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An Examination of the Quality of Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) Extracted Wind and Temperature Data Over Oklahoma Using the Computer-Assisted Artillery Meteorology BattleScale Forecast Model (CAAM BFM)

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A study centered on the Oklahoma area over a 2-month period in April and May of 1998 has been carried out analyzing the accuracy of the temperature and wind speed and direction values derived from both the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) Analysis Package and the International TOVS Processing Package 5.0. A hydrostatic mesoscale model, the Battlescale Forecast Model, part of Computer-Assisted Artillery Meteorology Battlescale Forecast Model, was used for the analysis.

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Preface

In an effort to find new sources of input data for the mesoscale model portion (Battlescale Forecast Model [BFM]) of Computer-Assisted Artillery Meteorology Battlescale Forecast Model (CAAMBFM), two Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) processing packages were utilized to look at the quality of the temperature and wind speed and direction values extracted from TOVS data. BFM, run in two modes, 3-d objective analysis (3dobj) only and the full model, was used to quantify the accuracy of the TOVS data. The 3dobj output wind speed and direction values were compared to data from five wind profiling radars within the Oklahoma region. The objective analysis used TOVS data as input. For the model output, the temperature and wind speed and direction values were compared to the 1200 Universal Time Coordinates (UTC) radiosonde observation from Norman, Oklahoma. The model runs also used TOVS data as input.

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Contents

Preface 1

Acknowledgements 3

Executive Summary 7

1.0 Introduction 9

2.0 Background 13

3.0 **Theory** 17
- 3.1 TOVS Preprocessor 17
- 3.2 Atmospheric Radiance Module.. 18
- 3.3 Stratospheric Mapper.. 18
- 3.4. Retrieval Module 18

4.0 **Processing** 19

5.0 Results 21

6.0 Discussion 29

7.0 Conclusions 33

References 33

Acronyms 35

Appendices
- Appendix A. Earth Location of Satellite Data 37
- Appendix B. Limb Correction.. 43
- Appendix C. Physical Retrieval Model 47

Distribution 51

Tables

1. 3dobj run with profiler radar winds; NOGAPS data not used 21
2. 3dobj run with profiler radar winds; NOGAPS data were used 22
3. CAAMBFM run with OUN raob, using climatology;
NOGAPS data were not used 23
4. CAAMBFM run with OUN raob, using regression;
NOGAPS data were not used 24
5. CAAMBFM run with OUN raob, using climatology;
NOGAPS data were used 25
6. CAAMBFM run with OUN raob, using regression;
NOGAPS data were used 26
7. 3dobj run with wind profiling radar, based on climatology;
NOGAPS data not used 27
8. 3dobj run with wind profiling radar, based on regression;
NOGAPS data not used 27

Executive Summary

A study centered on the Oklahoma area over a 2-month period in April and May of 1998 has been carried out analyzing the accuracy of the temperature and wind speed and direction values derived from both the Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) Analysis Package and the International TOVS Processing Package 5.0. A hydrostatic mesoscale model, the Battlescale Forecast Model (BFM), part of Computer-Assisted Artillery Meteorology Battlescale Forecast Model (CAAMBFM), was used for the analysis. The study was composed of two parts.

1. The accuracy of the wind speed and direction data from TOVS was analyzed using output from the 3-d objective analysis portion of BFM compared to up to five wind profiling radars in Oklahoma.

2. The accuracy of temperature and wind speed and direction data from TOVS was analyzed using the O-h forecast from CAAMBFM compared to the radiosonde observation taken at 1200 Universal time coordinates (UTC) in Norman, Oklahoma.

Theory behind the TOVS extraction process is given in three appendices to this report.

1 .O Introduction

In an effort to investigate new sources of data to serve as input into the Computer-Assisted Artillery Meteorology Battlescale Forecast Model (CAAMBFM), an analysis of the quality of the temperature and wind profiles extracted from Television Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) data has been carried out. This analysis has encompassed TOVS data sets derived from two different versions of the TOVS analysis software. The first software version is the TOVS Analysis Package (TAP) and was part of the software on the commercial SeaSpace computer at the time of this test. The second version is the International TOVS Processing Package (ITPP) 5.0.

The University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (CIMSS) developed both of these software packages. One difference between the ITPP 5.0 software and the SeaSpace TAP is the inclusion of the Thermodynamic Initial Guess Retrieval (TIGR) database in ITPP 5.0. French scientists at their Laboratoire de Meterologie Dynamique du Centre National de la Recherche Scientifique developed TIGR. TIGR is a set of 1800 archived atmospheric profiles classified by latitude and season that were derived from a starting set of 150,000 samples by statistical methods. From these data, coefficients for the regression relations can be determined, thus, yielding better first guess profiles. Another improvement is the ability to incorporate upper air data, and Advanced Very High-Resolution Radiometer (AVHRR) data into the analysis, all of which should generally improve the first guess profiles. The AVHRR data are of considerably higher resolution (1 km) than either the microwave or infrared sounding data. TOVS data have a horizontal resolution of approximately 75 km [1,2,3].

The CAAMBFM can, broadly speaking, be run in two different modes: with or without large-scale initialization data. The TOVS profile extraction process requires the user to decide,

- how the initial guess profiles will be created (climatology or regression) and
- whether the geostrophic/gradient wind component is desired.

Thus, a number of data combinations are possible when TOVS profiles are used as input to the CAAMBFM. Before the TOVS data could be used as input to the CAAMBFM, it was reformatted as a list of soundings, identified by latitude, longitude, and elevation, each with the following parameters.

- measurement
- height
- pressure
- temperature
- dew point temperature
- wind speed
- wind direction

Navy Operational Global Atmospheric Prediction System (NOGAPS) model data were used for the large-scale initialization. When NOGAPS data were used, the CAAMBFM first composites the surface data and TOVS soundings with the NOGAPS data. In addition, an initial field is created consisting of winds with constant direction (derived by averaging the NOGAPS wind directions) but with speeds that vary in the vertical based on the log wind profile. 3-d objective analysis (3dobj) is run on both the large-scale initialization data (in this case NOGAPS) temperature and mixing ratio fields to create the initial potential temperature and moisture fields respectively. This initial field then undergoes a 3-hour (model time) spin-up, whereby the equations of motion are used to "nudge" the initial field toward the composite of the TOVS and NOGAPS data. This creates a so-called O-h analysis field. It is this field of temperatures and wind speed and direction data, which were then compared to the Norman, Oklahoma radiosonde observation (raob) data, which are taken to be truth. Fortunately, there were National Oceanic and Atmosphere Administration (NOAA)-12 and NOAA-14 satellite passes with footprints over the Oklahoma area close to 1200 Universal time

coordinate (UTC) matching up with the daily 1200 UTC raob taken at Norman, Oklahoma.

In addition, wind fields output by the 3dobj portion of the CAAMBFM initialized with TOVS data, were compared with profiler wind data (the number of profilers used for comparisons each day varied between 4 and 5).

2.0 Background

Onboard the NOAA polar-orbiting satellites is the TOVS, which consists of three sounders, the High-resolution Infrared Radiation Sounder (HIRS), the Microwave Sounding Unit (MSU) and the Stratospheric Sounding Unit (SSU). Profiles of various meteorological parameters (the ones of interest here are temperature and wind speed and direction) are generated from the TOVS data by a multi-step process:

1. Create TOVS sensor datasets (TIROS Information Processor [TIP] files) from High Resolution Picture Transmission (HRPT) telemetry data

2. Decommutate HIRS and MSU data from TIP data

3. Calibrate and earth-locate (appendix A) HIRS and MSU data, perform limb-corrections (appendix B) and transform calibrated and earth-located HIRS/MSU data into data sets that can be displayed and retrieved.

4. Use a physical retrieval model (appendix C) to obtain vertical profiles of atmospheric temperature, humidity, geopotential height, and other parameters.

5. Eliminate soundings of questionable reliability by objective analysis of differences between infrared and microwave retrievals for the same location and of variability in 1000 to 500 mb thickness and long wave window versus surface temperature.

6. Determine the geostrophic or gradient wind for "good" soundings in retrieval file by least-squares objective analysis of the height fields. [4]

The domain used for the CAAMBFM runs was a grid of 41 by 41 points, 400 by 400 km, with a grid resolution of 10 km. It is centered in Oklahoma at 35.5 N, 97.5 W. The raob used as truth is the one from University of Oklahoma-Norman (OUN) taken daily at 1200 UTC located at 35.2 N, 97.5 W. The analysis period for the CAAMBFM runs using TOVS data compared with raob data cover 14 days in April and May 1998. Wind data were available

from five profiling radar sites within this domain. These radar systems can measure up to 17 km.

Gridded surface data needed to be created so that some of the TOVS profile extractions within ITPP 5.0 would have "tie-down" points for the first guess profiles. Raobs taken off the Integrated Meteorological System (IMETS) were interpolated to a Mercator grid (one version of a latitude/longitude-based grid) and the weighting factor scaled as

$$1 \text{ (distance from surface report to grid point)}^2 .$$

This method was used to create grids of both ambient temperature and dew point depression. Within the 400 x 400-km Oklahoma grid, approximately a dozen surface stations were reporting. Navy Operational Regional Atmospheric Prediction System (NORAPS) O-h analysis model (gridded) data (0.5" resolution) were used for the 1000 mb heights. Again, the data were interpolated to a Mercator grid using the same type of weighting function. The Mercator grid was created using a FORTRAN program available from the Naval Research Lab (NRL), at Monterey, California accessible through the Internet site, the Master Environment Library (MEL). The final step was to consolidate the Mercator gridded 1000 mb heights, ambient temperature, and dew point depressions into one file. The format required for this surface data are that used by the Man computer Interactive Data Access System (McIDAS) weather information processing and display computer system.

The first step was to extract TOVS sounding data using either the TAP or the ITPP 5.0 software package. As mentioned earlier, the user has several options when starting the extraction process. Among them is whether the user wants the first guess profile to be based on climatology or regression. The wind component generated can be either geostrophic or gradient. The geostrophic component assumes a balance between the horizontal pressure gradient force and the Coriolis force. For the gradient component, a three-way balance between the horizontal pressure gradient force, the Coriolis force, and the centrifugal force is assumed. Also, when using the ITPP 5.0 software the user has the choice of whether or not they want the TOVS extraction to utilize surface data for the first guess profiles as described above. Furthermore,

the user has the option of using the TIGR database. The author has created a shell script called "Run" which makes symbolic links to the requisite data files and to the parameter files which designate whether surface data are used or not, whether the TIGR database is used or not, etc. This shell script causes a list of data files from NOAA-12 and NOAA-14 satellite passes residing on the SeaSpace computer hard disk to be displayed. Upon choosing one, all of the TOVS processing algorithms are run.

3.0 Theory

TOVS soundings are the result of integrating data taken from three sounders: the High-resolution Infrared Radiation Sounding Unit (HIRS/2), the MSU, and the SSU. Four modules control the processing:

1. Preprocessor
2. Atmospheric Radiance Module
3. Stratospheric Mapper
4. Retrieval Module

3.1 TOVS Preprocessor

1. Sensor digital data are converted to radiances.

2. Each scan spot is earth-located.

3. Stratospheric Sounding data are passed on to the Stratospheric Mapper. The SSU does not have as wide a field-of-view as the Infrared and Microwave Sensors. This is compensated for by the Stratospheric Mapper, which holds a global map of SSU radiances (in continual update) on a latitude/longitude grid.

4. The infrared and microwave data are adjusted. Specifically, the microwave data are corrected for antenna side-lobes. Limb correction is also applied to both data types so that each scan can be treated as if taken at nadir. This limb correction is based on regression equations that have been built on synthesized radiance data.

5. The microwave data are interpolated to the scan spots of the HIRS/2 sounder to compensate for its poorer spatial resolution.

6. Initial guess values of skin (i.e., the surface) temperature and surface albedo are made; also, terrain elevation and solar zenith angle values are held for later stages of the processing.

3.2 Atmospheric Radiance Module

1. Provides spatially averaged, clear column radiances to the Retrieval Module.

2. The data are split into boxes:

   a. HIRS/2 cross-track spots

   b. HIRS/2 along-track spots.

3. One sounding is derived from this group of 63 scan spots.

4. The 63 scan spots are tested for cloud contamination.

5. If 4 or more of the 63 scan spots are deemed clear, the clear-column radiances are calculated to be a weighted average of the observed radiances from the clear scan spots.

6. If less than four clear scan spots are located, a more complicated scheme, the "adjacent-pair" technique is employed. It essentially looks for variances in cloud amounts in adjacent scan spots. If four or more good adjacent pairs are located, clear-column radiances are calculated. These soundings are termed "partly cloudy" or "second path" soundings.

7. Finally, if less than four good adjacent pairs are found, then the sounding is "overcast" and the HIRS/2 tropospheric data are not used. Rather, a sounding will be derived based on the MSU, SSU, and the stratospheric HIRS/2 channels. Soundings derived via this branch are called "cloudy" or "third path" soundings.

3.3 Stratospheric Mapper

1. The stratospheric mapper maintains a global map of SSU radiances on a latitude/longitude grid.

2. This map is in a process of continual update pending the arrival of newly sensed data.

3.4 Retrieval Module

This module comes up with the final product, the retrievals, by using the clear column radiances determined from the Atmospheric Radiance Module and the Stratospheric Mapper. It is an iterative scheme developed by Chahine (1970) (appendix C).

4.0 Processing

Once the TOVS binary file is created, the temperature, dew point temperature, and wind information is extracted and reformatted into a file that CAAMBFM can ingest. The CAAMBFM model was then run two different ways so that two comparisons could be made. One method was to run the "full-fledged" model (i.e., all model physics come into play; heretofore termed a CAAMBFM run) and the resultant temperature and wind field was compared to the OUN raob. In the other mode, only the preliminary 3dobj portion was run (heretofore referred as a 3dobj run) and the resultant wind field was compared to data from up to five wind profiling radars.

For each of the CAAMBFM runs, the model was spun-up to the O-h analysis field as described earlier. Then a shell script would automatically perform the following actions:

1. Extract constant pressure levels of the u- and v-components of the wind and the temperature field.

2. Pick out the pressure, height, temperature, wind speed, and wind direction fields from the OUN raob using a pattern-matching script language called "AWK".

3. Calculate the root mean square vector error (rmsve) for the u- and v-components and the root mean square error (rmse) in temperature with the OUN raob being used as truth. These rmsve and temperature rmse values are user-selectable as to what height levels are to be averaged over. Assuming there are good input values at all these heights, one can select from the following height ranges:

   - "low": 925,850 mb
   - "raid": 700, 500, 400 mb
   - "high": 300,250 mb
   - "all": 925 – 250 mb

The equations for the rmsve and the temperature rmse are as follows:

$$rmsve = \sqrt{(\sum_{i=1}^{N}((u_i - u_m)^2 + (v_i - v_m)^2)) / N} \quad (1)$$

where

u_i =the i-th u-component measured by the raob or profiler

u_m =the corresponding u-component output by the model (CAAMBFM)

v_i =the i-th v-component measured by the raob or profiler

v_m =the corresponding v-component output by the model (CAAMBFM)

N = number of measurements

$$\text{temperature rmse} = \sqrt{(\sum_{i=1}^{N}(T_i - T_m)^2) / N} \quad (2)$$

where

T_i = the i-th temperature measured by the raob

T_m = the corresponding temperature output by the model (CAAMBFM)

N = number of measurements

Again, a shell script controlled the processing for the 3dobj runs versus profiler data comparison.

1. Calling a FORTRAN program, which extracts the wind profiler data within our domain of interest and compares it to the wind data from the binary file created by 3dobj.

2. Calling a C program to calculate rmsve errors in the u- and v-components using the profiler data as truth.

5.0 Results

Two software packages were used in this analysis, TAP and ITPP 5.0. Tables 1 through 6 show the results of the analysis using the TAP software, and Tables 7 and 8, the results with the ITPP 5.0 software.

Table 1 shows the comparison of u-, v-components derived from 3dobj run with profiler radar winds, using TAP. NOGAPS data were not used. TOVS profiles are used as input to 3dobj. Climatology and regression refer to the method used to create the first guess profiles.

Table 1. 3dobj run with profiler radar winds; NOGAPS data not used

	Climatology rmsve (m/s)	**Regression rmsve (m/s)**
04-16-98	17.41	15.08
04-21-98	8.40	9.17
04-22-98	5.97	6.38
04-23-98	5.48	5.12
04-30-98	6.23	7.01
05-04-98	12.03	11.76
05-05-98	27.90	27.68
05-07-98	19.43	15.63
05-11-98	8.95	8.81
05-13-98	8.09	11.55
05-19-98	11.75	12.85
05-20-98	5.66	6.24
Mean rmsve	11.44	11.44

Table 2 shows the comparison of u-, v-components derived from 3dobj run with profiler radar winds. NOGAPS data were used in the 3dobj run, using TAP. TOVS profiles are used as input to 3dobj. Climatology and regression refer to the method used to create the first guess profiles.

Table 2. 3dobj run with profiler radar winds; NOGAPS data were used

	Climatology rmsve (m/s)	Regression rmsve (m/s)
04-16-98	9.40	10.13
04-21-98	11.92	14.91
04-22-98	7.93	9.89
04-23-98	6.70	5.93
04-30-98	6.34	9.56
05-04-98	13.06	12.31
05-07-98	17.18	9.23
05-11-98	8.95	9.00
05-13-98	8.20	12.23
05-19-98	12.02	12.58
Meanrmsve	10.17	10.58

Table 3 shows the comparison of temperature and u-, v-components derived from CAAMBFM run with OUN raob. TOVS profiles are used as input to CAAMBFM and the TOVS first guess profiles derived using climatology, using TAP. NOGAPS data were not used in the CAAMBFM runs.

Table 3. CAAMBFM run with OUN raob, using climatology; NOGAPS data were not used

	Low[1] T rmse (deg C)	Low rmsve (m/s)	Mid[2] T rmse (deg C)	Mid rmsve (m/s)	High[3] T rmse (deg C)	High rmsve (m/s)	All[4] T rmse (deg C)	All rmsve (m/s)
04-06-98	8.15	17.69	3.84	16.19	3.28	46.93	5.33	28.83
04-07-98	1.35	11.08	.81		2.37		1.55	
04-08-98	5.79	3.89	2.98	15.23	3.46	22.67	4.10	15.83
04-13-98	4.20	9.75	1.53	14.78	2.55		3.81	
04-14-98	4.64	13.37	1.23	3.80	2.31		2.89	
04-21-98	3.86	13.01	1.18	9.47	3.22	2.24	2.80	9.39
04-22-98	5.69	3.97	3.17	3.26	1.90	9.84	3.82	6.06
04-23-98	1.23	3.90	0.76	5.32	1.60	13.91	1.19	8.47
04-30-98	2.65	2.13	2.25	3.85	5.58	11.03	3.61	6.51
05-04-98	3.69	9.92	1.81	9.03	0.65	21.40	2.33	13.93
05-05-98	0.17	19.87	3.45	20.54	2.94	16.51	2.75	19.28
05-07-98	5.52	8.22	3.27	15.80	5.76		4.77	
05-11-98	2.81	12.59	1.69	6.75	3.44	14.33	2.62	11.11
05-13-98	6.26	9.69	2.38	7.32	7.07	4.96	5.28	7.54
Mean	4.00	9.93	2.17	10.10	3.30	16.38	3.28	12.70

Notes:

[1]Low=925,850 mb

[2]Mid=700,500,400 mb

[3]High=300,250 mb

[4]All=925,850,700,500,400,300,250 mb

Table 4 shows the comparison of temperature and u-, v-components derived from CAAMBFM run with OUN raob. TOVS profiles are used as input to CAAMBFM and the (TAP) TOVS first guess profiles derived using regression, using TAP. NOGAPS data were not used in the CAAMBFM runs.

Table 4. CAAMBFM run with OUN raob, using regression; NOGAPS data were not used

	Low[1] T rmse (deg C)	Low rmsve (m/s)	Mid[2] T rmse (deg C)	Mid rmsve (m/s)	High[3] T rmse (deg C)	High rmsve (m/s)	All[4] T rmse (deg C)	All rmsve (m/s)
04-07-98	1.77	10.05	0.49		3.07		1.92	
04-08-98	5.89	3.88	2.42	17.23	2.80	23.30	3.83	16.93
04-13-98	4.12	9.74	1.83	14.36	1.95		2.72	
04-14-98	5.50	13.23	1.57	3.86	1.71		3.25	
04-21-98	3.92	13.17	1.20	10.73	4.06	7.32	3.11	10.69
04-22-98	5.39	7.50	2.73	4.77	1.41	7.71	3.47	6.54
04-23-98	7.26	5.70	0.44	5.35	3.61	13.86	4.34	8.74
04-30-98	1.39	4.88	1.20	5.80	3.81	8.76	2.31	6.57
05-04-98	3.69	9.23	1.45	6.66	0.34	21.18	2.20	13.10
05-05-98	0.52	16.77	3.39	14.80	1.45	6.86	2.37	13.70
05-07-98	5.78	8.69	2.78	16.22	4.59		4.34	
05-11-98	2.59	13.93	1.63	8.27	1.81	10.80	2.00	10.87
05-13-98	6.61	11.88	3.26	10.72	5.59	8.80	5.10	10.57
Mean	4.19	9.90	1.88	9.90	2.28	12.07	3.15	10.86

Notes:

[1]Low=925,850 mb

[2]Mid=700,500,400 mb

[3]High=300,250 mb

[4]All=925,850,700,500,400,300,250 mb

Table 5 shows the comparison of temperature and u-, v-components derived from CAAMBFM run with OUN raob. TOVS profiles are used as input to CAAMBFM and the (TAP) TOVS first guess profiles derived using climatology, using TAP. NOGAPS data were used in CAAMBFM runs.

Table 5. CAAMBFM run with OUN raob, using climatology; NOGAPS data were used

	Low[1] T rmse (deg C)	Low rmsve (m/s)	Mid[2] T rmse (deg C)	Mid rmsve (m/s)	[3]High T rmse (deg C)	High rmsve (m/s)	[4]All T rmse (deg C)	All rmsve (m/s)
04-07-98	0.51	12.20	0.64		3.27		1.82	
04-08-98	4.33	3.25	2.87	15.99	3.47	24.49	3.51	16.85
04-13-98	4.47	11.05	1.59	14.02	1.63		2.75	
04-21-98	4.07	13.29	1.41	11.34	3.65	7.40	3.06	11.01
04-22-98	5.55	4.45	2.64	3.53	1.43	6.90	3.52	4.96
04-23-98	1.68	2.47	0.30	4.65	2.12	14.60	1.46	8.48
04-30-98	2.18	4.86	1.88	4.09	5.90	11.53	3.58	7.21
05-04-98	3.18	8.04	1.35	9.66	0.66	19.26	1.95	12.83
05-05-98	0.22	15.96	3.22	15.73	0.78	6.51	2.15	13.81
05-07-98	4.22	4.64	2.54	16.76	4.00		3.53	
05-11-98	2.41	12.71	1.56	6.94	1.57	12.11	1.85	10.43
05-13-98	5.93	10.51	2.47	8.24	4.76	3.72	4.37	8.04
Mean	3.23	8.62	1.87	10.09	2.77	11.84	2.80	10.40

Notes:

[1]Low=925,850 mb

[2]Mid=700,500,400 mb

[3]High=300,250 mb

[4]All=925,850,700,500,400,300,250 mb

Table 6 shows the comparison of temperature and u-, v-components derived from CAAMBFM run with OUN raob. TOVS profiles are used as input to CAAMBFM and the TOVS first guess profiles derived, using TAP. NOGAPS data were used in the CAAMBFM runs.

Table 6. CAAMBFM run with OUN raob, using regression; NOGAPS data were used

	Low[1] T rmse (deg C)	Low rmsve (m/s)	Mid[2] T rmse (deg C)	Mid rmsve (m/s)	High[3] T rmse (deg C)	High rmsve (m/s)	All[3] T rmse (deg C)	All rmsve (m/s)
04-07-98	0.97	11.43	0.61		3.93		2.20	
04-08-98	4.18	3.27	2.53	17.99	4.40	25.81	3.64	18.22
04-13-98	4.23	11.09	1.80	13.19	2.62		2.99	
04-21-98	3.88	13.74	1.25	10.90	3.99	7.07	3.09	10.92
04-22-98	5.31	7.90	2.30	4.61	1.12	6.33	3.27	6.19
04-23-98	6.85	5.45	1.33	5.47	5.23	14.02	4.69	8.80
04-30-98	1.39	5.59	1.20	5.11	4.67	7.46	2.72	6.00
05-04-98	3.39	8.03	1.53	7.16	0.30	21.06	2.08	12.93
05-05-98	0.45	15.33	3.35	14.63	1.16	9.55	2.29	13.60
05-07-98	4.71	7.61	2.28	15.45	5.11		4.00	
05-11-98	2.28	14.19	1.57	8.49	1.79	9.66	1.86	10.73
05-13-98	6.14	12.47	2.91	11.86	5.31	9.48	4.74	11.42
Mean	3.65	9.68	1.89	10.44	3.30	12.27	3.13	10.98

Notes:

[1]Low=925,850 mb
[2]Mid=700,500,400 mb
[3]High=300,250 mb
[4]All=925,850,700,500,400,300,250 mb

Table 7 shows the comparison of u-, v-components from 3dobj run with wind profiling radar, using ITPP 5.0. TOVS profiles with initial guess profiles based on climatology are inputs to 3dobj. NOGAPS data not used. Also the TOVS first guess profiles have gridded surface data for tie-down points.

Table 7. 3dobj run with wind profiling radar, based on climatology; NOGAPS data not used

	Geostrophic wind component rmsve (m/s)	Gradient wind component rmsve (m/s)
04-07-98	24.86	24.96
04-08-980921 UTC	15.26	17.42
04-08-981301 UTC	11.83	12.61
04-13-98	23.71	22.66
04-14-98	11.54	11.35
04-21-98	11.95	11.92
04-22-98	19.62	16.94
05-05-98	31.00	28.14
05-07-98	26.06	14.64
mean	19.54	17.85

Table 8 shows the comparison of u-, v-components from 3dobj run with wind profiling radar, using ITPP 5.0. TOVS profiles with initial guess profiles based on regression are inputs to 3dobj. NOGAPS data not used. Also the TOVS first guess profiles have gridded surface data for tie-down points.

Table 8. 3dobj run with wind profiling radar, based on regression; NOGAPS data not used

	Geostrophic wind component rmsve (m/s)	Gradient wind component rmsve (m/s)
04-07-98	24.41	24.18
04-08-98 0921 UTC	13.41	14.49
04-08-98 1301 UTC	13.45	12.78
04-13-98	25.48	22.70
04-14-98	15.76	16.69
04-21-98	12.84	11.15
04-22-98	18.15	15.46
05-05-98	58.31	60.30
05-07-98	13.35	13.26
mean	21.68	21.22

6.0 Discussion

Tables 1 and 2 provide the results (in terms of rmsve using up to five wind profiling radars as truth) of running 3dobj initialized with TOVS data from the TAP. Tests were done running 3dobj both with and without 12-h forecast NOGAPS data for large-scale initialization. Also the TOVS initial guess profiles were created using two different methods: climatology and regression. When NOGAPS data were not used, the mean rmsve was 11.44 m/s for both the climatology and the regression initial guess profile methods. This rmsve is for the entire profile from the surface to 11,250 m above ground level (45 levels). Introducing NOGAPS data into the 3dobj runs reduced the rmsve to 10.17 m/s for the climatology method and to 10.58 m/s for the regression method, which is an improvement of 11 percent and 8 percent respectively.

Tables 3 and 4 show comparisons between OUN raob data (used as truth) and the results of CAAMBFM runs using TOVS profiles as input that use either climatology or regression as the method to derive the first guess profiles. Note that regression is the superior method as improvement is seen in the mean rmse for all variables except temperature right at the surface. The largest improvement is at "high" (300, 250 mb) levels where the temperature rmse is decreased by 31 percent and the rmsve by 26 percent.

Tables 5 and 6 are again CAAMBFM runs compared to OUN raob data; however, NOGAPS data were used for these cases. Here the opposite trend is seen. Regression yields larger errors than climatology at all levels when NOGAPS is used in the CAAMBFM run.

Comparing the four different combinations possible (CAAMBFM runs with/without NOGAPS initialization and TOVS first guess profiles made using climatology or regression), the optimal combination in this study was the case where NOGAPS is used and the first guess method is climatology (table 5). For this case, the mean temperature rmse for "all" levels was 2.8" C and the mean rmsve for "all" levels was 10.4 m/s.

When the methods used for table 3 (CAAMBFM run without NOGAPS and climatology first guess profiles for TOVS) and table 5 (CAAMBFM run with NOGAPS and climatology first guess

profiles for TOVS) are compared, it is seen that NOGAPS reduces the temperature rmse and the rmsve at all levels. The biggest reduction in error is at "high" levels (300, 250 mb) where the temperature rmse and the rmsve are decreased by 28 percent and 15 percent respectively.

Comparing the methods of (1) CAAMBFM run without NOGAPS using regression for the TOVS first guess profiles with (2) CAAMBFM run with NOGAPS using regression for the TOVS first guess profiles as shown in tables 4 and 6 respectively, one sees that the introduction of NOGAPS data have decreased the temperature rmse at low levels only. However, the decrease is by such a relatively large amount, 13 percent, that the overall change when NOGAPS data are used is a 0.6 percent reduction in temperature rmse for "all" levels. Over "all" levels, rmsve increased by 1 percent.

Tables 7 and 8 display the rmsve when profiler wind data are compared to 3dobj output using TOVS data created with gridded surface data for tie-down points and either climatology or regression. The inclusion of surface data in the TOVS profile extraction process has actually increased the rmsve by 6 to 10 m/s. Climatology is the better method in this case, in particular, the gradient wind component, which has a mean rmsve of 17.85 m/s.

7.0 Conclusions

The worth of including NOGAPS 12-h forecast data are seen when 3dobj runs using TAP TOVS data as input were compared to profiler data. The rmsve is decreased, albeit by a small amount, when either climatology or regression is used as the method for derivation of first guess profiles in TOVS.

Four different combinations of CAAMBFM runs were made. They were:

1. without NOGAPS large-scale initialization data and climatology for the TOVS first guess profile
2. without NOGAPS large-scale initialization data and regression for the TOVS first guess profile
3. with NOGAPS large-scale initialization data and climatology for the TOVS first guess profile
4. with NOGAPS large-scale initialization data and regression for the TOVS first guess profile

The optimum scheme in terms of smallest mean temperature rmse and mean rmsve (2.8" C and 10.4 m/s respectively) was case 3. This is logical, as the NOGAPS 12-h forecast will generally provide good guidance. Case 1 produced the largest mean temperature rmse, 3.28" C and the largest mean rmsve, 12.70 m/s.

One interesting result was that for case 3, the mean temperature rmse for "all" levels was 15 percent smaller than for case 1. The mean rmsve for "all" levels was 18 percent smaller for case 3 than for case 1. For case 4, the mean temperature rmse for "all" levels was 0.6 percent smaller for "all" levels than for case 2 while the mean rmsve for "all" levels for case 4 was 1 percent larger. Thus, when climatology was used for the TOVS first guess profiles, NOGAPS had a significant impact. When regression was used for the TOVS first guess profiles, NOGAPS had virtually no impact.

The fact that the mean rmsve increased significantly, when surface data were used as tie-down points for the ITPP 5.0 TOVS initial guess profiles was disappointing. Horizontal interpolation of surface meteorological is inherently risky as one is "blindly"

spreading the parameters across varying terrain heights. Although the relief in Oklahoma is not dramatic, this may have played a role in the large errors.

Before TOVS data can be used as good model initialization data, the errors in the wind data must be decreased. It is hoped that the much higher resolution of infrared and microwave sensors set to be launched on both polar-orbiting and geostationary satellites will help reach that goal.

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Acronyms

3dobj	3-dimensional objective analysis
ARL	Army Research Laboratory
AVHRR	Advanced Very High Resolution Radiometer
BFM	Battlescale Forecast Model
CAAMBFM	Computer-Assisted Artillery Meteorology BattleScale Forecast Model
CIMSS	Cooperative Institute for Meteorological Satellite Studies
HIRS	High-resolution Infrared Radiation Sounder
HIRS/2	High-resolution Infrared Radiation Sounding Unit
HRPT	High Resolution Picture Transmission
IMETS	Integrated Meteorological System
ITPP	International TOVS Processing Package
McIDAS	Man computer Interactive Data Access System
MEL	Master Environmental Library
MSU	Microwave Sounding Unit
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmospheric Prediction System
NORM'S	Navy Operational Regional Atmospheric Prediction System
NRL	Navy Research Laboratory
OUN	University of Oklahoma – Norman
rmse	root mean square error
rmsve	root mean square vector error
roab	radiosonde observation

TAP	TOVS Analysis Package
TIGR	Thermodynamic Initial Guess Retrievals
TIP	TIROS Information Processor
TIROS	Television Infrared Observation Satellite
TOVS	TIROS Operational Vertical Sounder
UTC	Universal time coordinates

Appendix A

Earth Location of Satellite Data

Earth location, also referred to as "geolocation", is the determination of a latitude and longitude for each pixel in a satellite view. The expression "navigating the data" may be used in this context as well. In order to do this, one needs the satellite orbit and attitude parameters as well as the scanning geometry of the instrument used.

First, a right ascension-declination coordinate system is adopted. The right ascension is the angular displacement, measured counterclockwise from the x-axis, of the projection of a point in space in the equatorial plane. The declination of this point is its angular displacement measured northward from the equatorial plane.

The ascending node is the point where the satellite crosses the equatorial plane going north (ascending).

A satellite's orbit is described by its orbital elements defined as follows:

a = semimajor axis = the distance from the center of the ellipse to the perigee or apogee

ε = eccentricity = the distance from the center of the ellipse to one focus (to the center of the Earth) divided by the semimajor axis

i = inclination = angle between the equatorial plane and the orbital plane

ω_o = argument of perigee = the angle measured in the orbital plane between the ascending node (equatorial plane) and the perigee at time I,

Ω_o = right ascension of ascending node at time t_o

M_o = mean anomaly at time t_o

t_o = epoch time (valid time of the elements)

To get the position of the satellite at time t, one needs the current orbital elements. a, ε, and I are constants and are available from bulletins. M, Ω, and ω are calculated as:

$$M = M_o + dM / dt(t - t_o) \tag{A-1}$$

$$\Omega = \Omega_o + d\Omega / dt(t - t_o) \tag{A-2}$$

$$\omega = w_o + d\omega / dt(t - t_o) \tag{A-3}$$

Next, the satellite position is calculated using the vector rotation method.

First, solve for e, the eccentric anomaly using equation (A-4),

n = mean motion constant = $2\pi / T$ where T is the satellite period.

t_p = time of perigeal passage

$$M = n(t - t_p) = e - \varepsilon \sin(e) \tag{A-4}$$

Next, calculate θ, using

$$\cos\theta = (\cos e - \varepsilon) / (1 - \varepsilon \cos(e)) \tag{A-5}$$

Then calculate r using

$$r = (a(1 - \varepsilon^2)) / (1 + \varepsilon \cos(\theta)) \tag{A-6}$$

Form a vector pointing from the center of the earth to the satellite in right ascension-declination coordinate system.

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} r\cos\theta \\ r\sin\theta \\ 0 \end{pmatrix} \tag{A-7}$$

The orbital ellipse lies in the x-y plane with perigee on the positive x-axis. Rotate the vector about the z-axis through the argument of perigee. Multiplying the vector by a rotation matrix does this.

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos\varpi & -\sin\varpi & 0 \\ \sin\varpi & \cos\varpi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} x\cos\omega - y\sin\varpi \\ x\sin\varpi + y\cos\varpi \\ z \end{pmatrix} \quad \text{(A-8)}$$

Next, rotate the vector about the x-axis through the inclination angle.

$$\begin{pmatrix} x'' \\ y'' \\ z'' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos i & -\sin i \\ 0 & \sin i & \cos i \end{pmatrix} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} x' \\ y'\cos i - z'\sin i \\ y'\sin i + z'\cos i \end{pmatrix} \quad \text{(A-9)}$$

The last rotation is about the z-axis through the right ascension of the ascending node.

$$\begin{pmatrix} x''' \\ y''' \\ z''' \end{pmatrix} = \begin{pmatrix} \cos\Omega & -\sin\Omega & 0 \\ \sin\Omega & \cos\Omega & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x'' \\ y'' \\ z'' \end{pmatrix} = \begin{pmatrix} x''\cos\Omega - y''\sin\Omega \\ x''\sin\Omega + y''\cos\Omega \\ z'' \end{pmatrix} \quad \text{(A-10)}$$

The satellite radius is then

$$\sqrt{(x''')^2 + (y''')^2 + (z''')^2} = r_s \quad \text{(A-11)}$$

The declination of the satellite is given by

$$\sin^{-1}(z''' / r_s) = \delta_s \quad \text{(A-12)}$$

Right ascension of the satellite is

$$\tan^{-1}(y''' / x''') = \Omega_s \quad \text{(A-13)}$$

The latitude and longitude of the subsatellite point may now be determined. The latitude is simply given by the declination. The longitude is the difference between the right ascension of the satellite and the right ascension of the prime meridian (0° *longitude*) that passes through Greenwich, England (a value available in bulletins).

Appendix B

Limb Correction

Limb Correction is applied to the Microwave Sounding Unit and the High Resolution Infrared Sounder data in order to make the data as if it were taken at nadir. Regression equations based on synthesized radiance data are used.

At each step a correction is added to the radiance,

$$\Delta L_{jm} = \sum_{n=1}^{j} a_{jmn} L_{nm} + b_{jm}$$

where

L_{jm} = radiance in channel j at scan angle m

L_{nm} = radiance in channel n at scan angle m

Appendix C

Physical Retrieval Model

The physical retrieval model is an iterative process by which temperature at a given level is determined as follows:

1. A first guess temperature profile is selected.
2. Weighting functions are calculated.
3. Solve the forward problem to yield estimates of the radiance in each channel of the radiometer.
4. If the computed radiances match the observed radiances within the noise level of the radiometer, the current profile is accepted as the solution.
5. If convergence was not achieved, adjust the profile as in equation (A-15).
6. Repeat steps 3 to 5 until a solution is reached.

$$B_j(T_j^{(n+1)}) = B_j(T_j^{(n)})\left[L_j^{\sim} / L_j^{(n)}\right] \qquad \text{(C-1)}$$

where,

$T_j^{(n)}$ = the nth estimate of the temperature at the jth level

$B_j\ (T_j^{(n)})$ = the resultant Plank radiance at level j at the wavelength of channel j.

$L_j^{(n)}$ = the nth estimate of the radiance in channel j, calculated using the $T_j^{(n)}$

$L_j^{\sim}$ = the observed radiance in channel j.

The temperature at level j can then be calculated using the inverse Planck function.

There is a one-to-one correspondence between channel j of the radiometer and level j where the weighting function of channel j peaks. This formulation is logical in that if the calculated radiance is greater than the observed radiance, then the Planck radiance should be adjusted downward, which in turn implies a downward adjustment in temperature.

Moisture profiles can be similarly derived as follows.

$$q_{jk}^{(n+1)} = q_k^{(n)} \left[1 + (L_j^{\sim} - L_j^{(n)}) / \Gamma_j^{(n)} \right] \qquad \text{(C-2)}$$

$q_{jk}^{(n)}$ = the mixing ratio for level k at the wavelength of channel j

$q_k^{(n)}$ = the nth estimate of the mixing ratio at the kth level

$\Gamma_j^{(n)}$ is a factor that estimates the mixing ratio change necessary to correct for a given radiance imbalance.

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