

Monitoring tropical cyclone intensity in the Australian region using NOAA TOVS data

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From the late 1980s the Bureau of Meteorology has been able to monitor tropical cyclone intensity using NOAA (National Oceanographic and Atmospheric Administration) TOVS (TIROS Operational Vertical Sounder) observations received at satellite groundstations in Darwin, Melbourne and Perth. These observations provide near-continuous coverage of the tropical oceans surrounding mainland Australia. Tropical cyclones in both the Indian Ocean and Coral Sea basins have been analysed using the Bureau's operational TOVS processing system. Both MSU (microwave sounding unit) and stratospheric HIRS (high resolution infrared sounder) observations have been employed to estimate the upper-level temperature fields around the tropical cyclones. This note shows that the TOVS retrieval system can define upper-level tropospheric temperature anomaly fields, which then can be related to storm central pressure and maximum wind speed. The ground-truth data used in this study generally consisted of operational estimates of storm intensity. Based on these data, temperature anomaly and storm intensity were related in a way that results in regression curves which may be used for operational purposes. This note also briefly examines the capacity of the next generation operational polar-orbiting NOAA sounder, the advanced TOVS (ATOVS), which includes the advanced microwave sounding unit (AMSU) to monitor tropical cyclones. It appears that this sounder has the potential to provide an improved capacity for analysis of these temperature anomalies and hence tropical cyclone intensity.

Introduction

While high temporal resolution GMS (Geostationary Meteorological Satellite) Stretched VISSR (visible and infrared spin-scan radiometer) observations form a prime database for the monitoring and forecasting of tropical cyclones in the Indian Ocean and Coral Sea, NOAA TOVS

and advanced very high resolution radiometer (AVHRR) observations also provide important data. These include high resolution visible and infrared imagery, sea-surface temperatures, temperature and moisture soundings, cloud height and cloud amount. In a given area, these are generally available, twice daily, from each of the polar-orbiting satellites. Of particular interest is the NOAA satellites' ability to monitor the upper-tropospheric temperature anomalies associated with tropical cyclones.

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Studies of these anomalies from satellite were first reported in 1978 when Kidder et al. (1978), compared typhoon upper-tropospheric temperature anomalies from the scanning microwave spectrometer (SCAMS) on NIMBUS-6 to surface pressure anomalies, providing evidence to support the relationship between intensity and temperature anomaly. Kidder (1979) demonstrated that, if the storm is assumed to be in hydrostatic equilibrium, a linear relationship exists between the magnitude of the upper air temperature anomaly and the surface pressure anomaly. Results which developed and further illustrated this relationship have been subsequently published (see, e.g., Velden and Smith 1983; Velden et al. 1984; Velden 1989 and Velden et al. 1991).

This note briefly describes the tropical cyclone database used in this study and the TOVS retrieval methodology employed to generate the upper-level temperature fields. It then notes the factors affecting the accuracy of the retrieved fields and their application to the monitoring of tropical cyclone intensity.

The database

The satellite data used were derived from NOAA 10 to 14 TOVS observations of ten tropical cyclones (Table 1), between 1989 and 1995. These cyclones were well observed by the TOVS instrument and the data were available by direct read-out to the Australian groundstation network.

For these tropical cyclones, with a combined duration of 77 days, 24 of the NOAA orbits archived met the criterion that the orbit must pass directly over, or close to, the centre of the cyclone. This prevents errors at large viewing angles due to limb effects and non-centring of the cyclone in the MSU field of view (e.g., Merrill 1995). The conventional data used, namely surface pressure and maximum wind speed, were taken from manual analyses from the Australian National Meteorological Centre (NMC), or from best track data. These two sources were generally based on observations available in real time and did not represent a 'special observation' dataset. The wind intensity and surface pressure estimates for the cyclones were mainly derived using the Dvorak technique (Dvorak 1984), available surface pressure or wind speed observations and other information such as that available from Tropical Cyclone Warning Centres.

The TOVS data-processing system

The TOVS data retrieval scheme used is similar to that described in Le Marshall et al. (1994). The scheme employs a simultaneous linear solution of the Radiative Transfer Equation (RTE) for temperature and absorbing constituent similar to Smith et al. (1991).

It uses the perturbation form of the RTE

$$\delta R_v = \beta_v^0(P_s) \tau_v^0(P_s) \delta T_s - \sum_{i=1}^N \int_0^{P_s} \beta_v^0(p) \delta T_i(p) \tau_v^0(p) d \ln \tau_v^0(p) \dots 1$$

Table 1. The tropical cyclones quantitatively analysed to relate temperature anomaly and storm intensity. (DDTT indicates the date (DD) and time (TT) in hours, UTC.)

<i>Name</i>	<i>Commenced</i>	<i>Duration</i>	<i>Status (DDTT — max wind speed)</i>	<i>No. of orbits processed</i>
<i>Orson</i>	17 Apr 1989	8 days	Severe tropical cyclone (2118–217 km/h)	3
<i>Sam</i>	13 Jan 1990	8 days	Tropical cyclone/storm (1712–113 km/h)	2
<i>Tina</i>	24 Jan 1990	5 days	Tropical cyclone/storm (2706–103 km/h)	1
<i>Vincent</i>	2 Jan 1990	5 day	Severe tropical cyclone (0308–124 km/h)	3
<i>Ian</i>	27 Feb 1990	6 days	Severe tropical cyclone (0112–155 km/h)	5
<i>Lena</i>	24 Jan 1993	11 days	Tropical cyclone/storm (2506–100 km/h)	1
<i>Rewa</i>	29 Dec 1993	24 days	Severe tropical cyclone (1612–198 km/h)	3
<i>Sadie</i>	29 Jan 1994	3 days	Tropical cyclone/storm (3012–90 km/h)	3
<i>Violet</i>	4 Mar 1995	4 days	Severe tropical cyclone (0512–139 km/h)	1
<i>Warren</i>	5 Mar 1995	3 days	Tropical cyclone/storm (0512–89 km/h)	2

where R_v is the spectral radiance, N is the number of optically active atmospheric constituents, δ is the true minus initial value, the superscript 0 denotes the initial value of the variable, $\tau_v(p)$ is the total transmittance above pressure level p , τ_i is the transmittance of the i^{th} absorbing constituent, subscript v denotes the frequency of observation, $T_i(p)$ is the effective temperature of the i^{th} absorbing constituent, P_s is the surface pressure and

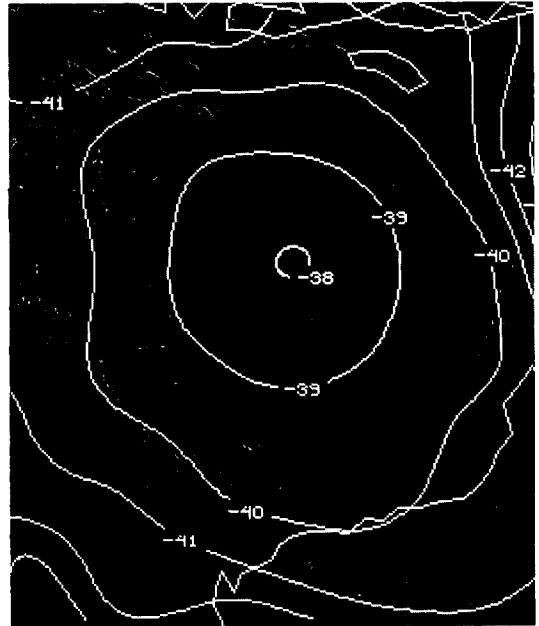
$$\beta_v^0(p) = \partial B_v(T^0) / \partial T \quad \dots 2$$

$$\delta T_i(p) = T_i(p) - T^0(p) \quad \dots 3$$

where $B_v(p)$ is the Planck radiance. This perturbation form of the RTE is solved using direct linear matrix inversion.

The first-guess options available to the system are forecast model or regression generated fields and climatology. In this study, the first guess was a climatology, specifically developed to provide an appropriate first guess for the Australian tropics. The differences in upper tropospheric tropical retrievals using model-based and climatology-based first-guess data were examined in great detail for late 1992, and indicated that there would be no significant impact on this study from a climatological first guess. The retrieval scheme was carefully quality controlled and also produced estimates of cloud amount and height, surface temperature and total ozone.

Fig. 1 Tropical cyclone *Orson* with TOVS 250 hPa temperature analysis (°C) at 0530 UTC on 27 October 1992



the smaller localised warming patterns associated with cyclones that are less intense, developing storms or small tropical cyclones. The effects of limb resolution may also lead to a reduction of the warm anomaly. In addition to these considerations, other factors to be borne in mind include the possibility that the MSU footprint may not be centred on the storm anomaly (misalignment) and there may be rainfall contamination associated with the observations. The effects of misalignment on the microwave observations, possibly lowering the anomaly by a degree or more, is demonstrated by van Burgel et al. (1994) and Merrill (1995). The cooling effect of precipitation, to an extent, can be gauged by viewing sequential passes, examination of the infrared imagery (where, for example, a very low 11 μm (Channel 8) brightness temperature often means rain contamination), the inspection of the retrieved fields and an examination of the manner in which limb-corrected microwave MSU-2 and MSU-3 varies across the swath through the storm centre.

Many of the problems arising from the considerations listed above may also be identified by the use of sequential observations from all of the current NOAA polar orbiters (NOAA- 11, 12 and 14) which presently provide these data for real-time use, six times per day.

Observing Australian region tropical cyclones with the TOVS

Temperature retrievals were carried out in the vicinity of the tropical cyclones using radiances from MSU channels 2, 3 and 4, as well as radiances from the stratospheric HIRS channels 1 and 2. The other channels were not used because of the influence of significant or total cloud cover, which limits the utility of the tropospheric HIRS retrievals around the storm. The TOVS 250 hPa temperature fields displayed the warm upper air anomalies associated with tropical cyclones. Such a field is displayed in Fig. 1 for tropical cyclone *Orson*. This temperature anomaly can be quantified at the 250 hPa level and a number of authors (Kidder et al. 1978; Velden and Smith 1983) have related this anomaly to tropical cyclone intensity, and, in particular, to storm central pressure and maximum wind speed.

When determining these anomalies, however, several points need to be considered. The major axis of the MSU footprint is approximately 113 km subsatellite and approximately 300 km at the limb and hence the MSU may not fully capture

Estimation of surface intensity

Tropical cyclones from several seasons (Table 1) have been examined in detail. The upper tropospheric temperature anomalies were determined using TOVS data and related to the analysed storm central surface pressure departure from ambient conditions. The 250 hPa temperature anomaly was estimated using differences between the temperature at the storm centre and a radius of 6°, and the surface pressure anomaly was the pressure difference between the cyclone centre and the environmental pressure at 6° radius. Where possible, sequential imagery and soundings from orbits passing close to the tropical cyclone (within 5°) have been employed.

Using twenty-four orbits taken between 1989 and 1995, linear regression was used to formulate the relationship between surface pressure anomaly, Δp (hPa), and the 250 hPa temperature anomaly ΔT_{250} (K). The least squares regression relationship, assuming no intercept, is

$$\Delta p = 19.1 \Delta T_{250} \text{ [hPa]} \quad \dots 4$$

The rms error associated with this is 11.9 hPa and the relationship is displayed in Fig. 2(a). The least squares regression relationship, allowing an intercept, is changed to

$$\Delta p = 14.9 \Delta T_{250} + 8.4 \text{ [hPa]} \quad \dots 5$$

This expression has an rms error of 11.4 hPa. Equation 4 is not dissimilar to that found by Velden (1989) for Atlantic hurricane cases, particularly those south of 30° N, where he found $\Delta p = 18.7 \Delta T_{250} - 3$ [hPa].

Fig. 2(a) Estimated surface pressure anomaly (hPa) versus tropical cyclone-related upper tropospheric temperature anomaly (K) from TOVS, assuming no intercept (datapoints plotted).

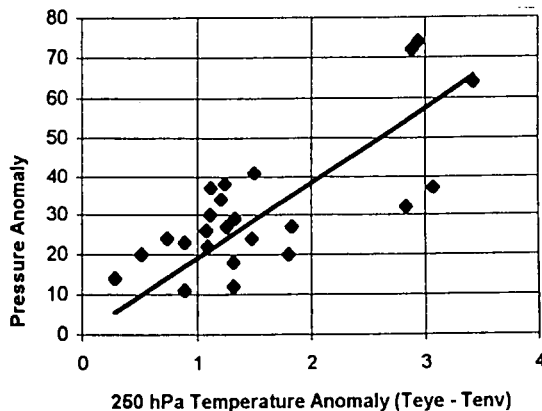
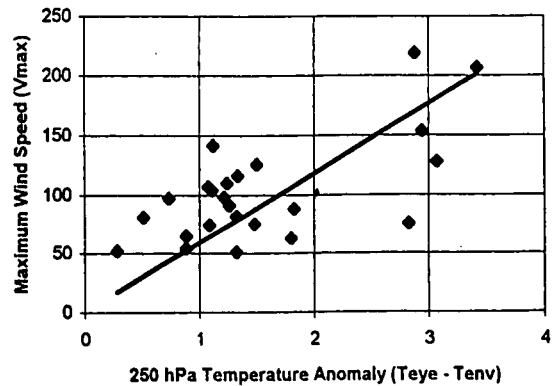


Fig. 2(b) Estimated maximum wind speed (km/h) versus tropical cyclone-related upper tropospheric temperature anomaly (K) from TOVS, assuming no intercept (datapoints plotted).



Estimation of maximum wind speed

The database at Table 1 was also used to define a relationship for maximum surface wind speed in terms of the 250 hPa temperature anomaly. Using the same twenty-four cases and linear regression and assuming no intercept, the relationship shown below was derived.

$$V_{max} = 58.9 \Delta T_{250} \text{ [km/h]} \quad \dots 6$$

This expression results in a rms error of 40.8 km/h and is plotted in Fig. 2 (b). Using linear regression and allowing an intercept, the relationship becomes

$$V_{max} = 34.0 \Delta T_{250} + 49.8 \text{ [km/h]} \quad \dots 7$$

This has an rms error of 33.7 km/h. In the case of maximum wind speed, however, it is important to note that the Tropical Cyclone Warning Centres do not derive their minimum pressure and maximum wind speed values independently. They usually derive maximum wind speed from minimum surface pressure, using methods similar to those described in Atkinson and Holliday (1977) and, as a result, the absolute accuracy of the relationships are difficult to determine. It also needs to be reiterated that these storm intensity relationships have been impacted by several sources of error; non-centring of the storm in the MSU footprint, radiometric noise, the influence of clouds and precipitation, vertical position of the maximum temperature anomaly varying from storm to storm, limb effects (e.g. Merrill 1995; van Burgel 1994) and errors in the ground-truth data.

Despite these problems, the relationships between the upper tropospheric temperature anomaly, storm intensity and surface pressure anomaly appear consistent with results found in earlier studies.

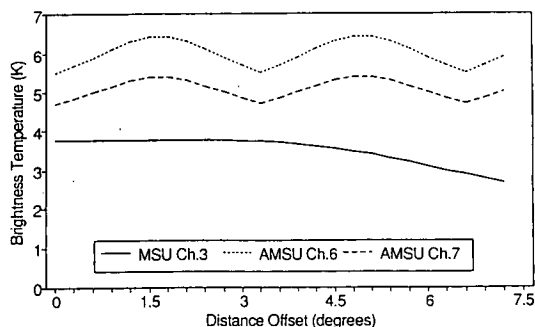
The future

As expected the warm temperature anomaly derived from MSU and stratospheric HIRS data (Fig. 2) is smaller in magnitude than that found using radiosonde or dropsonde data (e.g. Hawkins and Imbembo 1976).

The improved resolution (50 km subsatellite) of the advanced microwave sounding unit (AMSU), a component of the advanced TOVS (ATOVS) on the new generation operational NOAA satellites will, however, improve the ability to remotely sense the upper tropospheric cyclone-related temperature anomalies. The AMSU has a half-power beam width of 3.3° and the distance between adjacent scan spots is also 3.3° compared to 7.5° and 9.45° , respectively, for MSU, and as a result misalignment errors should be ameliorated.

A representative tropical cyclone temperature anomaly (obtained by compositing the hurricane *Inez* (1966) central core anomaly (Hawkins and Imbembo 1976) with a local broader-scale climatology from Western Australia) has been used to generate synthetic clear radiance fields seen by both the MSU and AMSU instruments (van Burgel et al. 1995). The variation of brightness temperature anomaly with position near nadir for two AMSU channels and for MSU 3 is displayed in Fig. 3 and shows the effect of the tropical cyclone position, relative to nadir, along a scan line. It should be noted that the MSU has a central footprint while the two central AMSU footprints straddle nadir. It is clear that the spectral characteristics and in particular the spatial resolution of the AMSU instrument has led to a higher microwave brightness temperature anomaly compared to the MSU instrument as well as less variation with misalignment for the same cyclone-related anomaly. As a result, the AMSU will provide improved resolution of the upper tropospheric temperature anomalies associated with tropical cyclones and increased variance and information content compared to the MSU. This should increase the ability to monitor tropical cyclone intensity.

Fig. 3 Representative variation of tropical cyclone related brightness temperature anomaly (K) for MSU channel 3 and for AMSU channels 6 and 7 with position of the tropical cyclone from nadir (degrees) along a scan line.



temperature and moisture soundings, total ozone estimates, cloud height and amount, skin temperatures and other datasets, for operational and research purposes (Le Marshall et al. 1994).

This note extends previous studies, in particular, those of Velden and Smith (1983); Velden (1989) and Velden et al. (1991). It examined an area of the tropics not previously studied, and, by use of twenty-four suitable observations of tropical cyclones by satellite, has developed relationships between upper tropospheric temperature anomalies, maximum wind speeds and surface pressure anomalies.

The relationships found are not dissimilar to those discussed in Velden (1989) and Velden et al. (1991) for tropical cyclones in the north Atlantic and northwest Pacific regions. The uncertainties associated with the relationships found are a little higher than those of Velden (1991) because the database consisted mainly of operational data and the study has not benefited from the comparisons with special *in situ* reconnaissance reports. These relationships should be enhanced by observations taken over future seasons.

As a result of this work, the TOVS data now provide a basic sounding capacity which can be used to provide fields of temperature and moisture for numerical forecasts and tropical cyclone intensity monitoring, a capability which may be used as an adjunct to the usual operational method of image interpretation (e.g., Dvorak's technique) to gauge tropical cyclone intensity. The surface pressure anomaly and wind speed algorithms reported in this paper will be tested over the 1996–1997 tropical cyclone season in the Western Australia Regional Office as a supplement to current techniques for estimating tropical cyclone intensity.

Summary and conclusions

The Australian NOAA S-band groundstation network and the associated TOVS/AVHRR processing capacity are being routinely used to produce

While future refinement will allow a fuller exploitation of this technique, the present results indicate the potential of TOVS data for estimating the intensity of tropical cyclones in the Australian region. It is important while estimating cyclone intensity to ensure as far as is possible that the temperature anomaly is not rain affected, is close to the centre of the orbit, is well centred in the MSU field of view and is consistent in consecutive orbits.

This study has also discussed the characteristics of the next generation operational instrument, the ATOVS, which carries the AMSU instrument. Microwave sounding using this instrument will benefit from an increased number of channels and higher spatial resolution. It has been shown the increased spatial resolution of the AMSU will result in better defined and larger temperature anomalies associated with a particular storm and it is expected to provide an improved monitoring capacity.

Overall, it is clear that the local groundstation network, in combination with the current operational processing algorithm, is a useful tool for monitoring tropical cyclone intensity. The utility of this system will clearly increase with the availability of the advanced microwave sounding unit data in 1997.

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