

A physically based operational atmospheric sounding system for TOVS data in the Australian region

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The Australian Bureau of Meteorology implemented a physically based real-time TOVS processing system in November 1987. This system provides atmospheric temperature and moisture soundings, total ozone concentration, and cloud height and amount information for the Australian region. The scheme uses either a statistical retrieval based, or an operational numerical weather prediction (NWP) model derived, first guess for temperature and moisture fields. Numerically forecast or current analysis-based first guess surface temperature and surface moisture fields are also used. In addition, in the retrieval process, the scheme uses operational numerical analysis and prognosis fields to control the quality of the processing of radiance data into meteorological parameters. Empirical adjustments to calibration and atmospheric transmittances are also used operationally, based on historic synchronous satellite and radiosonde data. This system has been run continuously in real-time from late 1987 and provides real-time data to the National Meteorological Centre, Regional Forecast Centres, and research workers.

Introduction

Since Christmas Day 1963, when the Australian Bureau of Meteorology (BOM) first received satellite imagery, analysis and forecasting in the Australian region have depended heavily on satellite data. These data have been used continuously by forecasters for a variety of operational purposes (BOM 1984) and they have also been used for several tasks within the National Meteorological Centre (NMC). From the late 1960s, use of the data at NMC was via subjective cloud picture interpretation (Guymier 1968; Zillman 1968; Rutherford 1968) providing quantitative estimates of mean sea level pressure (MSLP) and 1000–500 hPa thickness for the operational numerical analysis and prognosis system. Cloud images were also essential for nephanalysis and significant weather charts. In the later part of the 1970s, after the utility of satellite vertical temperature profiles was established, clear column radiance data from the Vertical Temperature Profile Radiometer (VTPR) instrument, carried on the NOAA polar orbiting satellites, were processed in NMC Melbourne and used in the operational hemispheric analysis.

The benefit of temperature and moisture profiles from the second generation of sounders on the TIROS-N series of satellites is long established (Kelly et al. 1978; Bourke et al. 1982) and these data have assumed an ever increasing role in the numerical analysis and prognosis system of the BOM. This role has been enhanced since May 1980 by the ability to receive and process these data locally in real-time (Kelly et al. 1983). Initially, the retrieval system involved a statistical procedure closely coupled to the operational analysis and prognosis scheme. The regression coefficients used in the retrieval process were determined largely by the latitude of the soundings being produced. This system was later replaced by one which used the microwave radiances and discriminant analysis to select regression coefficients for the retrieval process (Kelly and Le Marshall 1983), thereby selecting regression coefficients by synoptic type rather than by latitude bands.

In late 1985, partly as a result of a long-standing collaborative research program with the University of Wisconsin, the BOM implemented the

Australian Region McIDAS (ARM) (Le Marshall et al. 1987). This system was established in such a way that it provided real-time access to a very extensive historical and real-time data base (the NMC data base). The system also provided an extensive number of application programs to enable use to be made of the data base for operational and research purposes. It was within this environment that this physically based operational atmospheric sounding system, using TOVS data in the Australian region, was introduced. The retrievals in this system were made by using a simultaneous solution of the radiative transfer equation similar to that described by Smith et al. (1985).

This paper notes the advantages provided by a physical retrieval scheme compared to those associated with statistical schemes, and also notes the particular advantages of a scheme which provides simultaneous retrieval of temperature and moisture profiles and skin temperature. It describes the retrieval methodology, noting the important features of the new real-time retrieval system. It also provides verification data and illustrates some of the products derived from the system.

Physical basis of the retrieval system

The retrieval methodology

In the past, local processing of TOVS data for operational use in the BOM has been achieved using a statistical retrieval scheme (Le Marshall et al. 1985) which has used information from NMC's operational regional analysis and prognosis system to enhance and 'quality control' the retrieval process. The inherent advantages of a physically based retrieval scheme compared to a statistical retrieval scheme are, however, well known (see for example Smith et al. (1983)). These advantages include explicit treatment of surface parameters (such as skin temperature, emissivity and elevation), the computation of cloud height and amount in the processing scheme, and the proper treatment of non-nadir radiances to avoid the problems often inherent in statistical limb correction (Le Marshall and Schreiner 1985). With these considerations in mind and noting the results from previous inter-comparison studies, which compared temperature and moisture fields derived from TOVS data using different retrieval techniques (Le Marshall 1985), it was decided to implement, for operational purposes, a physically based retrieval scheme. Being aware of the chance of positive error feedback in some physical solutions which solve for temperature and moisture profile sequentially, and noting the advantages of solving simultaneously for skin temperature and atmospheric temperature and moisture (Smith et al. 1984), it was decided to implement an operational

system based on a perturbation solution of the radiative transfer equation similar to that of Smith et al. (1985). Using this method, the difference between the observed and estimated brightness temperature, δT^* , recorded by each channel of the satellite instrument is given by

$$\delta T^* = \delta T_s f_s \tau_s - \int_{p_s}^0 \delta U \left[\frac{\partial T}{\partial p} \frac{\partial \tau}{\partial U} f \right] dp + \int_{p_s}^0 \delta T \left[\left(\frac{\partial \tau}{\partial p} - \frac{\partial \tau}{\partial T} \right) f \right] dp$$

where T , U , p and B represent temperature, precipitable water, pressure and the Planck function respectively, and $f = (\partial B / \partial T) / (\partial B / \partial T^*)$. In addition, τ represents transmittance, while the subscript s refers to the surface and T^* denotes brightness temperature.

This equation is solved for δT , δU and δT_s from the satellite radiance observations after expressing the perturbed profiles in terms of pressure dependent basis functions. In this case the weighting functions for HIRS Channels 7, 11 and 12 are used as the water vapour basis functions, while the weighting functions for HIRS Channels 1, 3, 7 and MSU Channels 2, 3 and 4 are used for the temperature profile basis functions. The numerical solution is similar to that given by Smith et al. (1985).

First guess fields

In the operational scheme the first guess is provided by the operational regional analysis and prognosis scheme, or by using a statistical retrieval technique which incorporates discriminant analysis to provide a different mean profile and regression coefficients for atmospheres representative of different synoptic types. The important first guess surface temperature and moisture fields are at present derived from the regional optimum interpolation scheme of Keenan et al. (1986). This system can use a modelled diurnal cycle to provide a first guess for surface fields in consecutive three-hourly analyses.

Calibration and transmittance calculation

The calibration technique and transmittance functions used by this system were initially similar to those of Smith et al. (1985). However, from the calculation of synthetic radiances, using a large sample of synchronous radiosonde data, it has been found that consistent and systematic differences between satellite measured and theoretical radiances occur unless a careful empirical or observation-based adjustment to calibration procedures and transmittance functions are made. As a result, after determining the discriminant groups associated with the observed radiances using a method similar to that of Le Marshall et al.

(1986), estimates of instrumental bias, a correction to the transmittance and errors are calculated from the regional satellite and radiosonde match data. These are then subsequently used in the operational retrieval process.

Cloud

In the operational scheme partly cloudy radiances are used to determine the cloud pressure (P_c) which minimises the expression

$$(I_i - I_i^{cl}) \varepsilon_j \int_{p_s}^{p_c} \tau_j(p) \frac{\partial B_i}{\partial p} dp \\ - (I_j - I_j^{cl}) \varepsilon_i \int_{p_s}^{p_c} \tau_i(p) \frac{\partial B_j}{\partial p} dp$$

(after Smith and Platt 1977), where i and j are typically HIRS Channels 5 and 7. The variable I^{cl} represents a clear column radiance and ε represents cloud emissivity.

Subsequent to this the effective cloud amount (ne) is calculated using,

$$ne_i = I_i - I_i^{cl} / \int_{p_s}^{p_c} \tau_i(p) \frac{\partial B}{\partial p} dp$$

Alternative formulations for calculating cloud height and amount, using additional cloud channels, are under consideration for the scheme, while the use of real-time AVHRR data in the cloud algorithm will become a possibility as it becomes available from the BOM's full national network of S-band direct readout satellite groundstations.

Ozone

Total ozone amount is being calculated in real-time using a technique similar to that described by Ma et al. (1984). The technique uses the atmospheric channels of the HIRS instrument, namely Channels 1 to 4, to provide a first guess ozone concentration profile with a carefully positioned peak. Subsequently radiance data from the 9.6 micron ozone channel are used to provide total ozone concentration, from an iterative solution of the inverse radiative transfer equation.

An effort is being made to improve this technique in the Australian region by using historic synchronous and colocated Dobson spectrophotometer data from Melbourne, Hobart, Brisbane, Perth and Macquarie Island, to provide independent estimates of total ozone and Umkehr profiles. Ozone sonde flights from Melbourne are also being used.

The operational TOVS data utilisation system

Reception and processing hardware

TOVS data in Manipulated Information Rate Processor (MIRP) form are acquired directly in

digital HRPT format in Melbourne and Perth. These MIRP data contain information from the TOVS package as well as the ARGOS, Solar Environment Monitor (SEM) and other environmental packages. A schematic diagram showing the groundstations in Melbourne and Perth, their connections to the Fujitsu M180 mainframe in Melbourne and other hardware components in the data utilisation system are seen in Fig. 1. The data are processed by an automatically scheduled job within the ARM system and the products are put into a cyclic data set for access by NMC and other users after 20 minutes of processing.

The operational processing system

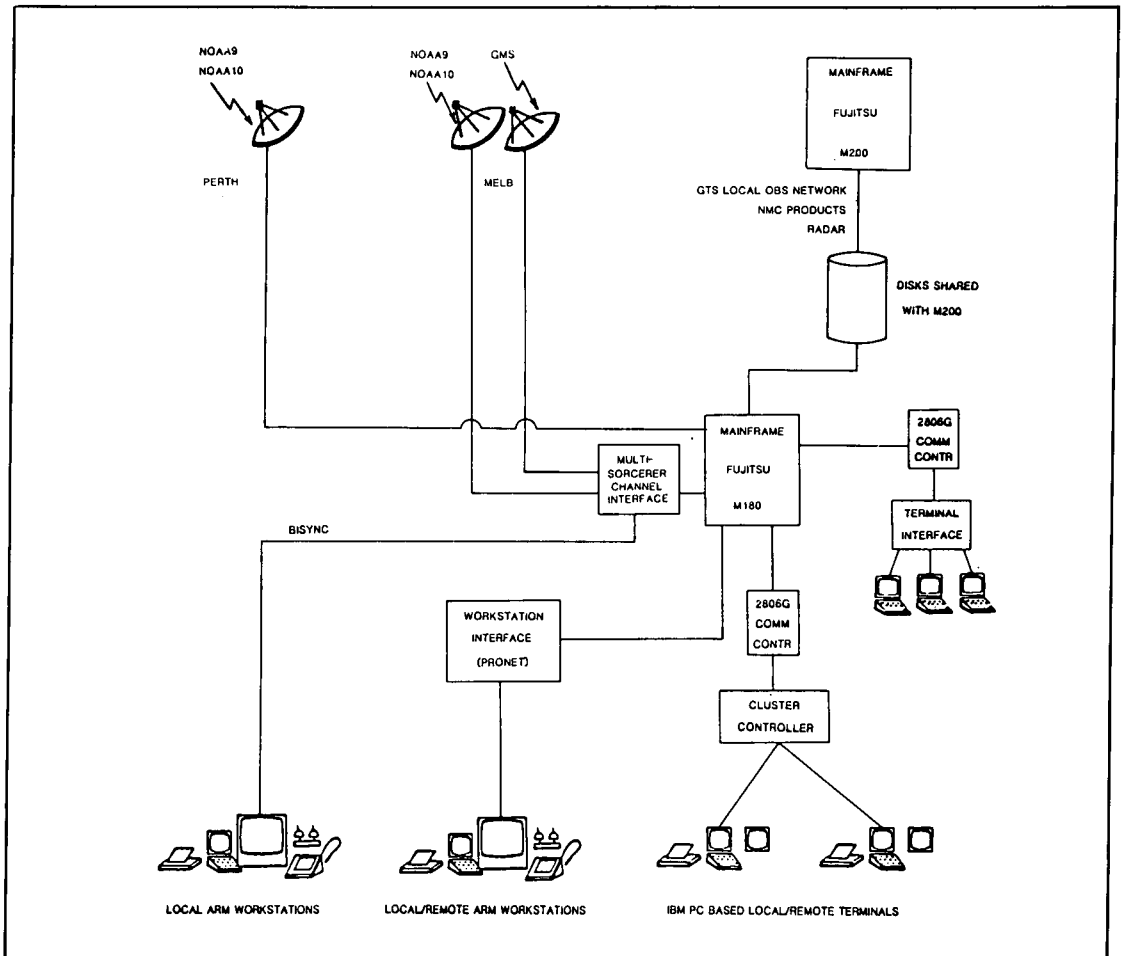
An overview of the present TOVS processing scheme is given in Fig. 2. An ensemble of eleven programs is necessary to fully process the data, using over twenty reference data files to filter and adjust the raw input into three main production files. The ensemble can be split into three main sections: preprocessing, sounding radiance preparation and retrieval. The preprocessing is done by the first four programs whose activities are listed in Fig. 2. These programs initiate processing for each orbit of reasonable length and move the satellite telemetry into computer length words. They interpolate analysis and prognosis fields to the orbit time for use in the processing, and finally earth locate and calibrate the high resolution infrared radiometer sounder (HIRS) and microwave sounding unit (MSU) data. Data collection platform (DCP) data, which includes data from buoys, fixed platforms and Antarctic stations, are also located and processed by this system.

Sounding radiance preparation is achieved by the fifth program. This program limb corrects the HIRS and MSU data as required for first guess calculations, the retrieval process, ozone calculation, display and other purposes. It colocates the HIRS and MSU data, checks the MSU data for rainfall contamination and edits the MSU data using the surface temperature and analysis/prognosis fields. The resultant data is then put into two production files.

The sixth program is the simultaneous retrieval algorithm, described in the previous section, which produces skin temperature, atmospheric temperature and moisture profiles, cloud height and amount, and total ozone estimates. These fields are automatically edited, where appropriate, using operational analysis and prognosis data. The remaining programs edit and filter the data and also generate wind and geopotential height fields.

The final program generates a TOVS archive, initiates the recording of synchronous satellite and radiosonde match data, and also generates regression coefficients and empirical correction data for calibration and the transmittance functions.

Fig. 1 The TOVS data utilisation system.



Results

The new retrieval scheme has been running in real-time since late 1987. Typical bias, standard difference and RMS difference plots compared to independent NMC analyses, interpolated to the satellite pass time, are seen in Fig. 3. The retrievals for a satellite-based 500 hPa temperature field and the related independent operational NMC analysis are seen in Fig. 4, along with a scatter diagram showing the relationship between the two fields. In general the scheme has performed with few problems during its initial period, with some differences compared to the previous operational scheme being recorded, particularly in relation to moisture and stability fields. A report showing quantitative differences between the two schemes will be completed in early 1989.

Use of the data in NWP has to date consisted of a number of mid-latitude and tropical case studies, using the new regional data assimilation scheme (RASP) which is described in Mills (1989). It is anticipated that this assimilation scheme will be operationally implemented in late 1989 and subsequent to real-time testing, will use TOVS data from this retrieval scheme.

Some early indication of the impact of these TOVS data on operational analyses may be gained by examination of Figs 5 and 6. Here assimilation analyses, generated using the new RASP scheme, are presented. Figures 5(a) and (b) show potential temperature cross-sections through a cold front for both the NMC operational analysis and an assimilation analysis from the RASP system using

Fig. 2 The TOVS data processing scheme.

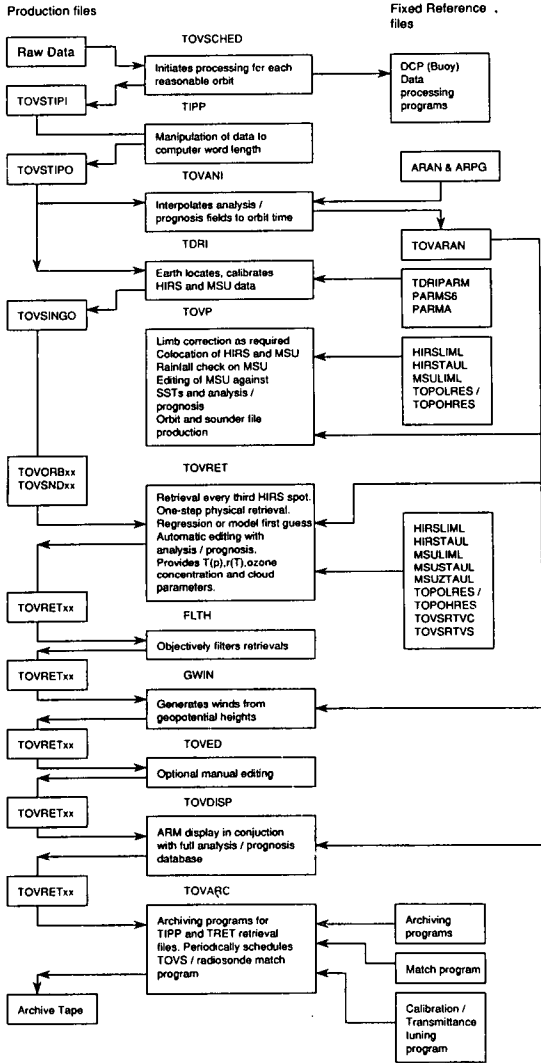


Fig. 3 Bias and standard difference (a) and RMS difference (b) comparing NMC temperature analyses to NOAA-10 temperatures for 1 March 1988.

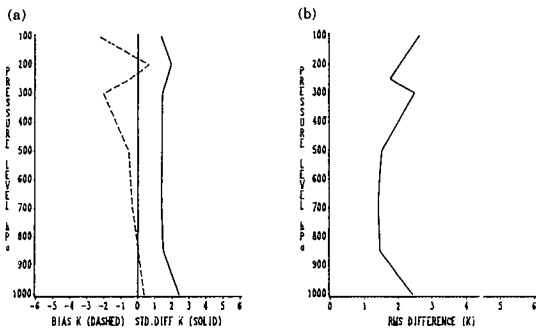
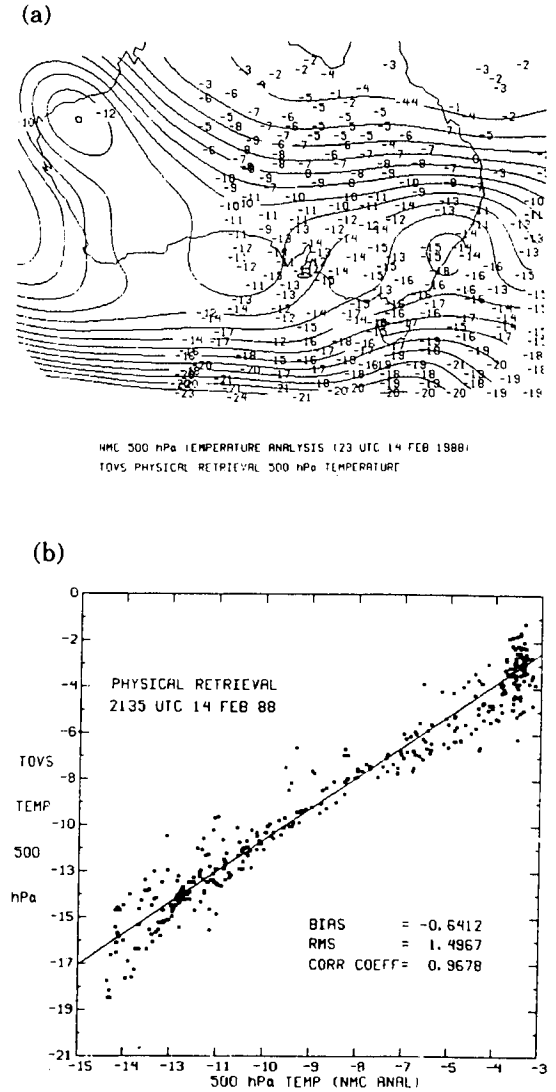


Fig. 4 500 hPa TOVS temperatures with a related independent NMC analysis (a), and the corresponding scatter diagram and statistics (b).



the TOVS data, while Figs 6(a) and (b) show the 1000–500 hPa thicknesses for the same cases. In both cases the representation is closer to that expected for a summertime cold front when high resolution TOVS data is used.

Verification of cloud height data generated by this system is to be assisted by a lidar-based observation program run through late 1988, while verification of ozone data is well underway. Running values of total ozone for Melbourne derived from both the TOVS instrument and a Dobson spectrophotometer may be seen in Fig. 7.

Fig. 5 Frontal potential temperature cross-section from the NMC archive (a) and the corresponding section from an assimilation analysis using high resolution TOVS data (b).

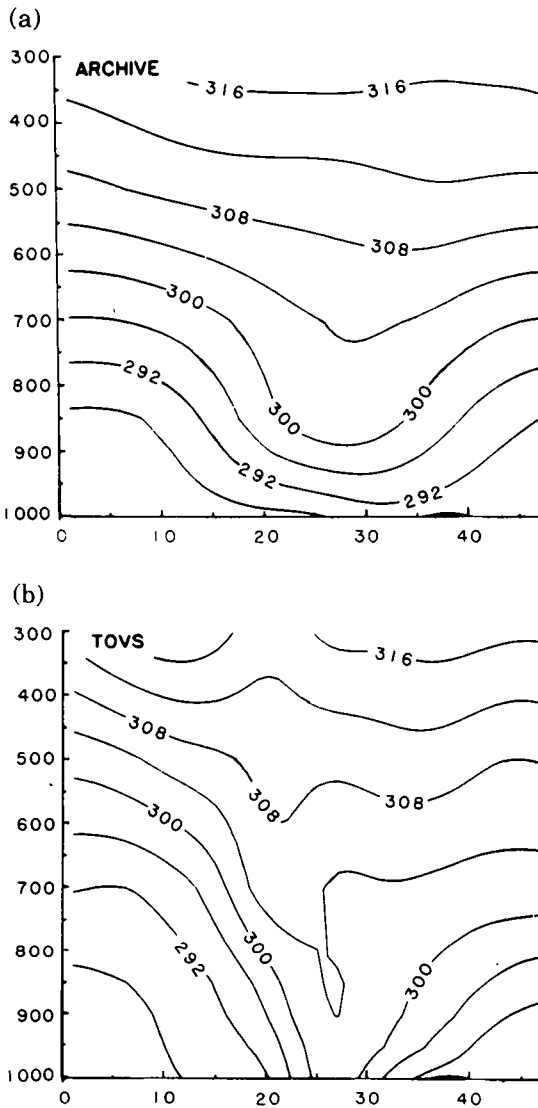


Fig. 6 1000 to 500 hPa analyses for the case noted in Fig. 5.

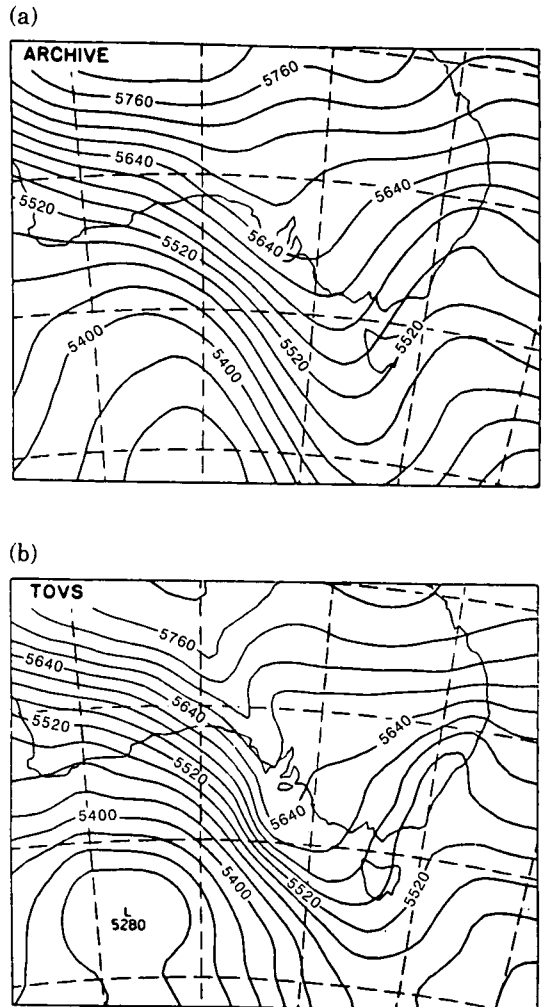
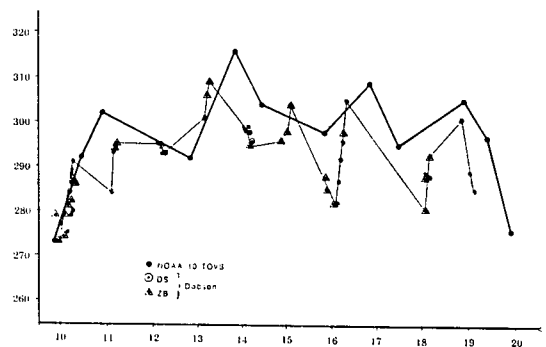


Fig. 7 Total ozone values from Dobson spectrophotometer and NOAA-10 data at Melbourne, 10 to 20 February 1988.



Conclusion

A physically based atmospheric sounding system, designed for operational use, has been running in real-time since late 1987. Results to date indicate the scheme is robust, free from gross errors and, subject to local calibration and transmittance tuning procedures, able to produce sounding data of good quality. The application of the data to NWP has been examined in a number of case studies and is about to be tested in an operational environment using the BOM's new regional NWP

system. Data from the system has also proved useful for several other applications including estimating total ozone and, for instance, calculating temperature anomalies associated with tropical cyclones and relating this data to storm intensity and maturity (Le Marshall et al. 1988). Exploitation of the data for mesoscale analysis and in an operational forecast office is just underway.

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