately solve for the integrated atmospheric contribution. Surface temperature and moisture can be determined independently in the ITPP using window channel radiances (4, 11 and 12 um). However, by using available surface reports from national weather services, the surface and lower atmosphere conditions can be more accurately described. With the surface term accurately described, a better estimation of the atmospheric contribution is made, which in turn provides for a more accurate vertical profile. Thus, by using independent surface data, the entire temperature and moisture profile is greatly improved. The inclusion of independent surface data in retrieval processing is highly recommended for all users of the ITPP.

TOVS Gradient winds

The TOVS gradient winds are created as a post-processing product of the temperature and moisture retrieval calculations. During the retrieval processing, a 1000 mb reference level geopotential height field is used with the temperature and moisture information to build geopotential heights for all pressure levels. To calculate the gradient winds, these geopotential heights from sounding retrievals are used to create quasi-horizontal geopotential pressure surfaces (e.g. 500 mb), which are put through a quality control algorithm and smoothing process. From the resulting geopotential fields a gradient wind approximation is applied to calculate a wind at each temperature sounding location that passed the quality control tests. The gradient wind is essentially the geostrophic wind calculated directly from the geopotential field, plus a correction for the curvature of the field. Additional detail is provided in the Methods section below.

3. DATA

The Space Science and Engineering Center (SSEC) has a very extensive atmospheric data base available through direct ingest and communication with other facilities. SSEC has direct readout capability of the U.S. geostationary data, and serves as the national archive for this GOES data. SSEC also receives direct readout of Meteosat (M-4 and M-5), and has an indirect link to acquire GMS geostationary satellite data. National Weather Service data (surface hourlies, radiosondes, profiler, numerical model output) and many other data types are also received directly through a satellite communications link.

The data brought into the SSEC is ingested into the Man-computer Interactive Data Access System (McIDAS, Soumi et. al., 1982) for display and data processing. McIDAS has two major features that make it a powerful scientific tool; the unique hardware design that includes "off the shelf" and SSEC engineered components, and the dynamic suite of scientific software to manipulate and display the extensive data base. For this project, the satellite data, radiosonde, profiler, aircraft, surface and numerical model data were all available through McIDAS.

Global AVHRR (4 km resolution) and TOVS data are routinely available at the SSEC through a geostationary communications link (DOMSAT-Shared Processing). The TIP (TIROS Information Processor) data, which contains AVHRR and TOVS, can be routed to IBM RISC 6000 series computers on which the ITPP is located. Both McIDAS and the IBM 6000 systems contain identical scientific versions of the TOVS temperature and moisture retrieval algorithm. There is difference in data structures and thus file configuration between the TOVS processing software in the two systems. The McIDAS environment has been extensively developed and provides a sophisticated suite of software for image display, comparison of results, plotting and contouring algorithms, and statistical packages. In this study TOVS retrievals were generated on the RISC 6000 and on McIDAS for several cases and compared. Since the temperature and moisture results were essentially the same in these cases (within 0.1 degree), the McIDAS platform was used for the remaining portion of the comparison study.

4. METHODS

This section describes, step by step, the methodology used and the options available in achieving this comparison study. There were several potential "branches" in the methodology, many which were explored and are discussed below.

The first step was selection of a region to do the study. Since it was desired to include NWS wind profiler data in the comparison, the midwestern U.S. is the only available regional candidate. (The current report provides only radiosonde - TOVS wind comparisons.) Figure 2 shows the location of radiosonde sites over the U.S. The NOAA 11 passes over the central U.S. around 2100 UTC ascending and 1000 UTC descending. The NOAA 12 passes over this region around 0100 UTC ascending and 1400 UTC descending. A selection of both satellites and both directions was collected for this study, but the majority of the cases were early morning descending passes from both satellites, since these data were readily available for temperature retrieval processing during that particular day. Appendix A contains a summary of the 43 TOVS passes, with supporting data, that were gathered for this comparison study.

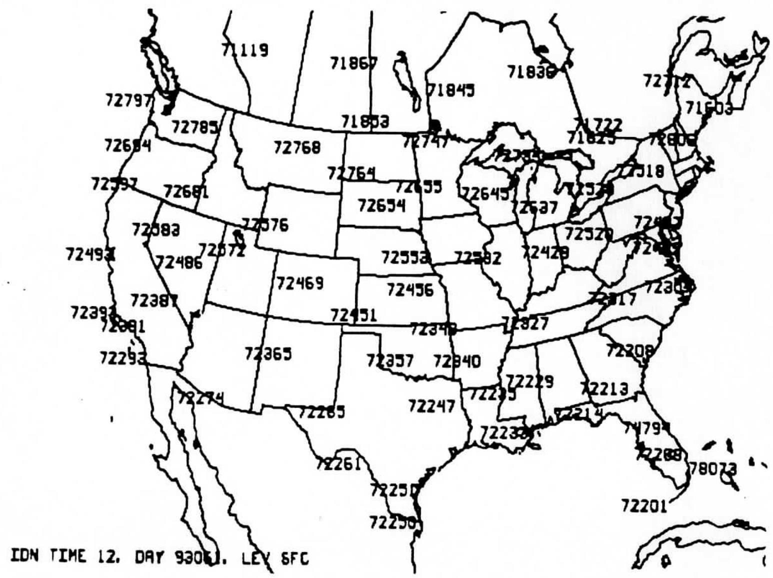

Figure 2. Station identifiers of NWS radiosonde sites that reported at 1200UTC on 2 March 1993.

Data Collection and TOVS Processing:

As the data was collected for each case, the TOVS retrieval processing was performed in near real time. The AVHRR GAC and TOVS data were sub sectored to cover a region from just north of the U.S. - Canadian border to just south of the U.S. - Mexican border. The 11 um window channel from TOVS was imaged on McIDAS to do a visual check for quality control and to provide a general evaluation for the meteorological conditions. If several bad data points existed in the 11 um window channel radiances, the pass was discarded.

Retrieval processing includes creating surface grid files of temperature, moisture and 1000 mb geopotential height from NWS hourly reports, and the creation of the first guess from NMC NGM model forecasts. In all cases a 12 hour forecast was used. The gridded surface data was visually compared with the individual NWS reports for quality control. Several numerical model first guess fields were displayed on McIDAS and visually checked for consistency.

The ITPP temperature and moisture retrieval algorithm was then invoked using the TOVS radiances, the surface grids and the first guess as input. Following the generation of TOVS retrievals, several temperature levels were plotted with matching radiosonde data, and the fields were visually inspected for consistency. These visual inspections serve only as a check against computer operator error, such as introducing the wrong surface or guess information. Following this inspection all data gathered and all data produced were saved to magnetic tape to create an archive. Figure 3a shows a TOVS 11 um image, with retrieval 500 mb temperature plotted in Fig 3b, to indicate the retrieval density (approximately 80 km spacing).

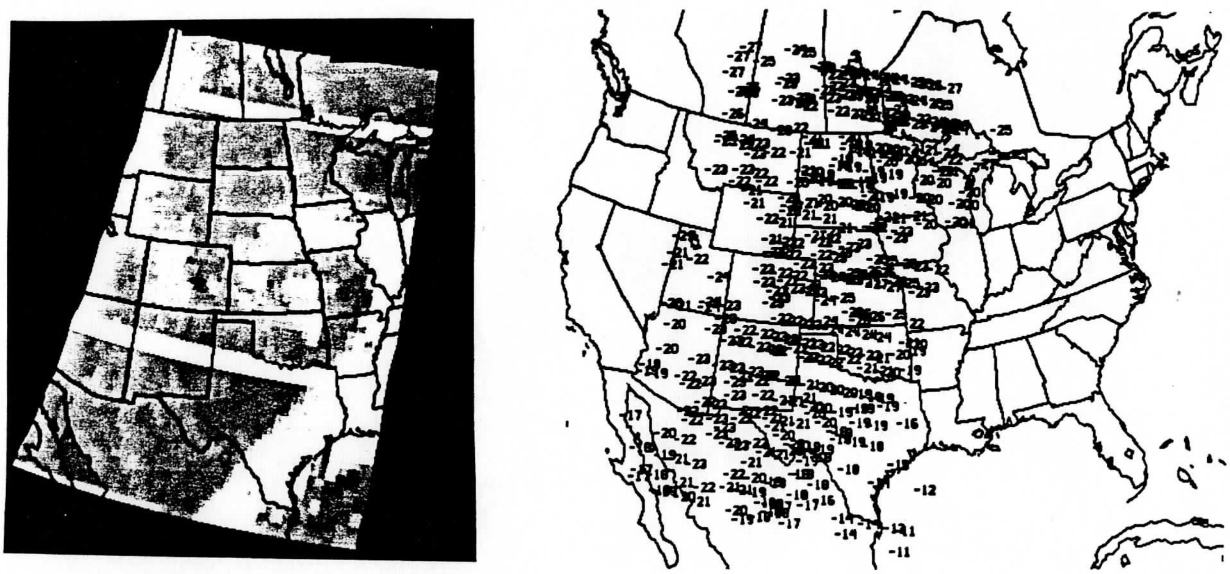

Figure 3. a) TOVS HIRS/2 image of 11 um radiances (band 8) indicating cloud pattern on 2 March 1993. Overpass is from 1438 to 1446 UTC. b) ITPP-derived 500 mb temperature (C) from the same day.

TOVS Winds Generation:

Before the creation of TOVS gradient winds, a quality control step is normally performed to remove any poor quality temperature retrievals. Since satellite instruments like HIRS/2 and MSU actually are measuring the radiative emission over a vertical layer of the atmosphere, geopotential thickness is the best first order calculation to perform quality control on the temperature information. The first step is to create geopotential thickness fields for the layers 1000-700 mb, 700-300 mb, and 300-100 mb. A recursive filter algorithm (Hayden and Purser, 1986, 1988) was used which has been developed primarily to improve grid interpolation techniques, since satellite data has unique characteristics such as gaps in data coverage due to extensive, thick cloud cover. The recursive filter algorithm has several input factors which effect the "smoothing" of the field. For gradient wind calculation it is desirable to remove "bulls-eyes" from the data, which will yield poor quality wind direction. Of course, features such as closed cyclonic circulations must be maintained. Thus, experimentation was done examining several cases to create the most representative field given the density of the data and the relative east-west narrowness of a single TOVS pass.

For quality control the thickness grids are compared with the actual TOVS retrieval thickness values. If the difference between the gridded (plus smoothed) and actual retrieval differs by a certain threshold (15m for 1000-700 mb, 20m for 700-300 mb and 40m for 300-100 mb), the retrieval is flagged as poor quality and not used in gradient wind calculations. The recursive filter algorithm is a recent addition to the ITPP and is available for use with any quantity in the retrieval output file.

Next, geopotential height grids are created, again using the recursive filter algorithm, for mandatory atmospheric levels. Figure 4a shows the TOVS derived 500 mb geopotential height contours. The final data production step is the calculation of the TOVS gradient wind. The height fields derived from TOVS temperature data are used to determine gradient wind values at grid points. For each retrieval location, the grid point value is interpolated and the TOVS retrieval file updated. The final retrieval record thus contains, temperature, moisture, geopotential height and wind speed and direction for each mandatory pressure level. Following gradient wind calculation a final quality control step it taken. TOVS gradients winds are plotted against the contours of the geopotential height and visually inspected, to assure consistency. Figure 4b shows the TOVS 500 mb gradient winds plotted at the retrieval locations. Finally, for purposes of comparison, figure 4c shows the 500 mb geopotential height contours (from radiosonde reports) and radiosonde winds from 1200 UTC for this day.

Winds Comparison:

Following the creation of TOVS gradient winds, the final step is to run a program which compares the two data sets, using one as a standard (radiosonde), and derives a statistical report. The program is run once for speed and once for direction at each mandatory level and the results are stored in a file for each case. To summarize the radiosonde - TOVS winds comparisons for all cases, these files are concatenated to produce 1 file that contains all 43 cases. The statistical report module of the data comparison program will then provide a statistical report for the complete data set.

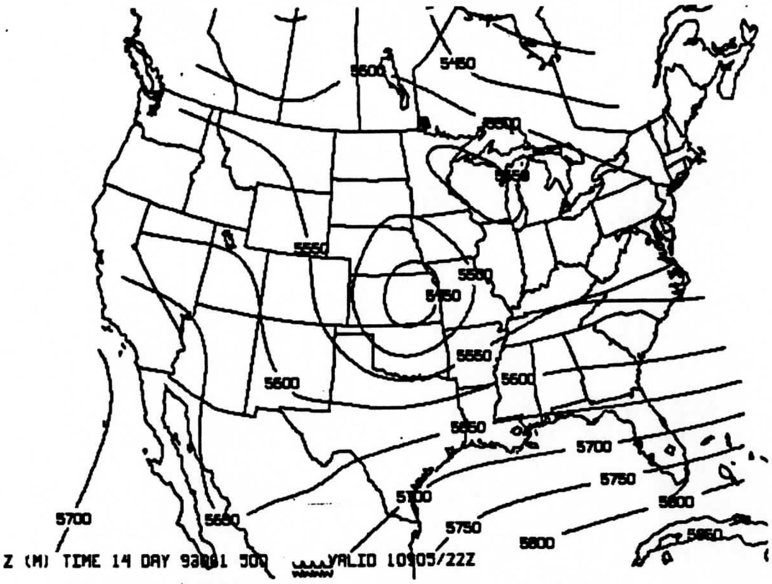

Figure 4a. 500 mb geopotential height (m) from TOVS retrievals on 1448 UTC, 2 March 1993.

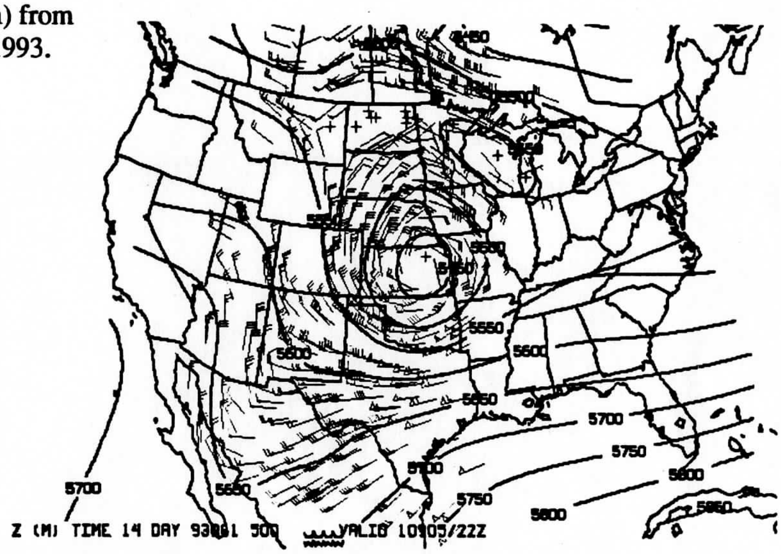

Figure 4b. Same as 4a with TOVS gradient winds added.

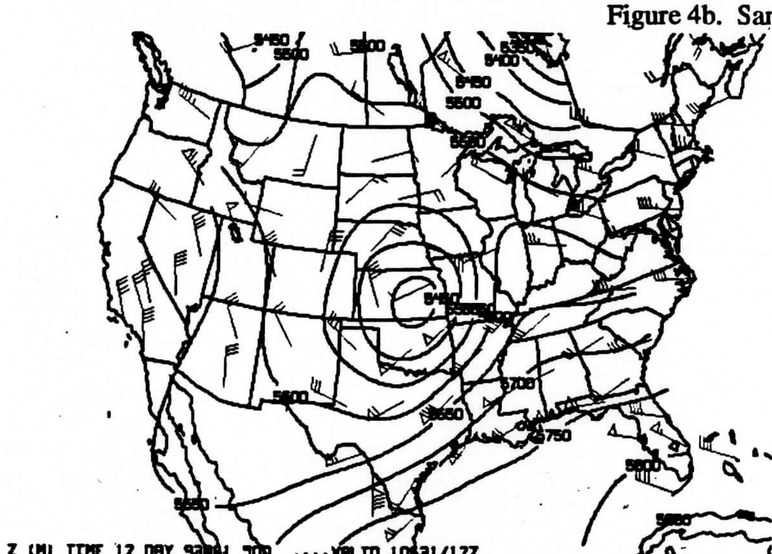

Figure 4c. 500 mb geopotential height from radiosonde data and radiosonde winds from 1200 UTC, 2 March 1993.

There are several parameters within the data base that can be selected to sort on limits to help evaluate the comparisons. These sorting limits essentially provide freedom to decide what matches provide the most accurate representation of the comparison. These comparison sorting parameters include:

a) time between comparisons,

b) horizontal distance between comparisons, and

c) minimum / maximum speed limits

The NOAA 11 and 12 passes normally cross the midwestern U.S. within 2-3 hours of radiosonde launch time. The time it takes the satellite to pass above the U.S. is less than 10 minutes. However, this time difference is an important source of error, especially in situations where a propagating trough or ridge axis is present within the TOVS overpass domain.

The initial statistical comparison program was run with the horizontal distance maximum of 2 degrees (around 110 km). This data set gave what we considered a compilation of all possible realistic matches. The TOVS retrieval algorithm uses a 3 x 3 field of view matrix to make one temperature retrieval. Since the nominal TOVS footprint is approximately 25 km at nadir, growing slightly as scan angle increases, the average horizontal coverage of the retrieval is about 80 km. That is, the TOVS retrieval describes a volume 80 km on a side. A horizontal match distance of 1.5 deg. best fits the TOVS retrieval volume, and was used to generate the final results given below. It is also the match distance selected in previous studies of this type (Lord, et. al., 1984).

The final comparison sorting parameter used in this study is wind speed. It is known that winds normally increase with height. Since atmospheric upper air anticyclones produce light and variable winds, and taking in to account the time and space differences already noted, it was found that wind direction statistics suffered from large errors in light wind cases that would distort the representativeness of the entire sample. Thus, in the final wind evaluation, winds less than 5 m/s were excluded from the comparison at 1000, 850 and 700 mb, and winds less than 10 m/s were excluded at 500, 400, 300 and 250 mb. It was decided that the wind speed should use the same sorting parameters as wind direction to maintain consistency with the wind direction data set comparison; thus the same sorting limit was applied to wind speed and direction.

5. RESULTS AND CONCLUSIONS

The procedure described above was conducted on 43 cases of TOVS and radiosonde data over the midwestern U.S. from October 1992 to March 1993. Appendix A contains a summary of the cases used in this study. Figures 5a and 5b show graphically the resultant RMSD for the wind speed and direction for all cases.

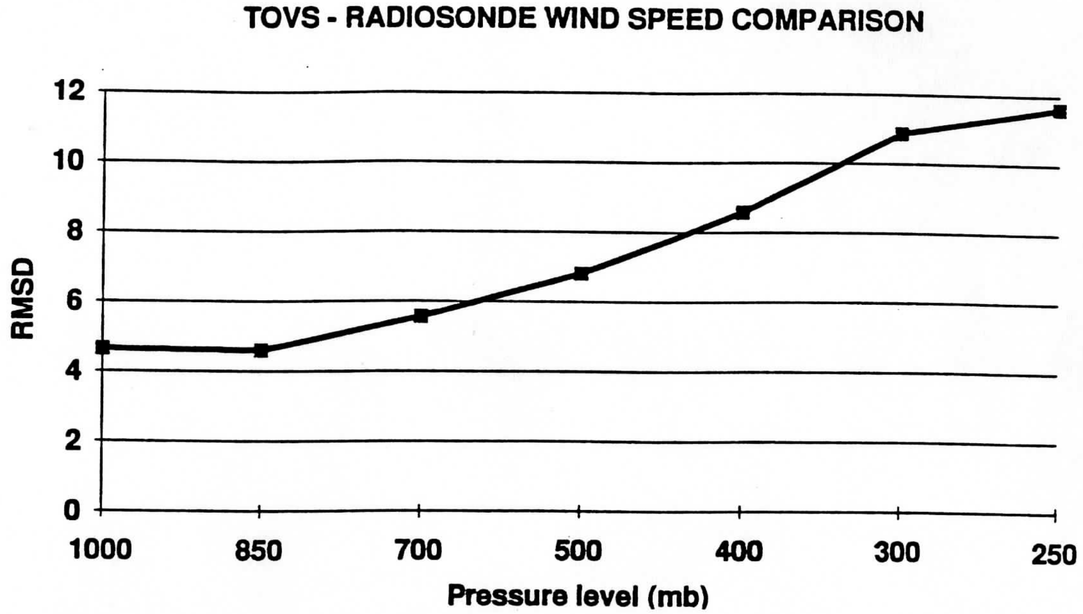

Figure 5a. RMSD values of wind speed at mandatory pressure levels for 43 cases of TOVS-Radiosonde comparisons

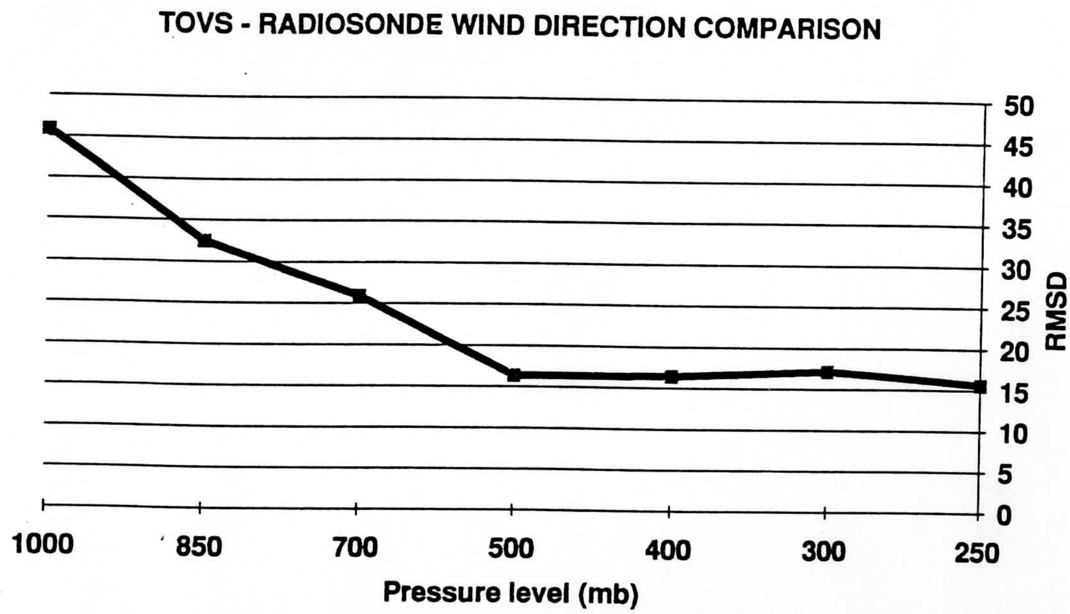

Figure 5b. RMSD values of wind direction at mandatory pressure levels for 43 cases of TOVS-Radiosonde comparisons

A more detailed presentation of the statistical results is given in Table 2 below, which shows results obtained using the procedures described above for all mandatory levels. Included in Table 2 is the following information:

NUMBER OF COMPARISONS: Number of Raodiosonde-TOVS matches that make up the statistical sample

RAOB AVE: Radiosonde average wind speed (direction)

RAOB SIGMA: Radiosonde standard deviation

TOVS AVE: TOVS average gradient wind speed (direction)

TOVS SIGMA: TOVS standard deviation

BIAS: the average difference between matches (positive value means TOVS is faster (speed) or a great number of degrees (direction)

RMSD: root mean square difference of the two samples

RMSE: root mean square error of the two samples

CC: Correlation Coefficient

Table 2

Accumulated Statistics for TOVS Vgr - Radiosonde Comparison: All Cases

SPD 1000

NUMBER OF COMPARISONS = 240		
RAOB & TOVS AVE	7.38	9.11
RAOB & TOVS SIGMA	1.83	4.59
BIAS =	1.73	
RMSD =	4.65	
RMSE =	4.97	
CC=	0.17	

DIR 1000

NUMBER OF COMPARISONS =240		
RAOB & TOVS AVE	199.70	196.23
RAOB & TOVS SIGMA	92.75	79.61
BIAS =	26.52	
RMSD =	45.87	
RMSE =	52.99	
CC=	0.51	

SPD 850

NUMBER OF COMPARISONS =2427		
RAOB & TOVS AVE	12.44	10.09
RAOB & TOVS SIGMA	5.08	4.69
BIAS =	-2.36	
RMSD =	4.60	
RMSE =	5.16	
CC =	0.56	

DIR 850

NUMBER OF COMPARISONS =2427		
RAOB & TOVS AVE	243.41	247.55
RAOB & TOVS SIGMA	70.46	63.56
BIAS =	1.02	
RMSD =	32.48	
RMSE =	32.50	
CC =	0.55	

SPD 700

NUMBER OF COMPARISONS= 3025		
RAOB & TOVS AVE	14.95	14.09
RAOB & TOVS SIGMA	6.57	6.22
BIAS =	-0.86	
RMSD =	5.57	
RMSE =	5.63	
CC =	0.62	

DIR 700

NUMBER OF COMPARISONS= 3025		
RAOB & TOVS AVE	256.38	256.11
RAOB & TOVS SIGMA	49.33	46.35
BIAS =	-0.74	
RMSD =	25.87	
RMSE =	25.88	
CC =	0.58	

SPD 500

NUMBER OF COMPARISONS= 2902		
RAOB & TOVS AVE	25.02	23.78
RAOB & TOVS SIGMA	9.45	9.62
BIAS =	-1.24	
RMSD =	6.81	
RMSE =	6.92	
CC =	0.74	

DIR 500

NUMBER OF COMPARISONS= 2902		
RAOB & TOVS AVE	255.94	255.43
RAOB & TOVS SIGMA	38.08	36.93
BIAS =	-0.01	
RMSD =	16.34	
RMSE =	16.34	
CC =	0.78	

SPD 400

NUMBER OF COMPARISONS= 2949		
RAOB & TOVS AVE	30.38	29.05
RAOB & TOVS SIGMA	11.92	11.98
BIAS =	-1.33	
RMSD =	8.58	
RMSE =	8.68	
CC =	0.74	

DIR 400

NUMBER OF COMPARISONS= 2949		
RAOB & TOVS AVE	252.09	253.50
RAOB & TOVS SIGMA	38.65	34.77
BIAS =	0.80	
RMSD =	16.41	
RMSE =	16.43	
CC =	0.71	

SPD 300

NUMBER OF COMPARISONS= 2970		
RAOB & TOVS AVE	36.46	34.06
RAOB & TOVS SIGMA	14.82	14.07
BIAS =	-2.40	
RMSD =	10.87	
RMSE =	11.13	
CC =	0.72	

DIR 300

NUMBER OF COMPARISONS= 2970		
RAOB & TOVS AVE	250.98	251.28
RAOB & TOVS SIGMA	42.21	37.27
BIAS =	-2.01	
RMSD =	17.17	
RMSE =	17.28	
CC =	0.64	

SPD 250

NUMBER OF COMPARISONS= 2601		
RAOB & TOVS AVE	38.79	35.68
RAOB & TOVS SIGMA	16.05	14.27
BIAS =	-3.10	
RMSD =	11.64	
RMSE =	12.04	
CC =	0.71	

DIR 250

NUMBER OF COMPARISONS= 2601		
RAOB & TOVS AVE	252.14	253.18
RAOB & TOVS SIGMA	41.72	35.96
BIAS =	-0.49	
RMSD =	15.59	
RMSE =	15.60	
CC =	0.69	

A total of over 31,000 comparisons were achieved in this 43 case study. When the sorting restrictions were applied (no time limit, 1.5 degree horizontal distance and the 5 or 10 m/s speed minimum) the number of comparisons applied in the statistic report for each level were,

Level	Number
1000 mb	240
850 mb	2,427
700 mb	3,025
500 mb	2,902
400 mb	2,949
300 mb	2,970
200 mb	2,601
Total	17,114

At the 1000 mb level there were relatively few comparisons, since this level is often below the surface in the high plains or during low atmospheric pressure. When there are comparisons at 1000 mb, they are often near the surface, and thus the wind speed and direction are prone to be affected by topography. For this reason the wind direction RMSD is very large at 1000 mb and the bias is not worthy of note. Since wind speeds are relatively light at near surface levels, the wind speed RMSD is smaller than higher atmospheric levels.

At the 850 mb level the number of comparisons rises to over 2,000. There are somewhat less comparisons than at higher levels because some higher elevation stations in a few of the TOVS passes did not report 850 mb data. The wind speed RMSD is about the same as the 1000 mb value, although the average wind speed rises from about 8 m/s to around 11 m/s. This seems to indicate that getting away from surface effects creates a relative improvement in wind speed accuracy from TOVS. The wind direction accuracy is also improved. The bias becomes very small as atmospheric flow becomes more geostrophic/gradient. The RMSD for direction is still large at this level, probably because of the influence of closed atmospheric circulations in the lower troposphere and the time difference between radiosonde launches and the NOAA satellite overpasses. This time difference in closed circulations will significantly distort wind direction comparisons.

At the 700 mb level the number of comparisons peaks at slightly greater than 3,000. The speed bias shows TOVS is slightly slower than radiosonde. In fact there is a slow bias to TOVS gradient winds at all levels except 1000 mb. Although this wind speed bias is relatively small at all levels except 300 mb and 250 mb, this may be a case where the TOVS gradient wind software can be adjusted (improved) to remove the bias. The wind speed RMSD is about 1 m/s higher

(5.57 m/s) than at 850 mb (4.6 m/s). The wind direction RMSD remained high, likely due to the relatively frequent occurrence of closed circulations at 700 mb.

The 500 mb level (and 700 mb) are the most commonly used atmospheric levels for wind comparison studies. The thin ribbon of strong jet stream winds and the lower polar tropopause do not affect these levels, and these levels are high enough (especially 500 mb) that closed circulations are less common. Thus for winds comparison, the 500 mb level is perhaps the best indicator of accuracy. In this study the average wind speed for 2,902 comparisons was just over 24 m/s, with a slow TOVS bias of 1.24 m/s, about 4% of the wind speed. The wind speed RMSD increases from the 700 mb level to the 500 mb level, from 5.57 m/s (700 mb) to 6.81 m/s (500 mb). The correlation coefficient also increases to 0.74 at 500 mb, reaching its peak value (along with 400 mb) for this comparison study. The wind direction bias is very small at 500 mb (-0.01) and the direction RMSD decreases from 25.87 degrees at 700 mb to 16.34 degrees at 500 mb. As the winds become more generally westerly at higher tropospheric levels, the tendency is for the wind direction RMSD to decrease, then level off at 500 mb and above.

The 400 mb level exhibits characteristics very similar to 500 mb. Wind speeds are somewhat stronger, the bias increases very slightly, and the wind speed RMSD is larger. The correlation coefficient remains the same (0.74) as 500 mb. The wind direction bias is larger at this level (0.80), but the RMSD for direction remains about the same. The correlation coefficient for direction decreases from its highest value (0.78) at 500 mb to 0.71.

At the 300 mb level wind speeds continue to rise to an average of near 35 m/s. With the stronger wind speeds from 700 to 500 to 400 to 300 mb, the bias and the speed RMSD all rise in response to the increase. The direction bias increases and changes sign, but the RMSD for direction increases only slightly.

The 250 mb level is very similar to the 300 mb level. There is a slight increase in wind speed, bias and RMSD. Wind direction bias and RMSD decrease and the correlation increases.

In summary, the large sample size has brought out several expected characteristics, discussed above, which lend confidence to the algorithm, the data used and the methods of the study. It also brings confidence to the speed and direction bias, RMSD and correlation results. It should be noted that the vast majority of these cases were taken during the winter season over the U.S., and thus during a period when strong closed circulations and jet stream winds are present. This has undoubtedly biased the sample towards stronger winds and greater RMSD differences that go with deep circulations.

The results achieved here can now be used as a benchmark to work on improving the TOVS gradient wind algorithm software. There are essentially two ways the TOVS gradient winds can be improved; first to improve the temperature and moisture profiles from which the geopotential height and the gradient wind is calculated. This is an ongoing process at CIMSS; however, a major upgrade to the software is nearing completion and ITPP v5.0 will be released in late 1993. These case studies will be used to evaluate the software changes to ITPP v5.0. The second method to improve the winds is to re-examine the gradient wind calculation software, and work to adjust for the bias. There are several steps in the wind generation process that can be further studied (e.g. recursive filter algorithm, automated quality control). More work will be done in this regard.

Daily Comparison of 500 mb Winds

It is also insightful to look at the distribution of wind comparisons for the 43 individual days. One level, 500 mb, is displayed in Table 3, with the same values as Table 2, except for the individual days at 500 mb instead of multiple levels for all days combined.

Examining the speed bias, one can see that the overall slow (negative) bias of the TOVS gradient winds is due to several occasions when the daily bias was very large (case 1, 13, 17, 20, 31, 35, and 38 through 40). However, the wind speed RMSD is not significantly higher in those cases, so one cannot attribute the bias to cases of extremely strong winds. Also, for the cases with a high speed bias, several of them show a strong direction RMSD, which may indicate closed circulation and/or strong curvature may lead to speed bias. However, several cases near the end of the study have large speed bias but do not exhibit the large directional RMSD.

The speed RMSD ranges from 3.88 m/s (case 4) to 10.75 m/s (case 33). It is interesting that the directional RMSD decreased significantly during the last 10 cases. By examining the wind fields, it was found that this period was one of strong zonal flow over the U.S. with embedded short waves moving quickly through the mid U.S. Thus, for these cases the wind direction did not vary as greatly as with deeper, more closed circulations.

Table 3: 500 mb Winds Comparison for Individual Days

(positive Bias is greater TOVS Vgr speed and direction)

						SPD	SPD			DIR	DIR	
				No.	BIAS	RMSD	RMSE	CC	BIAS	RMSD	RMSE	CC
Case	Day	Sat	Time		500 mb				500 mb			
1	92279	12	1400	38	-4.36	5.01	6.64	0.25	-15.21	23.15	27.70	0.99
2	92281	12	1034	63	-1.71	6.19	6.42	0.50	-4.30	29.50	29.81	0.49
3	92287	12	1430	57	-0.23	6.56	6.56	0.59	-12.53	21.11	24.54	-0.01
4	92288	12	1408	64	1.02	3.88	4.01	0.87	3.30	13.36	13.76	0.81
5	92289	12	1038	80	2.18	6.13	6.51	0.69	1.59	17.82	17.89	0.60
6	92301	12	0953	54	-0.17	4.00	4.01	0.49	-2.69	16.46	16.68	0.56
7	92315	12	1433	69	-0.40	6.28	6.29	0.66	0.88	14.28	14.30	0.42
8	92316	11	1013	46	-2.29	6.17	6.59	0.59	10.13	14.48	17.67	0.94
9	92316	12	1412	50	-2.10	6.67	6.99	0.53	-0.04	15.87	15.87	0.54
10	92317	11	2127	71	0.21	5.13	5.13	0.85	1.77	12.22	12.35	0.76
11	92323	12	0141	67	-1.69	4.61	4.91	0.73	1.07	13.70	13.75	0.69
12	92325	11	1005	62	-1.12	4.59	4.73	0.57	0.32	23.63	23.63	0.71
13	92337	12	1044	87	-4.90	7.51	8.97	0.77	-1.26	29.98	30.00	0.61
14	92339	11	1420	78	-0.71	6.59	6.63	0.79	1.00	12.04	12.08	0.71
15	92342	12	0058	86	-2.11	7.17	7.47	0.79	-0.47	12.19	12.20	0.75
16	92343	11	2114	72	-0.51	5.13	5.16	0.46	-1.96	14.83	14.96	0.89
17	92344	12	1413	49	-3.56	8.29	9.02	0.43	-1.18	23.51	23.54	0.75
18	92347	12	0050	87	-2.12	5.35	5.75	0.83	-1.69	17.36	17.44	0.56
19	92351	12	1505	56	-2.18	8.43	8.70	0.55	-1.05	18.93	18.96	0.89
20	92349	11	1018	55	-5.94	6.94	9.14	0.58	-9.78	27.34	29.04	-0.54
21	92352	12	1443	64	1.52	6.13	6.31	0.67	-6.94	22.39	23.44	0.21
						SPD	SPD			DIR	DIR	
				No.	BIAS	RMSD	RMSE	CC	BIAS	RMSD	RMSE	CC
Case	Day	Sat	Time		500 mb				500 mb			
22	92353	12	1422	80	1.40	5.03	5.22	0.62	-5.72	11.61	12.95	0.45
23	92355	12	1338	69	-0.51	6.87	6.89	0.86	1.14	11.92	11.98	0.70
24	92356	12	1458	62	-1.66	6.14	6.36	0.55	0.31	18.56	18.56	0.52
25	92357	12	1437	84	1.09	7.12	7.20	0.36	4.17	13.05	13.70	0.67
26	92358	12	1414	85	1.14	5.66	5.77	0.82	1.82	14.29	14.41	0.67
27	92360	12	1331	87	-0.61	5.29	5.32	0.81	-1.29	16.42	16.47	-0.19
28	92361	12	1450	49	-0.74	7.54	7.58	0.45	-2.98	16.73	16.99	0.41
29	92362	12	1429	68	-0.75	6.04	6.09	0.43	-6.26	9.92	11.73	0.23
30	92363	12	1408	67	-2.51	6.76	7.21	0.11	-10.66	11.72	15.84	0.76
31	92365	12	1325	27	-6.49	6.61	9.26	0.20	1.85	12.83	12.96	0.20
32	92366	12	1444	65	0.10	8.03	8.03	0.43	7.34	19.37	20.71	0.50
33	93004	12	1458	81	2.20	10.75	10.97	0.16	1.60	10.46	40.48	0.38
34	93050	12	0116	95	-2.27	8.41	8.71	0.33	5.42	7.35	9.13	0.82
35	93051	12	1453	72	-5.43	5.70	7.87	0.73	3.99	9.09	9.93	0.23
36	93053	11	0153	87	-0.90	6.31	6.37	0.81	2.96	4.78	5.62	0.51
37	93056	11	1039	70	-0.84	7.45	7.50	0.73	1.44	4.63	4.85	0.84
38	93060	11	2116	42	-3.85	7.57	8.50	0.54	2.89	7.41	7.95	0.72
39	93061	11	1119	30	-5.01	5.53	7.46	0.50	3.75	7.84	8.69	0.83
40	93061	12	1438	62	-3.45	6.35	7.23	0.64	3.25	9.53	10.07	0.95
41	93063	11	2221	70	-2.89	6.00	6.66	0.33	5.41	5.73	7.88	0.98
42	93071	11	0916	104	0.39	6.23	6.24	0.79	2.92	6.25	6.90	0.84
43	93071	11	1059	92	-1.88	5.22	5.55	0.69	3.88	7.76	8.67	0.95
	Total for 43 cases			2902	-1.24	6.81	6.92	0.74	-0.01	16.34	16.34	0.78

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APPENDIX A: SUMMARY OF CASES FOR WINDS COMPARISON STUDY

CASE	DATE	JULDAY	TIME	SAT	TIP	RAOB	PROFILER	AIRCRAFT
1	5-Oct-92	92279	1400	N12	N	Y	Y	Y
2	7-Oct-92	92281	1034	N11	N	Y	Y	Y
3	13-Oct-92	92287	1430	N12	Y	Y	Y	Y
4	14-Oct-92	92288	1408	N12	Y	Y	Y	Y
5	15-Oct-92	92289	1038	N11	Y	Y	Y	Y
6	27-Oct-92	92301	0953	N11	Y	Y	Y	N
7	10-Nov-92	92315	1433	N12	Y	Y	Y	Y
8	11-Nov-92	92316	1013	N11	Y	Y	Y	Y
9	11-Nov-92	92316	1412	N12	N	Y	Y	N
10	12-Nov-92	92317	2127	N11	Y	Y	Y	Y
11	18-Nov-92	92323	0141	N12	Y	Y	Y	Y
12	20-Nov-92	92325	1005	N11	Y	Y	Y	Y
13	2-Dec-92	92337	1044	N12	Y	Y	Y	Y
14	4-Dec-92	92339	1420	N11	Y	Y	Y	Y
15	7-Dec-92	92342	0058	N12	Y	Y	Y	Y
16	8-Dec-92	92343	2114	N11	Y	Y	Y	Y
17	9-Dec-92	92344	1413	N12	Y	Y	Y	N
18	12-Dec-92	92347	0050	N12	Y	Y	Y	Y
19	16-Dec-92	92351	1505	N12	Y	Y	Y	Y
20	14-Dec-92	92349	1018	N11	Y	Y	Y	N
21	17-Dec-92	92352	1443	N12	Y	Y	Y	N
CASE	DATE	JULDAY	TIME	SAT	TIP	RAOB	PROF	ACFT
22	18-Dec-92	92353	1422	N12	Y	Y	Y	Y
23	20-Dec-92	92355	1338	N12	Y	Y	Y	Y
24	21-Dec-92	92356	1458	N12	Y	Y	Y	Y
25	22-Dec-93	92357	1437	N12	Y	Y	Y	Y
26	23-Dec-92	92358	1414	N12	Y	Y	Y	N
27	25-Dec-92	92360	1331	N12	Y	Y	Y	N
28	26-Dec-92	92361	1450	N12	Y	Y	Y	N
29	27-Dec-92	92362	1429	N12	Y	Y	Y	N
30	28-Dec-92	92363	1408	N12	Y	Y	Y	N
31	29-Dec-92	92364	1345	N12	Y	Y	Y	N
32	30-Dec-92	92365	1325	N12	Y	Y	Y	N
33	31-Dec-92	92366	1444	N12	Y	Y	Y	N
34	4-Jan-93	93004	1458	N12	Y	Y	Y	N
35	19-Feb-93	93050	0116	N12	Y	Y	N	N
36	20-Feb-93	93051	1453	N12	Y	Y	Y	Y
37	22-Feb-93	93053	0153	N11	Y	Y	Y	Y
38	25-Feb-93	93056	1039	N11	Y	Y	Y	Y
39	1-Mar-93	93060	2116	N11	Y	Y	Y	Y
40	2-Mar-93	93061	1119	N11	Y	Y	Y	Y
41	2-Mar-93	93061	1438	N12	Y	Y	Y	N
42	4-Mar-93	93063	2221	N11	Y	Y	Y	Y
43	12-Mar-93	93071	1059	N11	Y	Y	N	N