The warm-core structure of Super Typhoon Rammasun derived by FY-3C microwave temperature sounder measurements

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Abstract

The microwave temperature sounder (MWTS) on board the third FengYun satellite (FY-3C) is well suited for the detection of tropical cyclones because the observed radiance is insignificantly affected by non-precipitating clouds. In this study, a stepwise multiple linear regression technique is proposed to retrieve the atmospheric temperature profiles based on MWTS measurements. Under clear-sky conditions, the root-mean-square error of retrieved temperature is no >1.4 K, which is low enough to monitor the thermal structure within typhoons. An application of this method to the Super Typhoon Rammasun resolves the warm-core eye and temperature gradients across the eye-wall very well.

Keywords: microwave temperature sounder; warm core; FengYun satellite

1. Introduction

The warm-core structure is one of the most notable characteristics of typhoons. Typhoons are cyclonic circulations, and the establishment of the high-level warm-core structure is the main marker of typhoon generation. Wang et al. (2010) made some efforts to study the formation of typhoon warm cores and noted that the warm core is a result of huge release of latent heat from the warm and moist inflow during the upward movement of air in the storm’s core. Palmen and Newton (1969) found that the precipitation from typhoons is correlated with the area of the warm core: the larger the area of the warm core, the greater the precipitation. In general, the maximum of temperature anomaly for most typhoons appears in the upper troposphere (approximately 200–400 hPa). The warm-core thermal structure forms at the development stage of typhoon, and it reaches its maximum strength at the mature stage. Once the warm-core structure weakens and disappears, the typhoon will dissipate.

It is well known that typhoons develop over the open ocean; due to the lack of traditional observations, there has been a major increase in the use of satellite observations, especially microwave measurements, to detect typhoons. As early as 1978, the Nimbus-6 scanning microwave spectrometer measurements were utilized to study Typhoon June, and a warm-core structure was first imaged (Rosenkranz et al., 1978). During the same year, through microwave sensors, Kidder et al. (1978) verified that the warm anomaly was correlated to the typhoon’s minimum sea level pressure and maximum wind speed. Later on, microwave radiance data from a microwave sounding unit was used to estimate the intensity of a large sample of typhoons (Velden and Smith, 1983; Velden, 1989; Velden et al., 1991). Kidder et al. (2000) and Zhu et al. (2002) used brightness temperature data from an advanced microwave sounding unit to retrieve atmospheric temperature profiles and found that the root-mean-square error of the data was <2 K. With the launch of the Suomi NPP satellite, the sounding channels of the advanced technology microwave sounder (ATMS) onboard the Suomi NPP have also been utilized to detect the warm-core structure of typhoons (Zhu and Weng, 2013).

A new generation of polar-orbiting satellite series, the FY-3 fleet, will consist of seven satellites; each one will be launched approximately every 2 years (Zhang et al., 2009). The first operational satellite, FY-3C, was successfully launched into morning-configured orbit on 23 September 2013. MWTS on board FY-3C are designed with many more channels, finer spatial resolution, and better sensor precision than previous instruments (Dong et al., 2009; Wang and Li, 2014), which makes MWTS measurements more capable to detect the thermal features of typhoons.

2. MWTS instrument and typhoon case description

MWTS is a total power cross-track radiometer, and it has a maximum scan angle of 49.5°. Along each
scan line, there are 90 fields of view (FOVs), and the scan stepping angle and beam width of each FOV is 2.2°; therefore, the nominal spatial resolution at nadir is approximately 33 km, which can depict the thermal structure within typhoon better than previous instruments (Weng et al., 2012). Compared to the MWTS onboard the FY-3A/B, the MWTS on board the FY-3C has a total of 13 channels in the oxygen band, whose central frequencies are located from 50 to 60 GHz. The purpose of MWTS sounding channels is to record temperature information from the low troposphere to the upper stratosphere because the absorption and emission of microwave radiation by atmospheric oxygen enables the MWTS to passively sound temperature as a function of altitude. Some selected channel characteristics, such as channel central frequency, 3-dB bandwidth, sensor measurement precision (noise-equivalent delta temperature), and the height of peak weighting functions, are listed in Table 1. The weighting functions for the 13 MWTS channels (1–13 from bottom to top), which are calculated using a standard US atmospheric profile, such as the Community Radiative Transfer Model (CRTM) input, are given in Figure 1. The CRTM was developed by the US Joint Centre for Satellite Data Assimilation (Han et al., 2007; Weng, 2007). Measurements from MWTS channels 3 to 10 will be used to retrieve the atmospheric temperature profile in this article.

Super Typhoon Rammasun formed as a tropical depression over the northwest Pacific Ocean on the morning of 11 July. It intensified gradually and moved westwards steadily in the following few days. Rammasun developed into a severe typhoon on 15 and 16 July, moving across the central part of the Philippines and entering the South China Sea. After weakening over land, Rammasun reorganized over the South China Sea and intensified into a super typhoon on 18 July, reaching its peak intensity with an estimated sustained wind of 52 m s⁻¹ and minimum sea level pressure of 935 hPa. Figure 2 shows the spatial distributions of brightness temperatures observed from MWTS channel 1 within Super Typhoon Rammasun at 1353 UTC on 18 July 2014. The centre of typhoon is indicated by a typhoon symbol in white.

### Table 1. Channel characteristics of MWTS.

| Channel | Central frequency (GHz) | Bandwidth (MHz) | NEDT (K) | Peak weighting (hPa) |
|---------|-------------------------|-----------------|----------|---------------------|
| 1       | 50.300                  | 180             | 1.20     | Surface             |
| 2       | 51.760                  | 400             | 0.75     | Surface             |
| 3       | 52.800                  | 400             | 0.75     | 950                 |
| 4       | 53.596                  | 400             | 0.75     | 700                 |
| 5       | 54.400                  | 400             | 0.75     | 400                 |
| 6       | 54.940                  | 400             | 0.75     | 270                 |
| 7       | 55.500                  | 330             | 0.75     | 180                 |
| 8       | 57.290 (f₁)            | 330             | 0.75     | 90                  |
| 9       | f₀ ± 0.217              | 78              | 1.20     | 50                  |
| 10      | f₀ ± 0.322 ± 0.048      | 36              | 1.20     | 20                  |
| 11      | f₀ ± 0.322 ± 0.022      | 16              | 1.70     | 12                  |
| 12      | f₀ ± 0.322 ± 0.010      | 8               | 2.40     | 5                   |
| 13      | f₀ ± 0.322 ± 0.005      | 3               | 3.60     | 2                   |

### Figure 1. Vertical distribution of FY-3C MWTS channels 1–13 weighting functions calculated using US standard atmosphere.

### Figure 2. Distributions of observed brightness temperature from FY-3C MWTS channel 1 around Typhoon Rammasun at 1353 UTC on 18 July 2014. The centre of typhoon is indicated by a typhoon symbol in white.

3. **MWTS-derived warm-core structure**

As it is well known that the radiance in microwave bands is linearly proportional to the entire layer of atmospheric temperature, and the weighting functions of all MWTS sounding channels are essentially steady, the atmospheric temperature at a given pressure may be expressed as a linear combination of brightness temperatures measured at different sounding channels (Janssen, 1993). Following the similar algorithm proposed in Zhu et al. (2002), Equation (1) is utilized to retrieve the atmospheric temperature profiles; that is

\[
T(p) = \beta_0(p, \theta) + \sum_{i=1}^{n} \beta_i(p, \theta) T_b(v_i, \theta) \quad (1)
\]
where $p$ is the given pressure, $\nu_i$ is the central frequency for the chosen channel, $\theta$ represents the scan angle, and $T_b$ is the MWTS brightness temperature.

Practically, it may be not economical to utilize all sounding channel measurements because some of them may be correlated, providing redundant information. Therefore, the coefficients $\beta_0$ and $\beta_i$ (responding to the selected channels) are determined using a stepwise linear regression method at a 1% significance level. In fact, however, I tried stepwise regression and found that all channels are needed. The data collected from the collocated MWTS observations and Global Forecast System reanalysis field over ocean and land between 30°S and 30°N latitudes during 11–17 July 2014 are separately used to obtain the regression coefficients. Under a clear-sky condition, brightness temperatures from channels 3 to 10 are used to retrieve the temperatures at 21 pressure levels from 100 to 1000 hPa. Because the brightness temperatures of the surface and lower troposphere could be contaminated by large cloud and rain droplets, channels 3 and 4 are not used for the retrieval under precipitation conditions. In this article, the cloud emission and scattering index (CESI) method is first used to identify the cloud regions. The CESI can be defined (Han et al., 2015):

$$\text{CESI} = T_{\text{reg}}^{\text{MWHS}} - T_{\text{obs}}^{\text{MWHS}}$$

where $T_{\text{obs}}^{\text{MWHS}}$ is the microwave humidity sounder (MWHS) measurements and $T_{\text{reg}}^{\text{MWHS}}$ is calculated from the MWTS measurements using linear regression.

Figure 3 shows the spatial distributions of CESI within Super Typhoon Rammasun at 1353 UTC on 18 July 2014 derived from three selected paired channels: MWHS channel 5 (centred at 118.75 ± 0.8 GHz) and MWTS channel 6, MWHS channel 6 (centred at 118.75 ± 1.1 GHz) and MWTS channel 5, and MWHS channel 7 (centred at 118.75 ± 2.5 GHz) and MWTS channel 3. As shown in the figure, Super Typhoon Rammasun’s eye, eye-wall, and rain-bands are clearly captured in the CESI distributions. In this article, the observation will be treated as cloudy as long as one of the CESI for the three pairs is greater than zero.

The performance of the temperature retrieval from the MWTS brightness temperature is verified from a vertical profile of the root-mean-square error, which is computed using all of the collocated data set. As shown in Figure 4, the root-mean-square error is within 1.4 K, which is good enough to monitor the warm-core structure within typhoons. In addition, the author has verified against an independent subset of the same data used for training and found the similar results.

The vertical cross-sections of temperature anomaly of Typhoon Rammasun at the mature stage (1353 UTC on 18 July 2014) along 110.3°E are shown in Figure 5, respectively. The temperature anomaly is defined as a
deviation from the unperturbed environment. A warm core can be identified throughout the troposphere with a maximum anomaly of 8–10°C near 200 hPa and extending to the sea surface, which is similar to other observations. From the anomaly field, the radius of the Typhoon eye at the sea surface is observed to be approximately 100 km, and the eye tilts outward with height.

4. Summary

The three-dimensional warm-core structure is one of the most important parameters in monitoring typhoon intensity, studying typhoon inner core dynamics, and constructing the initial vortex for a typhoon simulation. In this study, we investigated the derivation of this structure from FY-3C MWTS measurements. To retrieve atmospheric temperature profiles from MWTS measurements, a stepwise regression algorithm was developed by using the collocated MWTS data and Global Forecast System (GFS) reanalysis field for each scan angle. The root-mean-square errors are <1.4 K at all pressure levels from 100 to 1000 hPa. An application to the Super Typhoon Rammasun shows that the warm-core eye and temperature gradients across the eye-wall can be captured very well. There is no doubt that the MWTS is extremely promising for improving our knowledge of typhoons and hurricanes.

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