TOVS DATA RECEPTION AND ASSIMILATION
IN THE BUREAU OF METEOROLOGY - RECENT DEVELOPMENTS

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ABSTRACT

This paper describes the current, physically-based, real time retrieval system employed at the Bureau of Meteorology. It describes in detail cloud height and ozone determination methods and the radiance tuning technique employed in the system. It discusses recent numerical experiments designed to investigate the impact of locally processed TOVS data from the system on operational Australian Region numerical weather prediction. These experiments are being done against a background data environment which includes NESDIS low resolution TOVS data and locally generated cloud drift winds. It describes initial work in the implementation of a 1-dimensional variational retrieval scheme within the BMRC Global Assimilation and Prognosis Scheme. It also describes the implementation of a PC-based TOVS processing system in a McIDAS environment and its application to research and operations.

Introduction

The Bureau of Meteorology (BoM) has been receiving and utilising NOAA second generation sounding data and Geostationary Meteorological Satellite (GMS) visible and infrared (IR) data for over a decade. The real time use of these data in the Australian BoM is vital for numerical weather analysis and prediction in the Australian Region.

The benefits of temperature and moisture profiles from NIMBUS 6 (NASA, 1975), TIROS-N (Smith et al., 1979) and subsequent satellites with second generation sounders are now long demonstrated (Kelly et al., 1978; Bourke et al., 1982).

These data, enhanced by the ability to receive and process the data from regional groundstations (Melbourne, Perth, Darwin and Casey) locally in real time (Le Marshall et al., 1985), have assumed increasing importance in the Bureau of Meteorology. More recently, sequential geostationary satellite imagery, received locally from GMS, in Stretched VISSR (S-VISSR) format have been used to generate Cloud Drift Winds across the Australian Region (Le Marshall and Pescod, 1991). These wind data are being assimilated into the local operational Analysis and Prognosis system and have been shown to improve accuracy of weather forecasting in the Australian Region. The assimilation experiments described in this document records the impact of local TOVS data on a numerical system which already contains the full operational data base of the National Meteorological Centre (NMC), Melbourne, including low resolution NESDIS soundings where available and local cloud drift winds.

The current real time linear simultaneous physical retrieval scheme is described in this
document, as is an implementation of a 1-D variational scheme which is intended to be used for TOVS data assimilation in the Global Assimilation Prognosis (GASP) Scheme. This work is being done in collaboration with ECMWF.

The real time physical retrieval scheme has also been implemented in a PC-Australian Region McIDAS (PC-ARM) environment and versions of this are being used for tropical and Antarctic research, and for operations with Philippines Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) in Manila.

The Real Time Physical Retrieval Scheme

The TOVS physical retrieval scheme, described below, is similar to that described in Le Marshall et al., 1989, but has undergone several significant upgrades. The scheme now uses the simultaneous linear solution of the Radiative Transfer Equation (RTE) for temperature and absorbing constituent of Smith et al., 1988, which uses the perturbation form of the RTE.

\[
\delta R_v = \beta_0^T(P) \tau^0(P) \delta T_e - \sum_{i=1}^{N} \int_0^p \beta_i^T_s(p) \delta T_s(p) \tau^0_i(p) d\ln \tau^0_i(p)
\]  

(1)

where \( R_v \) is spectral radiance, \( N \) is the number of optically active atmospheric constituents, \( \delta \) is the true minus initial value (superscript 0), \( \tau_s(p) \) is total transmittance above \( p \), \( \tau_i(p) \) is transmittance of \( i_{th} \) absorbing constituent, \( \mu_i \) is concentration of \( i_{th} \) absorbing constituent, \( T_s(p) \) is effective temperature of \( i_{th} \) absorbing constituent, and

\[
\delta B_s^T(p) = \delta B(T^0) \frac{\partial \dot{T}}{\partial T} \text{ and } \delta T_s(p) = T(p) - T^0(p)
\]  

(2)

where \( B_s(p) \) is Planck radiance.

This perturbation form of the RTE is solved using direct linear matrix inversion.

The first guess may be climatology, a statistical retrieval or a forecast from the Regional or Global Numerical Weather Prediction scheme. The first guess surface temperature and moisture fields are derived from the regional optimum interpolation scheme of Keenan et al., 1986. The scheme also produces estimates of cloud amount and height, skin temperature and total ozone, and is
quality controlled, using analysis and forecast fields from the operational global or regional model. The retrieval scheme also uses a local radiance bias correction scheme (Le Marshall et al., 1989). The TOVS data retrieval scheme is embedded in the Australian Region McIDAS (ARM) (Le Marshall et al., 1987). A block diagram describing this system is seen in Fig. 1. Features of the scheme with regard to ozone estimation, bias correction and cloud height estimation are also described below.

**Total Ozone Estimation**

A new method to calculate total ozone has been developed from that of Ma et al., 1984, which is the basis of the algorithm used in the International TOVS Processing Package (ITPP). The new method employs the Radiative Transfer Equation and uses statistical relationships between HIRS channels 1 to 4 radiiances and ozone amount to establish a first guess profile as in Ma et al., 1984.

**TABLE 1**

The root mean square (R.M.S.) differences and bias (Dobson units) for Ma et al.’s and the present scheme versus Dobson spectrophotometer observations, and those for the present scheme versus Ma et al.’s for Melbourne and Brisbane (from 1 January to 30 April 1991).

<table>
<thead>
<tr>
<th>Site</th>
<th>No. of obs.</th>
<th>Ma et al’s alg. vs Dobson data</th>
<th>Present alg. vs Dobson data</th>
<th>Present alg. vs Ma et al’s alg.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bias</td>
<td>R.M.S.</td>
<td>Bias</td>
<td>R.M.S.</td>
</tr>
<tr>
<td>Melbourne</td>
<td>39</td>
<td>13.4</td>
<td>19.7</td>
<td>8.1</td>
</tr>
<tr>
<td></td>
<td>R.M.S. diff.</td>
<td>8.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brisbane</td>
<td>49</td>
<td>-27.3</td>
<td>31.2</td>
<td>-15.3</td>
</tr>
<tr>
<td></td>
<td>R.M.S. diff.</td>
<td>15.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both sites</td>
<td>88</td>
<td>-9.2</td>
<td>26.7</td>
<td>-4.9</td>
</tr>
<tr>
<td></td>
<td>R.M.S. diff.</td>
<td>13.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Several enhancements, however, have been made to the Ma et al. algorithm to improve the accuracy of the estimate of total ozone and these are described in Wu and Le Marshall, 1990. Briefly, they include a change to include the water vapour transmittance calculations in all transmittance associated with the TOVS 9.7 μm channel, a new formulation of the algorithm, which provides quicker convergence to a final ozone profile and an iteration step for the final part of the algorithm.

**Figure 2.** Total Ozone over SE Australia estimated from NOAA TOVS data on 13 March 1993.
Results from the new algorithm have been compared with those from the original scheme and with surface-based observations, taken using a Dobson spectrophotometer and these indicate an increase in accuracy, as can be seen in Table 1.

An example of the use of the algorithm is seen in figure 2, where an image of total ozone over south-eastern Australia is shown.

Radiance Tuning

Radiance tuning is similar to that described in Le Marshall et al., 1988 and is based on a dataset of collocated near contemporaneous radiosonde and TOVS soundings. The tuning employs limb corrected MSU data, which are used to separate the radiance sample into 8 synoptically distinct groups, using discriminant analysis. Subsequent to this, an estimate of radiance bias by group can be made and, using the probabilities of being in one of the 8 groups a bias correction for each channel can be calculated.

Cloud Estimation

Changes have also been made to the cloud estimation scheme. A new CO₂ slicing method is now under test in the BoM. This method uses all the satellite infrared CO₂ channels simultaneously to determine the cloud height and coverage and should provide high accuracy with computational efficiency.

The basic equation governing the relationship between effective cloud coverage rate A and cloud pressure P_{cl} for an infrared observing channel of wave number ν can be expressed in the following form (Smith et al., 1974):

\[ I_{cl} - I_{cl0} = A \int_{p_{*}}^{P_{cl}} \tau(p) dB(p) \]  

where \( \tau(p) \) is atmospheric transmittance between the top of the atmosphere and pressure level \( p \), \( B(p) \) is the Planck radiance corresponding to the temperature at pressure \( p \) and \( P_{sfc} \) is the pressure at the surface. \( I_{cl0} \) is the observed radiance emitted from a cloudy sky and \( I_{cl} \) is the radiance from a clear sky, where:

\[ I_{cl} = B(p_{sfc}) \tau(p_{sfc}) + \int_{p_{*}}^{0} B(p) d\tau(p) \]  

If we consider a set of CO₂ channels of wave number \( ν_1 \) to \( ν_n \), from equation (3), we have:

\[ A = \frac{I_{cl}^{1} - I_{cl0}^{1}}{\int_{p_{*}}^{P_{cl}} \tau^{1}(p) dB^{1}(p)} = \ldots = \frac{I_{cl}^{n} - I_{cl0}^{n}}{\int_{p_{*}}^{P_{cl}} \tau^{n}(p) dB^{n}(p)} \]  

where superscripts \( 1, 2, \ldots, n \) refer to channels of wave number \( ν_1 \) to \( ν_2 \).

If we then draw a curve of cloud amount versus cloud coverage for the observed radiance in each channel according to equation (5), then, in the A-P cloud plane, we
get Fig. 3.

The point which is closest to all curves may be chosen as the solution. Here, the closest point \( P \) is the point which minimises \( \sum_1^n D^2 \sigma^2 \). In this case, (Fig. 3), the closest point corresponds to a level of 475 hPa and the cloud coverage is 37%.

**The Soundings**

The linear simultaneous system described currently runs in real time in the Australian Region McIDAS (ARM) environment at the Australian Bureau of Meteorology (BoM). Typical verification statistics can be seen in Fig. 4, where the RMS differences in comparison to radiosondes can be seen to lie between 1 and 2 degrees Kelvin through most of the troposphere.

The data have demonstrated their utility in several ways. They can be shown to be useful in synoptic applications as well as beneficial to numerical weather prediction (NWP) in the Australian Region.

**Synoptic Applications**

The local high resolution TOVS data can provide estimates of sub-synoptic scale fields such as total ozone, cloud height and cloud amount, it can provide wind shears...
for use in upgrading aviation grid point winds and it can also provide fields such as stability indices, whose utility is demonstrated in the following case.

Figure 5 (a) shows the TOVS Total Totals index calculated from NOAA orbits between 16 and 19 UTC on 26 October 1992, overlaying the 17 UTC GMS IR image of South Australia. A maximum in Total Totals can be seen to the north west of Adelaide. This predawn indication of high convective instability was supported by both the jetstream structure and lower tropospheric moisture which favoured convective development. The resulting development is depicted in Figure 5 (b) which shows the 16 - 19 UTC Total-Totals fields, overlaying the 07 UTC GMS IR late afternoon image for 27 October, 1992. Here, the severe storms can be seen to have developed in the areas consistent the Total Totals maximum shown in Figure 5 (a).

In this case, the horizontal resolution of these stability fields which are sensitive to both low level temperature and moisture have proved useful in defining areas of potential storm development.

Regional Data Assimilation

In addition to the synoptic and other applications cited above, the TOVS data have also been used in a series of real time data assimilation experiments in the Australian Region to gauge their impact on operational forecasts. The impacts gained in these real time data assimilation experiments have been obtained against the full NMC
data base. This includes all GTS data available at the regional cutoff time (T + 1.5 hrs.), such as low resolution NESDIS TOVS data (SATEMs) and GMS cloud winds (SATOBs) data, as well as locally generated cloud drift winds which have provided high density coverage (400 to 600 vectors every 6 hours) over the Australian Region. These winds have been shown to provide consistent improvement of near one SI skill score point for most forecast fields (e.g. MSLP, 500 hPa and 300 hPa geopotential heights).

The Regional Assimilation and Prognosis System (RASP)

The Limited Area Regional Assimilation and Prognosis System (RASP), used for this experiment, was the BoM operational system and has been described, in detail, by Mills and Seaman, 1990. It consists of a static analysis of deviations of data from a short-term forecast on pressure surfaces, followed by an interpolation of these analysis increments to the sigma surfaces of the Australian Region Primitive Equation model, the addition of these increments to the forecast model variables and integration of the model forward to the next analysis time. Hence, at each data insertion time, the analyses reflect the observations, but have a strong dynamic constraint provided by the forward forecast model.

MSLP and geopotential layer thickness are analysed, using 2-dimensional univariate statistical interpolation. Wind components are analysed using 3-dimensional SI and temperature and dewpoint are analysed using the successive correction method. Mass and wind increment analyses are mutually adjusted to reflect their respective analysis accuracies, using variational techniques and separate analyses of screen level temperatures and dewpoints are merged with the tropospheric analyses. Data are analysed at 11 pressure levels and the forecast model has 15 sigma levels. Both the analysis and forecast models have a horizontal grid spacing of 150 km.

The Experimental Results

A series of data assimilation cycles, using the local real time, physically retrieved TOVS data have been completed. In these experiments, these remotely sensed data have been added to the data used in the operational RASP Scheme which is run routinely in the National Meteorological Centre and which provides operational regional forecasts. The analyses resulting from the addition of these locally retrieved TOVS data have been used to produce 12, 24-hour and 36-hour forecasts, using the operational RASP forecast model in real time. The output from these forecasts has then been compared to the operational forecasts, which act as the control.

It has been found that, despite recent improvements in the Analysis and Forecast model and the use of data such as low resolution NESDIS TOVS data, single level aircraft data and locally derived high resolution cloud drift winds, that the high resolution TOVS data still provide significant impact. An example of this can be seen in Fig. 6, which shows the development of a low in the Great Australian Bight and a trough to the east of Australia. It was found that the 24 and 36 hour local TOVS forecasts depicted these development far better than the NMC control (and, for example, the relaxed RASP or ECMWF prognoses).
S1 skill scores for the local TOVS data assimilation (TOVS/RASP) forecasts and matching Control (NMC) forecasts (RASP) for the period 23UTC 17-12-92 to 23UTC 12-01-93. Both the Assimilation and NMC analyses have been used for verification.

<table>
<thead>
<tr>
<th>FORECAST TYPE</th>
<th>S1 SKILL SCORE (Assim. Anal.)</th>
<th>S1 SKILL SCORE (NMC Anal.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSLP</td>
<td>500 hPa</td>
</tr>
<tr>
<td>RASP (+12H)</td>
<td>31.8</td>
<td>16.8</td>
</tr>
<tr>
<td>TOVS/RASP (+12H)</td>
<td>31.4</td>
<td>14.5</td>
</tr>
<tr>
<td>RASP (+24H)</td>
<td>39.4</td>
<td>22.5</td>
</tr>
<tr>
<td>TOVS/RASP (+24H)</td>
<td>38.7</td>
<td>21.2</td>
</tr>
<tr>
<td>RASP (+36H)</td>
<td>47.2</td>
<td>29.2</td>
</tr>
<tr>
<td>TOVS/RASP (+36H)</td>
<td>46.8</td>
<td>27.6</td>
</tr>
</tbody>
</table>

From 7 December, 1992, the TOVS system was provided with a first guess from GASP, tuned and stabilised. Forecasts, run in real time from 7 December, 1992 to 11
January, 1993, have been used to produce the S1 skill score table, (Table 2).

In this table, forecasts generated in real time, using the RASP and local TOVS data have been compared to forecasts produced by the RASP in NMC. Verifications were performed using both the experimental system and operational NMC analyses.

Regardless of the comparison standard (experimental or operational analyses), for every forecast interval from +12 to +36 hours and for MSLP, 500 hPa and 300 hPa, the system using the high resolution TOVS data has, on average, outperformed the operational system.

This assimilation experiment is continuing and a real time operational trial is expected to start in late February, 1993.

The 1-D Variational Retrieval Scheme

In 1992, the Bureau of Meteorology, in collaboration with ECMWF has implemented the one-dimensional (1-D) variational retrieval scheme (Eyre et al., 1989) which it finally intends to embed in the analysis cycle of the GASP. This retrieval scheme is, at present, a 1-dimensional, standalone scheme, using NESDIS 250 km clear-column, limb corrected radiances. Initial work has consisted of tuning the scheme to operate optimally within the GASP system. Early verification statistics indicate that the scheme is producing high quality soundings and measurement of forecast impact is at present, underway. Locally derived TOVS clear radiance data have also been provided to the system in test mode and it is intended to undertake an operational regional data assimilation experiment in the near future, after further testing of the quality of the local cloud cleared radiances.

The PC-ARM Retrieval System

During 1990/91, the real time operational retrieval scheme was moved to the PC environment. This development was to support the BoM's Darwin and Antarctic satellite groundstations and also to provide a research tool at the BoM and Institute of Antarctic and Southern Ocean Studies (IASOS). Subsequently, the system was introduced at PAGASA in Manila, where it is used in an operational support role. Early collaborative work between PAGASA and the BoM has examined several applications to regional operational meteorology. In particular, over 100 orbits containing typhoons in the Western Pacific during the 91/92 typhoon season have been collected and processed in a study of typhoon intensity, maturity and related upper atmospheric temperatures anomalies. A typical example from this study is shown in Figs. 7 (a) and (b), which shows the TOVS 250 hPa estimates over the cloud image of typhoon LUSING and the related 250 hPa analysed temperature field.

These temperature anomalies have been related to the surface pressure anomaly and wind speed to produce a lookup table for operational application at PAGASA.
Summary and Conclusions

The Bureau of Meteorology has implemented within BMRC and is now routinely using two physical retrieval schemes. One is the linear simultaneous method of Smith et al., 1988 and a more recent implementation is the 1-D variational scheme of Eyre et al., 1989. Both schemes are producing high resolution soundings and it would appear that the data from both schemes will impact positively on regional forecasts. The linear simultaneous scheme is already being used in real time regional assimilation studies and is about to undergo an operational trial. In the near future, it is anticipated to further develop the 1-D variational retrieval scheme and to undertake extensive data impact studies in the region as a precursor to operational use of soundings from this system.

A PC-ARM implementation of the linear simultaneous method has been completed and the system has been used to provide quality soundings for both operational and research purposes.

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References


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