REPORT TO CBS ON TOVS DATA RETRIEVAL METHODS

P. MENZEL[1] AND J. LE MARSHALL[2]
ITOVS WORKING GROUP RAPPORTEURS TO CBS

[1] CIMSS
Madison, WI, USA

[2] BMRC
Melbourne, Australia

1. Background

This report summarizes the recent developments in satellite sounding methods and data applications. It draws heavily on the work of the International TOVS (TIROS Operational Vertical Sounder) Working Group (ITWG). The major focus is the polar orbiting satellite, but geostationary satellite applications are also discussed. The ongoing activities of the ITWG are highlighted and the major recommendations from the ITWG for CBS consideration are included. This report updates the previous contribution to CBS-IX in Geneva, 25 Jan - 5 Feb 1988 (Item 6.2, CBS-IX, PINK 13, Appendix A, p.6)

As a working group of the International Radiation Commission, the international community of TOVS processors and users convenes every eighteen months at the International TOVS Study Conferences (ITSC) to review the science and application of temperature and moisture sounding from the NOAA polar orbiting satellites. The ITWG has been meeting since 1983. It has approximately 100 participants representing 25 countries. Each ITSC has produced a Study Report and a Technical Proceedings which have been distributed to the WMO. These meetings generate many recommendations offered to the WMO members regarding better use of sounding data (and more generally satellite data).

2. Data Reduction Techniques

a. The Techniques

The data reduction techniques used to process TOVS measured radiances into meteorological parameters are usually classified into three basic types; they are the statistical retrieval techniques where TOVS measured brightness temperatures are related statistically to atmospheric temperature and moisture values, the physical retrieval techniques where a full solution to the radiative transfer equation provides temperature and moisture profiles along with surface skin temperature and cloud height and amount, and direct techniques where raw or cloud cleared radiances are used in meteorological analysis schemes to produce meteorological fields. Advanced Very High Resolution Radiometer (AVHRR) data can also enhance the retrieval process by locating clouds accurately, estimating surface and cloud top temperatures, and determining cloud heights and amounts.

When the TOVS radiances are used either directly or in a physical retrieval algorithm, a significant outstanding problem relates to the "forward model". This refers to the computation of the observed TOVS radiances with the radiative transfer equation for a given atmospheric state. The output of the "forward models" must be accurate, well characterized, and properly used, if physical and direct assimilation methods are to yield information which is to have an optimal effect on numerical weather prediction (NWP). This is because relatively small temperature errors are found in the six hour NWP forecasts, which are often used as the first guess or background field in the TOVS retrieval process. Several contributing problems have been identified and need to be solved. One involves determination of the error characteristics in all radiosonde data used to estimate forward model error characteristics. A second concerns generation of appropriate methods for extrapolating radiosonde and model profiles to the top pressure level of the forward models. A third concerns the degree of collocation in space and time of the matched radiosonde and satellite data.

The effect of clouds also represents a significant remaining problem in the inversion of infrared measurements. A variety of methods have been applied to the problem; the most favored approach attempts cloud clearing before angle correcting the radiances to nadir view. Further intercomparison studies of cloud fields and cleared radiance fields are necessary. Optimal cloud clearing requires simultaneous infrared and microwave measurements.

b. Comparison of the Techniques

As reported to CBS-IX, intercomparisons of data from statistical and physical retrieval techniques show similar results when fields of temperature, geopotential thickness, and precipitable water vapor are compared to radiosonde data or ECMWF (European Center for Medium-range Weather Forecasts) analyses. RMS temperature differences between satellite and radiosonde measurements were generally near or below two degrees Kelvin (2K) in the mid-troposphere (700-400 mb) and 3K or 4K near the tropopause. At the tropopause and the earth surface, larger differences are seen. The differences are not solely due to retrieval error, as they also include contributions due to radiosonde error, collocation differences in time and space, and analysis error. The accuracy of the retrieval schemes noted here was determined in 1985 and since that time refinements to the schemes have resulted in a small but steady improvement in overall accuracy.

A combination of physical and statistical retrieval schemes are commonly used for the retrieval process. The most commonly used algorithms at present are the International TOVS Processing Package (ITPP-3), the Improved Initialization Inversion (3I) system, and variants thereof. The ITPP and 3I systems represent significant investments of resources over long periods of time. The ITPP from the Cooperative Institute for Meteorological Satellite Studies (CIMSS), Wisconsin has been widely distributed to the international community for testing and developing retrieval techniques; it has gone through three major upgrades in order to improve the quality of the temperature and moisture retrievals it produces. Further, a number of research groups and centers have adapted the ITPP to their local needs using variants of the processing algorithm and locally derived parameters for bias and transmittance tuning. The 3I system developed at the Laboratory de Meteorologie Dynamique (LMD), France is also

being distributed to a growing number of research groups and meteorological services. The 3I system has contributed to the intercomparison campaigns reported in the literature (Le Marshall, 1985) and has been used in the international community for impact studies on numerical weather forecasting.

Several other algorithms are in use. These include the operational physical retrieval scheme used at the National Environmental Satellite Data and Information Service (NESDIS), USA, which provides data for distribution via the GTS. Others use optimal estimation retrieval techniques. Many of the retrieval schemes use numerical forecast models for their first guess and use forecast error covariances to enhance the retrieval process. Increasing interest is also being shown in the direct use of radiances in meteorological analyses schemes, sometimes in combination with variational analysis techniques.

c. Summary

The International TOVS (ITOVS) Working Group has seen the continuing expansion of the user community in several directions. Considerable retrieval research and numerical weather prediction impact studies have been undertaken using the 3I and the ITPP schemes. These schemes have been further developed and documented to facilitate implementation by more diverse users. However, user familiarity with the content and optimal use of these software systems is essential for obtaining accurate and reliable results. Training and dialogue between users and providers are strongly encouraged.

There has also been increased effort applied to optimal estimation methods and the direct use of radiance data in analysis schemes, where the radiative transfer equation is solved taking account of all other observational data.

3. Applications

a. General Applications

TOVS observations measure atmospheric temperature and moisture, surface temperature, and cloud parameters. They are used in a large range of applications that include:

(i) subsynoptic scale temperature and moisture analyses for (severe) weather monitoring and prediction;
(ii) subsynoptic scale analysis of surface temperature;
(iii) subsynoptic scale analysis of atmospheric stability;
(iv) subsynoptic scale updating of aviation grid point temperature and wind fields;
(v) estimation of the cloud height and amount;
(vi) estimation of tropical cyclone intensity, maximum wind strength, and central position; and
(vii) estimation of total ozone amount.

These applications are pertinent to nowcasting as well as operational short-range forecasting. Their quality indicates that there is cause for optimism in the application of TOVS products. It has been recognized that the application of these data has not been exhaustive and that there appears to be considerable potential for use of TOVS products in the operational practices of weather services. Timeliness and continuity of data, as well as proper understanding of the meteorological content of the derived products, are essential for successful use of TOVS in operational forecasting.

b. Use in Numerical Weather Prediction

The use of TOVS products by the meteorological community has played an important role in improving numerical weather prediction over the past ten years. The use of TOVS data has been vital for global analysis, and on the average the impact of TOVS on global forecasts has been significant and positive.

TOVS data are used in a range of operational and experimental NWP models. These include (i) global and hemispheric models with horizontal resolutions of the order of 100-300 km providing short to medium range forecasts of one to ten days, (ii) regional models with horizontal resolutions of about 50-100 km for short range forecasts of one to three days, and (iii) mesoscale models of 10-50 km resolution for very short range forecasting of less than 24 hours. They are run by national meteorological services, international organizations such as ECMWF, and meteorological research centers and university groups.

In the southern hemisphere, the use of TOVS data is essential for accurate analysis, and has produced on the average a large and positive impact on the resulting forecasts. In the northern hemisphere, the forecast impact has been small on the average, with large regional variations in individual cases.

Optimal use of the temperature, moisture and cloud data available from the TOVS instrument in numerical analysis and prediction is still to be achieved. Many data assimilation systems still use the sounding data in much the same way that radiosonde data (i.e., temperature and moisture profiles or derived thickness and precipitable water) are used. Often this occurs without properly accounting for the broad vertical resolution and error characteristics of the TOVS data or ensuring that the final analysis is consistent in an optimal fashion with the TOVS measured radiances.

Several workshops have recently addressed the problem of retrieval methods, data assimilation, and impact on NWP. The importance of a fast and accurate forward model, quality control, the first guess, variance/covariance matrices and the data assimilation methodology has been noted. With respect to assimilation, the continued requirements for high resolution data for global centers and for direct readout and local data processing for high resolution NWP was noted. Recent northern hemisphere impact studies which have failed to fully exploit the information content of TOVS have resulted in moves to use variational methods which will allow the retrieval to be done as part of the analysis cycle. The contribution

of these systems to northern hemisphere NWP should be felt during the next few years. Continuation of impact studies with more attention to improving the assimilation methodology is anticipated.

The main limiting factor in temperature and humidity remote sensing resides in the inherently poor vertical resolution of the present sounders. There is both theoretical and experimental evidence that advanced sounders with high spectral resolution produce soundings with higher vertical resolution and markedly smaller RMS error (about 1K) in cloud-free areas and through partially opaque clouds. Additionally, the anticipated improved horizontal resolution will improve the ability to sound below broken cloud cover producing more uniform coverage. This has led the ITOVS community to the important recommendation that programs to implement high spectral and spatial resolution sounders should be accelerated as much as possible.

Geostationary satellites provide another product important for the numerical weather prediction models; these are the cloud motion vectors. Wind data in general have a significant impact on numerical forecasts. Recently as the models have improved, derived winds from tracking clouds in satellite images have been shown to suffer from excessive noise and slow biases, especially in areas of strong winds. Research is proceeding in several areas to improve the quality of satellite winds.

A new direct physical calculation of cloud height has been studied as a possible replacement for statistical, climatological, or simpler physical methods. This method ameliorates the height assignment problem known to occur for transmissive thin high clouds, where the brightness temperature in the infrared window typically suggests a height assignment that is too low in the atmosphere (because it is too warm). Using observed radiances in a carbon dioxide or a water vapor sensitive channel (13.3 or 6.7 microns), cloud top pressures are calculated in a radiative transfer formulation that accounts for cloud emissivity and fractional cloud cover. For several test periods, the overall result was lower noise in the upper levels and generally reduced need for manual editing. Systematic intercomparison of the various techniques is currently being undertaken.

In the American quadrant winds will soon be derived from 15 rather than 30 minute interval infrared window images. In past studies, the 15 minute interval winds have been found to be superior to the 30 minute interval winds. It is possible to modify the GOES schedule to routinely produce full disk 15 minute image loops four times per day; schedule changes will be implemented early in 1990 contingent upon ongoing investigations.

It is hoped that the present positive impact of satellite winds over the southern hemisphere can be extended, through the introduction of improved techniques, to the northern hemisphere, where the denser distribution of conventional data means higher quality satellite observations are required for positive impact in NWP.

c. Tropical Cyclone Applications

The Microwave Sounding Unit (MSU) on the TOVS has been used to investigate the strength of tropical cyclones. For several parts of the globe a relationship has been established between the temperature anomaly created

by the upper tropospheric warm core associated with most tropical cyclones and the surface intensity. The MSU temperature gradients at 250 mb are found to have a linear dependence on the surface central pressure and maximum sustained wind speed in the storm eye wall. Operational use is limited by the inadequate temporal resolution of the polar orbiters. Improved storm location would be realized with higher horizontal resolution (better than 30 km) data. Although promise is shown by this MSU application, reconnaissance reports remain an important tool for tropical storm delineation.

The AVHRR sea surface temperature (SST) fields provide good horizontal coverage and detail which is useful to the hurricane forecaster using large scale SST analyses to help estimate hurricane intensity. Ongoing studies suggest that hurricane wind speeds are influenced by the warmth of the underlying SST.

The geostationary water vapor imagery often reveals mid to upper tropospheric structure in the tropical cyclone environment that is not always apparent in the usual infrared or visible images. Loops of water vapor images available from the VAS (VISSR Atmospheric Sounder) and METEOSAT are now regularly used to track the synoptic features of hurricane flow.

Wind measurements remain a most important satellite product for hurricane forecasting. High and low level cloud drift are determined from image loops in the visible and infrared window. Mid-level water vapor drift winds can be calculated from the water vapor sensitive spectral bands. In clear areas the thermal gradient wind can be inferred from satellite sounding. The combined deep layer mean wind field has been shown to be useful for indicating the steering current of hurricane movement. In a recent study in the USA of the 1989 hurricane season, these satellite derived wind analyses produced a 10% reduction in the mean forecast error in hurricane track prediction.

d. Summary

TOVS data continue to fill important data voids at synoptic scales (for example over the oceans). Furthermore, they provide some definition of meteorological fields at the subsynoptic scales of weather where conventional networks (even over land areas) provide insufficient data density to support detailed subsynoptic scale objective analyses. As such they contain important information for nowcasting and short range forecasting. The satellite observations augment the conventional surface observations; the combination of the two observing systems provides the best depiction of the atmospheric state.

Better use of the sounding data in NWP relies on improved analysis methodology, availability of data with higher vertical and horizontal resolution, and use of quality control information concerning radiance measurements, cloud cover, and first guess (when relevant). Better results in NWP from the use of satellite derived cloud motion vectors await enhancements such as improved cloud height definition and fifteen minute image loops; both of which are expected to be available in 1990.

Processing software for TOVS data such as the 3I and ITPP continue to be distributed to more users; over 50 institutes are using these software packages. A uniformly high standard of retrieval skill has been established in the international user community.

Timely availability of TOVS data, as is currently available through direct readout, remains vital for nowcasting as well as short range and mesoscale NWP.

4. Trends

a. Future Space-Based Systems

In the next decade significant advances in instrumentation and subsequent products are planned. These include the Advanced TOVS (ATOVS) planned for NOAA-KLM consisting of the new Advanced Microwave Sounding Unit (AMSU) and the existing High resolution Infrared Radiation Sounder (HIRS/2). The ATOVS will considerably improve the sounding performance in cloudy areas and the horizontal resolution of the products. However, the vertical resolution of these instruments is still inadequate to meet the needs of the NWP models expected in the early 1990s. Recent instrument developments in interferometers (such as the High resolution Interferometer Sounder, HIS) and planned spectrometers (such as Advanced Infrared Sounder, AIRS) offer the hope of significantly improved spectral coverage and spectral resolution leading to better vertical resolution.

The sounding science community continues to stress the need for coordinated infrared and microwave instrumentation on the same platforms to enable all weather sounding. The complementary capabilities of these sensors are superior to either component by itself.

The growth of world climate programs, and the earth observing systems under development to support these programs, are providing new opportunities for satellite remote sensing to contribute further to the global change and climate data base. This will be done through activities such as the monitoring of global distributions of cloud cover, temperature, and moisture. In addition there also will be many opportunities to improve weather nowcasting and forecasting. The ITWG will stay informed on the progress of these programs.

b. Small Processing Systems

Traditionally a significant investment in antennas, receivers, and computer hardware was required to collect, process, and present products derived from satellite data. Such receiving systems were large and required significant maintenance, thereby requiring users to have sophisticated ground station facilities. With developments in analog electronics and microcomputer technology comes the ability to implement low cost portable ground receiving systems suitable for use in developing countries and in field experiments. Through the use of standard commercial components, such systems can be readily constructed, distributed, and maintained. Personal computer (PC) technology standards are starting to facilitate international

scientific software exchange and development. Many new opportunities for satellite research are presented through the emerging PC technology.

The PC activities within the sounding community are rapidly progressing toward nowcasting using TOVS data processed in real time in a stand alone mode. In addition, PCs are used for collaborative research through case study distribution and data analysis and for educational programs. A PC version of the ITPP has been prepared and the ability to process TOVS data on a PC locally with the ITPP has been demonstrated. Use of similar hardware components in these systems for compatibility of disk operating systems has been suggested by the ITOVS scientists. A micro-VAX version of the 3I has also been prepared and is currently running in several centers. However, further work remains before such packages can be distributed widely.

The local small computer processing of TOVS data depends upon easy inexpensive access to the data stream. The TIP (TIROS Information Processor) beacon has been exemplary in providing this in the past and NOAA plans to continue it through NOAA-M into the mid 1990s (beyond that NOAA will attempt to accommodate the user community with comparable support). Another example of small computer access to weather information is the Meteorological Data Dissemination (MDD) service provided by EUMETSAT to provide conventional meteorological information to Europe and Africa. This has recently been enhanced with digital image dissemination whereby Meteosat images are processed and transmitted to primary data user stations every hour. A final example is the NOAA Electronic Bulletin Board which has been providing access to general information regarding satellites (orbit, health, and launch dates) for some time to the international satellite users.

5. ITOVS Working Group

a. Status of the ITWG

The International TOVS Working Group continues to focus on (i) improving satellite products via calibration refinements, retrieval method comparisons, verification, and case studies; (ii) expanding the TOVS user community through distribution of processing software, information exchange, and development of software for low cost processing systems; (iii) investigating the growing number of applications of satellite products in numerical weather prediction and climate studies; (iv) making recommendations to national agencies regarding the development of future satellite sounding instruments for both polar and geostationary platforms; and (v) encouraging an effective level of international cooperation on the above goals for the mutual benefit of the participating countries.

The ITOVS community plans an active work program at an international level over the next few years in satellite sounding retrievals and utilization of sounding data. The ITOVS Working Group wishes to inform the Commission of its progress, a task which may be achieved via the CBS rapporteurs on TOVS retrieval methods.

The next meeting of the ITOVS Working Group will be in May 1991.

b. Collaboration on ATOVS Software Development

The ITOVS community recognizes the considerable efforts necessary to prepare for the processing and use of ATOVS data after launch in 1993/4. Increased international collaboration will be essential to assure that ATOVS data are exploited fully and effectively, particularly for NWP applications. A subcommittee of the ITWG has been nominated to prepare a software development strategy.

The ITWG will endeavor to organize a coordinated research and development effort to prepare ATOVS software that can be shared by the international community and enhanced for the benefit of all.

c. The Baseline Upper Air Network (BUAN)

The BUAN gathered data from a carefully selected set of stations providing representative data from many regions of differing climate, for the first six months of 1988. It is believed that the BUAN data archive, after proper quality control, will enable identification of some of the error characteristics of radiosonde sounding systems as well as certain inadequacies in current forward models. The ITOVS Working Group noted that it is important to appreciate that the "forward model" problem is inextricably connected with radiosonde measurement errors. Radiosonde errors first must be characterized before the forward model problems can be identified.

The ITWG intends to pursue further study of the BUAN data and report to WMO members on their subsequent evaluations of the error characteristics of both radiosonde systems as well as the forward calculations of radiative transfer.

6. CBS Considerations

a. Improved Sounders

There is a consensus in the ITOVS community and beyond that the need to improve the quality of atmospheric soundings is urgent. This can be partially achieved through the flight of high spectral resolution instruments such as AIRS (Atmospheric Infrared Sounder planned for the Earth Observing System) or HIS.

- It is recommended that the CBS should support the earliest possible deployment of such instrumentation on polar and or geostationary platforms and that the CBS encourage international collaboration on the development of such systems to try to assure commonality of observing systems.

b. Collaboration on ATOVS Software Development

Because of the considerable efforts that will be required for the processing and use of ATOVS in 1993/4, international collaboration will be essential to assure that ATOVS data are exploited fully and effectively. A

subcommittee of the ITWG has been nominated to prepare a software development strategy.

- It is recommended that the commission record its support for a coordinated research and development effort to prepare ATOVS software that can be shared by the international community for the benefit of all.

c. Direct Readout Services

Given the present and future importance of satellite data to meteorology and noting the particular importance of real time satellite data in monitoring and predicting severe (local) weather:

- It is recommended that the Commission note the great practical significance of direct readout services from meteorological satellites and urge satellite operators to continue these services. These should continue for the next generation advanced sounders.

d. Sounding Community Expansion

As the interest in satellite soundings increases and the difficulty and cost of obtaining and processing the data diminishes, there is a growing need for coordinated international training programs.

- The ITOVS community through the ITWG is prepared to help, where the WMO deems appropriate, with international training programs.

e. Planning an OWSE-SAT

To make a successful transition from the current utilization of meteorological satellite data to operational procedures later this decade, it seems prudent to conduct a campaign (1) to assess the possible impact on WWW programs expected from the changes in the satellite capabilities planned for the mid-1990s, and (2) to establish the minimum performance characteristics of work stations for the collection and use of information available from the satellites, including the support, training, and experience needed for effective use.

- The rapporteurs of the ITOVS Working Group are prepared to participate in the planning and implementation such an OWSE-SAT.

TECHNICAL PROCEEDINGS OF THE SIXTH INTERNATIONAL TOVS STUDY CONFERENCE

AIRLIE, VIRGINIA

1-6 MAY 1991

Edited by

W. P. Menzel

Cooperative Institute for Meteorlogical Satellite Studies
Space Scienceand Engineering Center
University of Wisconsin
1225 West Dayton Street
Madison, Wisconsin

July 1991