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INVERSION OF TEMPERATURE FROM AMSU−A AND ITS APPLICATION ON WARM−CORE OF TROPICAL DEPRESSION OVER THE SOUTH CHINA SEA

YUAN Jin-nan (袁金南), MENG Wei-guang (蒙伟光), ZHANG Yan-xia (张艳霞), JIANG De-hai (蒋德海), LI Chun-hui (李春晖), MAO Wei-kang (毛伟康), HUANG Hui-jun (黄辉军)

(Guangzhou Institute of Tropical and Marine Meteorology/Guangdong Provincial Key Laboratory of Regional Numerical Weather Prediction, CMA, Guangzhou 510080 China)

Abstract: The linear regression and horizontally stepwise correction are conducted on the observational data from AMSU-A L1B of NOAA polar orbit satellite to invert a 40-layers (from 1,000 hPa to 0.1 hPa) dataset of atmospheric temperature with a horizontal resolution of 0.5°×0.5° after the correction of satellite antenna pattern and limb adjustment. Case study shows that the inversion data of temperature can reveal the detail structure of warm core in tropical cyclone. We choose two categories of tropical depressions (TDs) over the South China Sea, including the non-developing TDs and developing TDs. Both of them are developed downward from the middle and upper level to the lower level. Comparison between the evolutions of warm core in the two categories of TDs indicates that the warm core is developed downward from the middle and upper troposphere to the sea surface in all the downward-developing TDs. The difference is that in the group of further developing TDs, the warm core in the upper troposphere is intensified suddenly when it is extending to the sea surface. The warm core in the upper and lower troposphere is strengthened in a meantime. But the similar feature is not observed in the non-developing TDs. Then it may be helpful to judge the TD development by monitoring the change in its warm-core structure.

Key words: warm core structure; inversion of temperature from AMSU-A; tropical depression over the South China Sea; comparison analysis

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1 INTRODUCTION

The Advanced Microwave Sounding Unit (AMSU) carried by the NOAA-KLM polar orbit satellites can penetrate the clouds to observe the temperature and humidity. The AMSU is composed of AMSU-A and AMSU-B. And the AMSU-A is made up by AMSU-A1 and AMSU-A2, including 15 microwave sounding channels. In detail, the AMSU-A1 has 13 channels, including the 3rd, 4th to 14th and 15th channel, corresponding to the frequency of 50.3 GHz, 52.8-57.3 GHz and 89.0 GHz. And the AMSU-A2 has the 1st and 2nd channel with the frequency of 23.8 GHz and 31.4 GHz, respectively (Goodrum [1]). The 1st, 2nd, 3rd and 15th channel of AMSU-A is used to detect the surface elements, while the 4th to 14th channel are in charge of vertical sounding of air temperature. The 5 channels of AMSU-B observe the air humidity in vertical. The AMSU-A is able to receive the radiation values from 30 different earth views within a scan angle from −48.33° to +48.33°, and the spatial resolution at nadir is 48 km.

The methods inverting the temperature from AMSU-A observation include the statistic regression inversion, the physical inversion and the physical-statistic synthesized inversion (Wei and Xu[2]), as well as the neural network inversion, etc (Shi [3]). Considering its high horizontal resolution and ability of detecting the temperature in vertical, the AMSU-A observation has been inverted to temperature and applied to study the temperature structure of Tropical Cyclones (TCs) at home and abroad. Knaff et al.[4] used the temperature inverted from AMSU-A to analyze the thermal structure of two cyclones, and pointed out that the vertical thermal difference is very distinct between the two systems which resemble each other in the pictures from routine infrared satellite. Kidder et al.[5] argued that the AMSU observation, which is little affected by the cloud, was benefit of the TC sounding. Wei et al.[2, 6] have investigated the TC Dujuan and the 15 TCs landing on China from 2002 to 2003 according to the inversion temperature from AMSU-A, which can

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Biography: YUAN Jin-nan, Ph.D., primarily undertaking research on tropical cyclones.

Corresponding author: YUAN Jin-nan, e-mail: yuanjn@grmc.gov.cn

clearly describe the warm core structure in TC. And they also suggested that the temperature anomaly is well correlated with the central wind speed and minimum sea surface pressure.

The vortex in the middle troposphere is mostly located between 700 hPa and 500 hPa over the South China Sea (SCS), accompanied by the thermal structure of lower-cooling and upper-warming. And the TC (including the tropical depression, TD) over the SCS is developed from such mid-layer vortex by its downward strengthening from the middle and upper troposphere (Liang [7]). This is a typical process of TC formation. And the lack of observation on the ocean in the past has prevented the detail research on the thermal structure of TC generating from the downward extension of mid-layer vortex. In recent years, the advanced microwave sensor of satellites could detect the vertical distribution of air temperature, facilitating the study on the evolution of warm core structure in the TCs over the SCS induced by mid-layer vortex. This paper will use the 3-dimensional air temperature inverted from the AMSU-A observation to examine the evolution of warm core in the TDs over the SCS induced by mid-layer vortex, and to compare the difference of warm core structure between the developing and non-developing TDs. And we hope to search some clues of determining the development of such TDs over the SCS according to their thermal structure.

2 DATA AND METHOD OF INVERTING TEMPERATURE FROM AMSU-A OBSERVATION

2.1 *Data description*

The TD data is extracted from the TC best track data supplied by Joint Typhoon Warning Center (JTWC) in the United States. The dataset contains the 6-hourly longitude and latitude of TC center, the maximum wind speed near the TC center, etc. If the TD is not recorded before the TC formation or after the TC damping, the 850 hPa relative vorticity calculated from the global 6-hourly NCEP/NCAR reanalysis dataset with a horizontal resolution of 1°×1° will be employed to determine the position of TD center.

Here we only focus on the TDs which are developed from the middle and upper troposphere over the SCS. And this kind of TDs is identified according to the NCEP/NCAR reanalysis dataset, the infrared brightness temperature observed by TRMM satellites and the sea surface wind obtained by QSCAT satellites. Moreover, the TDs developed from the middle and upper troposphere can be divided into two categories. One includes the TDs that cannot strengthen to the TCs, and the other includes the TDs developing to TCs or even stronger cyclone systems later. Each category has 3 samples (Table 1).

The NOAA-15 satellite, which is a member of NOAA-KLM polar orbit satellites, is launched in May 1998. It has run for a long time to collect a long-record AMSU data. Thus the AMSU-A L1B dataset observed by NOAA-15 polar orbit satellite is used in this paper. According to the 6 TDs over the SCS listed in Table 1, the 6 months records of global AMSU-A L1B dataset are selected, including December 1999, August 2001, September 2002, May 2004, August 2007 and November 2008, respectively. The time when the warm core in TD arriving at the sea surface reaches its maximum strength is defined as the reference time. And a period from 48 hours before the reference time to 12 hours after the reference time are picked up to study the downward evolution of warm core and to compare their difference between the two categories of TDs. The duration of each case is 60 hours, which is shown in Table 1.

Table 1. The developed and non-developed TDs over the SCS.

Category	TD Name	Study period
Non-developed TDs over the SCS	TD9933	1999121312-1999121600 UTC
	TD0405	2004051312-2004051600 UTC
	TD0706	2007080100-2007080312 UTC
Developed TDs over the SCS	Usagi	2001080700-2001080912 UTC
	Mekkhala	2002092012-2002092300 UTC
	Maysak	2008110300-2008110512 UTC

2.2 *Method of inverting temperature from AMSU-A data*

Since the AMSU-A L1B does not supply the brightness temperature directly, we have to calculate the radiation to evaluate the brightness temperature. Then the MO scheme (Mo [8]) is adopted to conduct the Antenna Pattern Correction on the 15 AMSU-A sounding channels. Fig. 1 exhibits the corrected value ΔT of 30 earth views in the 15 AMSU-A sounding channels. Result implicates that the brightness temperature rises 0.3-2.7 K after the Antenna Pattern Correction, although the corrected value of brightness temperature is changed with the channels and earth views.

There are 30 earth scenes in AMSU-A, consistent with 30 different scan angles. And the peak height of weight function in channels is increased with the larger scan angle. This is termed of the limb effect, which has great impact on the AMSU-A observation with a maximum disturbance of 30 K. Also the influence of limb effect is varied in different channels and earth views (Fig.2). Hence the limb adjustment is required to further correct the brightness temperature after the Antenna Pattern Correction.

Many methods can be used to perform the limb

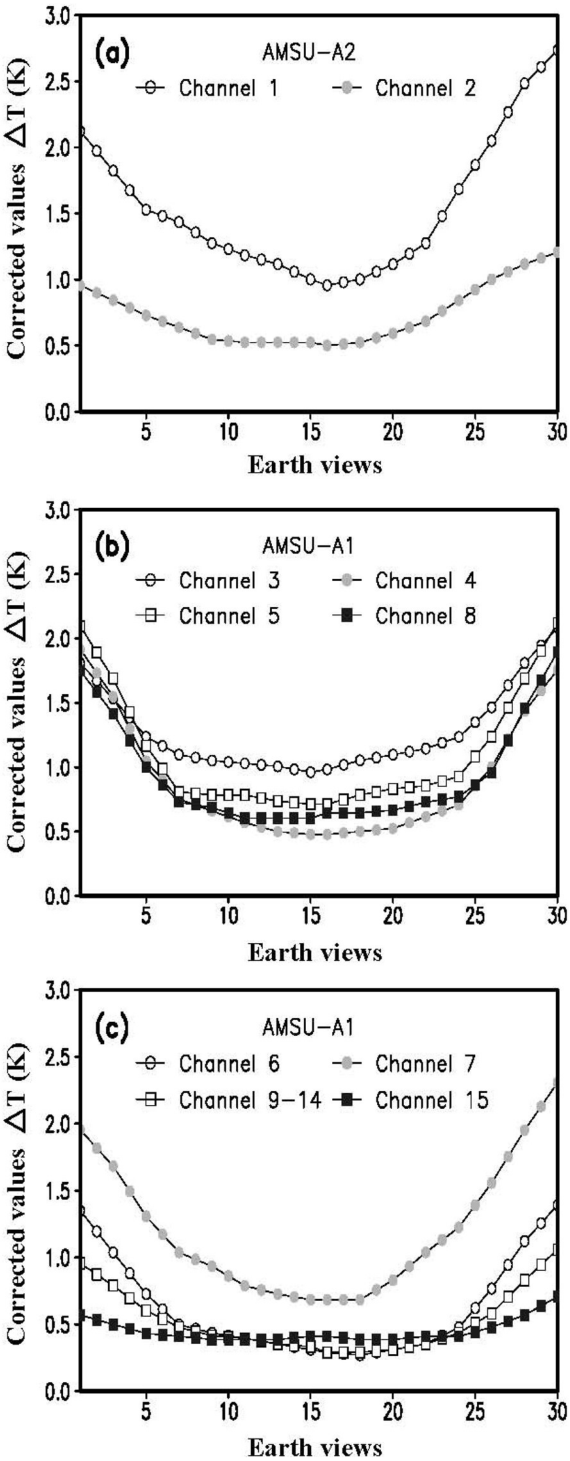


Figure 1. The corrected value ΔT of the 30 earth views in the 15 sounding channels of AMSU-A (units: K). (a): the 1st and 2nd channel, (b): the 3rd, 4th, 5th and 8th channel, (c): the 6th, 7th, 9th-14th and 15th channel. The abscissa is for the 30 earth views.

adjustment on the AMSU-A data (Tan et al.[9]). Here we adopt the regression method proposed by Wark [10], referring to some processes mentioned by Goldberg et al. [11, 12] and Kidder et al. [5]. The detail procedure is as follows. (1) The global data is divided into 90 latitudinal bands with a latitude interval of 2°. (2) Considering the influence of underlying surface, the 1st to 5th and the 15th channel are classified into two types, i.e., sea surface and non-sea surface. While such division is not conducted on the 6th to 14th channel. (3) The scan angles are divided into 30 parts according to the 1st to 30th scan angle. (4) The upward and downward orbits are treated separately.

The regression coefficient is achieved by conducting the multiple regression with 3 correlation channels on the selected one month brightness temperature. There are two coefficients of the sea surface and non-sea surface for the 1st to 5th and the 15th channel, but only one for the 6th to 14th channel. The correlation channels of multiple regressions resemble that in Goldberg et al.[12]. In detail, the 4th to 13th channel is regressed by itself and the adjacent channels, e.g., the 4th channel is regressed by the 3rd, 4th and 5th channel, and the 13th channel is regressed by the 12th, 13th and 14th channel. While the 1st, 2nd and 15th channel is regressed by the 1st, 2nd and 15th channel, and the 3rd channel is regressed by the 3rd, 4th and 5th channel, also the 14th channel is regressed by the 12th, 13th and 14th channel. The limb adjustment could well remove the increment of brightness temperature with the larger scan angle in each channel of AMSU-A (Fig.3).

Based on the correlation channels selected by the method mentioned above, the regression coefficients can be calculated by using the one month record. Then the limb adjustment of brightness temperature in every channel of AMSU-A is carried on by regression at each moment in this month. On 18 August 2001, the brightness temperature observed by the 7th AMSU-A channel of NOAA-15 satellite in its upward orbit is unusable before the limb adjustment. However, after the limb adjustment, the evident warm core structure can be recognized in the upper troposphere between 20°N and 30°N where the TC Pabuk is situated (Fig.4).

The brightness temperature with limb adjustment is inverted to the air temperature on 40 isobaric surfaces from 1 000 hPa to 0.1 hPa in vertical by the IAPP (the International Advanced TOVS (ATOVS) Processing Package) linear regression method (Goldberg[11]). The 40 isobaric surfaces include 1 000 hPa, 950 hPa, 920 hPa, 850 hPa, 780 hPa, 700 hPa, 670 hPa, 620 hPa, 570 hPa, 500 hPa, 475 hPa, 430 hPa, 400 hPa, 350 hPa, 300 hPa, 250 hPa, 200 hPa, 150 hPa 135 hPa, 115 hPa, 100 hPa, 85 hPa, 70 hPa, 60 hPa, 50 hPa, 30 hPa, 25 hPa, 20 hPa, 15 hPa, 10 hPa, 7 hPa, 5 hPa, 4 hPa, 3 hPa, 2 hPa, 1.5 hPa, 1 hPa, 0.5 hPa, 0.2 hPa, 0.1 hPa. Afterwards the inverted air temperature is interpolated into the grid points with a horizontal resolution of 0.5°×0.5° by the Cressman[13] stepwise correction.

The root-mean-square deviation of inverted air temperature from the equator to 30°N is less than 2℃ according to the Goldberg [11] statistic method.

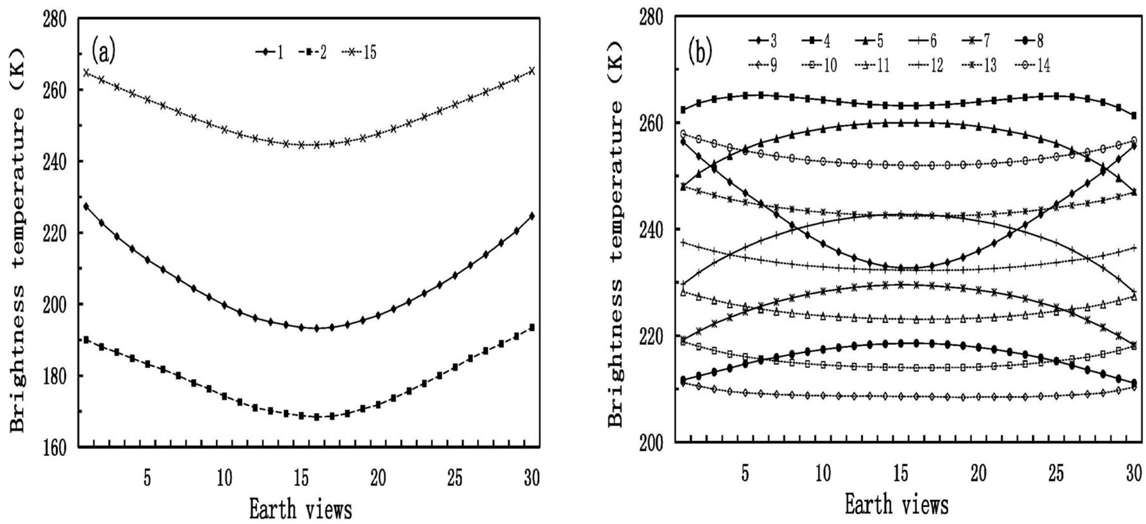


Figure 2. Monthly mean brightness temperature observed by the 15 channels of AMSU-A in August 2001 without limb adjustment (units: K. a: the 1st, 2nd and 15th channel; b: the 3rd to 14th channel).

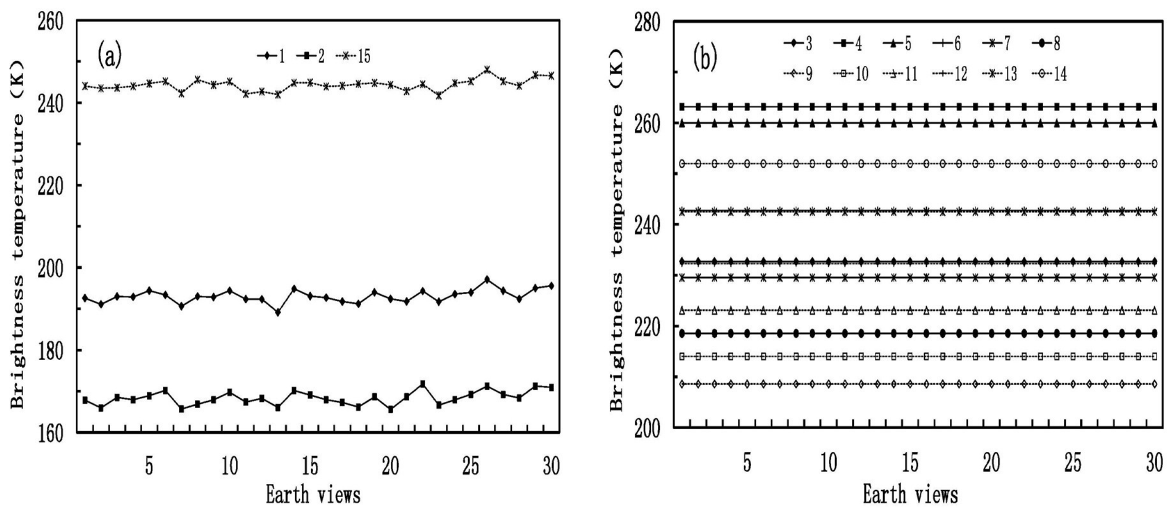


Figure 3. The same as Fig.2, but is for the results with limb adjustment.

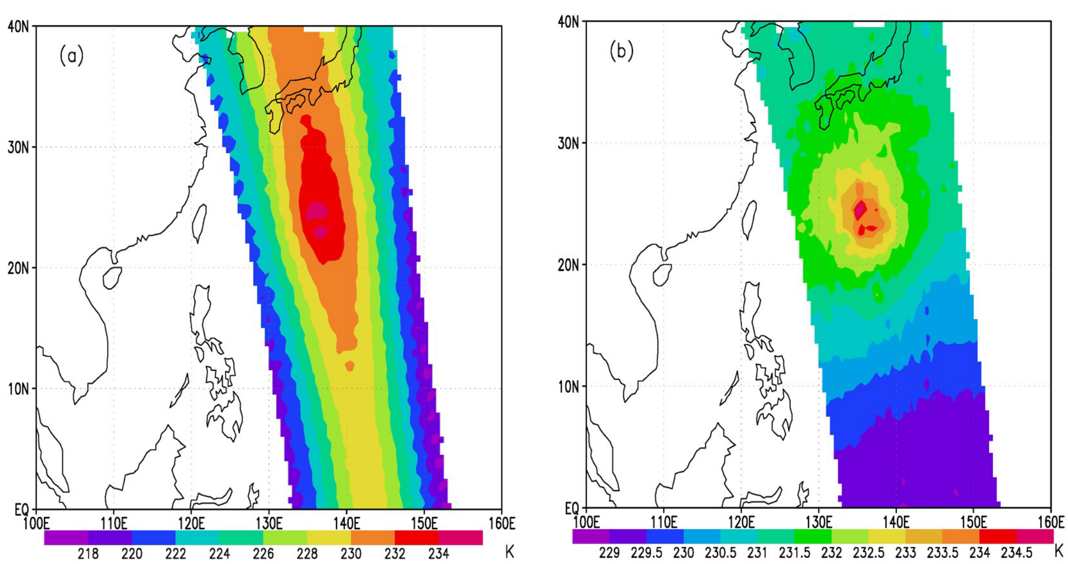
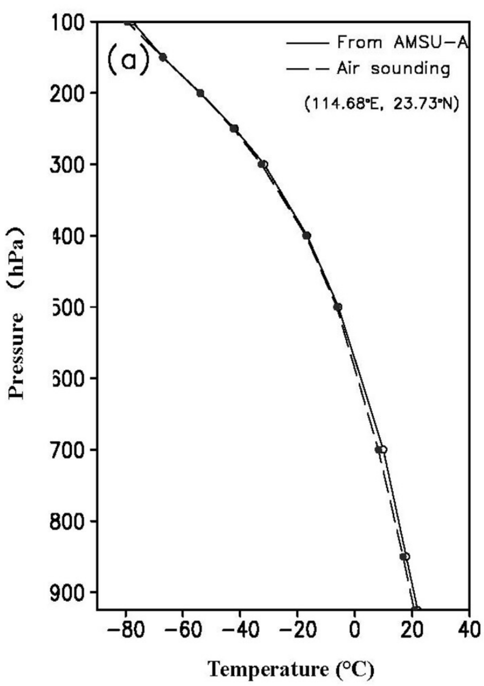


Figure 4. The distribution of brightness temperature observed by the 7th AMSU-A channel of NOAA-15 satellite in its upward orbit on 18 August 2001 (units: K. a: before limb adjustment, b: after limb adjustment).

Comparison between the inversion result and the 925-100 hPa radiosonde observation of Dongyuan, Guangdong province demonstrates that the vertical profile of inverted air temperature is similar to that of observation at 12:00 on 04 November 2008. The deviation of air temperature is less than 2℃ on each level, and the inversion result is a little higher than the observation (Fig.5).

The temperature averaged over (100°–160°E, 0°–40°N) is used to analyze deviation of temperature. The pressure-longitude cross section of temperature deviation passing through the center of TC Pabuk at 09:00 of 18 August 2001 is shown in Fig.6. Instead of a warm core above the TC center, there are two evident warm centers at 200 hPa located to the east and west of TC center with the maximum deviation of 4.5℃. At 900 hPa is occupied by two strong cold centers with their minimum deviation of −2.5℃ (Fig.6). The warm cores to the east and west of TC Pabuk center superpose the cold centers in vertical. And the configuration of upper-positive and lower-negative deviation of temperature is consistent with the strongest ascent near the eye wall of TC. The negative deviation of temperature in the lower troposphere is perhaps associated with the rainfall pollution and the adiabatic cooling due to ascent of lower flow. Whereas the positive deviation in the upper troposphere is ascribed to the latent heating released by the convection. Meanwhile, the temperature deviation is zonal asymmetric between the western and eastern side of TC, presenting that the western/eastern center of the deviation is about 1.1°/1.5° longitude away from the TC center. Furthermore, the area of deviation center to the west is larger than that of deviation center to the east of TC center in both upper and lower troposphere. Thus the inverted temperature from AMSU-A data could well reflect the detail structure of ware core in TC Pabuk.



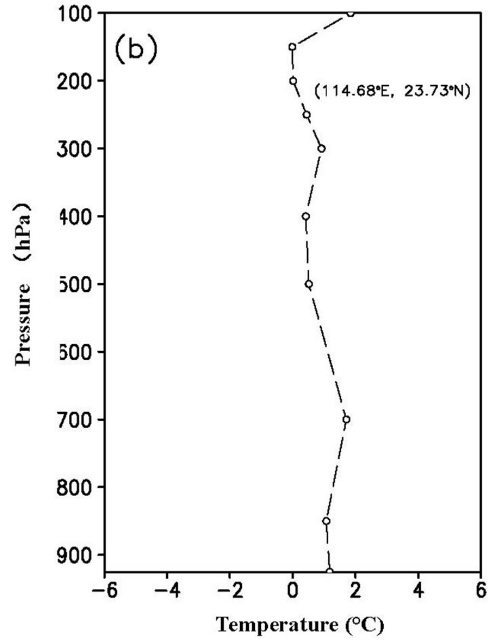


Figure 5. (a) The inverted (solid line) and observed (dashed line) air temperature of radiosonde station of Dongyuan, Guangdong province at 12:00 on 4 November 2008. (b) The deviation of inverted air temperature from the observation (units: ℃).

3 DIFFERENCE OF WARM CORE STURCTURE BETWEEN DIFFERENT TYPES OF TDS OVER THE SCS

3.1 *Non–developing TDs over the SCS*

Three different non-developing TDs over the SCS are selected to study the evolution of warm core in this type of TDs extending downward from the middle and upper troposphere. As shown in Table 1, the 3 TDs are TD9933 in middle December of 1999, TD0405 in middle May of 2004, and TD0706 in the early August of 2007. Since these TDs have not been named officially, their names in this paper are described as follows: the "TD" in their names is for Tropical Depression, and the two numbers in the middle of their names are for the years, then the serial numbers of TDs in the best track achieve from JTWC are expressed by the last two numbers of their names. The non-developing TDs over the SCS cannot strengthen to TCs in their lifecycle. And they are originated from the middle and upper troposphere, rather than the sea surface. This type of TDs is generally featured by the downward extension of warm core from the middle and upper troposphere. The inner core of TC is indentified as a region within 2° away from the TC center according to Mundell's definition in 1990[14]. Therefore, the averaged temperature deviation within the region 2°

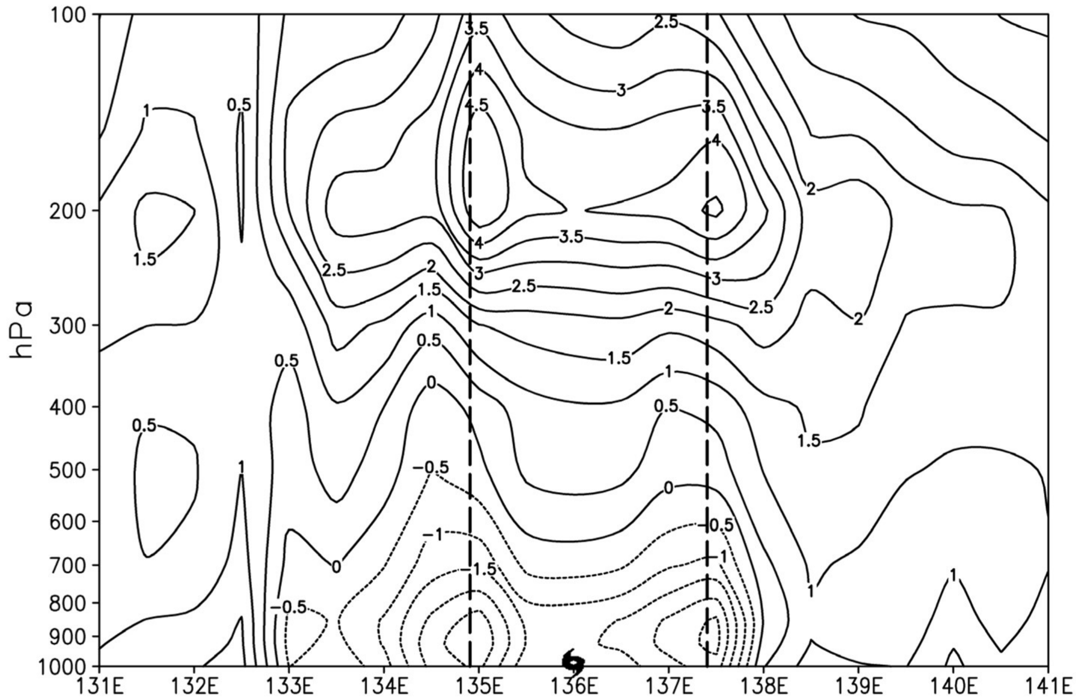


Figure 6. Pressure-longitude cross section of temperature deviation passing through the center of TC Pabuk at 09:00 of 18 August 2001 (units: K. Typhoon symbol is for the position of TC center, and the perpendicular dashed lines are for the position of warm and cold centers of temperature deviation, respectively).

away from the TD center is treated as the temperature deviation of TD center. Here the start time of study period is marked by 0 h for convenient.

Figure 7 portrays the pressure-time cross section of temperature deviation in the center of the 3 non-developing TDs. It is indicated that the large positive temperature deviation exists in the middle and upper troposphere (above 700 hPa) in the beginning, while the counterpart in the lower troposphere is relative small or even negative. Subsequently the large positive temperature deviation is extending downward gradually, and it reaches the sea surface at 48 h, when the most evident positive temperature deviation is near the sea surface. In the beginning of TD9933, the large positive deviation appears near 400 hPa, accompanied by the relative weak positive temperature deviation near the sea surface. Then the positive temperature deviation is enhanced and uplifted in the middle and upper troposphere from 12 to 24 h, but the positive temperature deviation near the sea surface is weakened to negative in the meantime. From 36 to 48 h the positive temperature deviation is developed downward from the middle and upper troposphere, and the large positive temperature deviation is between 550 to 350 hPa with its maximum of 2.2℃ at 48 h. Meanwhile, the temperature deviation near the sea surface is above 2.2℃, implicating the arrival of warm core in TD at the sea surface. Afterwards the positive temperature deviation is weakened near the sea surface at 60 h, and the large positive temperature deviation goes down to 600-400 hPa (Fig.7a). For the TD0405, the positive temperature deviation is large near 250 hPa, accompanied by another positive temperature deviation near the sea surface at first. Then the positive temperature deviation near the 250 hPa is enhanced to 1.4 ℃ at 24 h, and the near-surface temperature deviation is becoming negative at this moment. Thereafter, the TD warm core in the middle and upper troposphere is developing downward and reaches the sea surface from 24 to 48 h, appearing the positive temperature in the middle and upper troposphere is most obvious at 36h and begins to decrease at 48h. At 60 h the positive temperature deviation is evidently dampened from the sea surface to the middle and upper troposphere (Fig.7b). As to the TD0706, the positive temperature deviation in its center is located near 250 hPa, whereas the temperature deviation is negative below 500 hPa. The positive temperature deviation is extending downward from 24 to 48 h. During this stage a maximum of positive temperature deviation appears near 250 hPa at 36 h. And the TD warm core developing downward arrives to the sea surface at 48 h, corresponding to a positive temperature deviation of 1.2℃ near the sea surface. Also the positive temperature deviation in the upper troposphere has been weakened by now. The large positive temperature deviation is situated at 250 hPa. The positive temperature deviation of 0.6℃ exists at 250 hPa at 60 h, when the positive temperature deviation is greatly declined near the sea surface (Fig.7c).

Briefly, the height of warm core in TD9933 is descending during its downward developing, and this may prevent the further strengthening of the TD. And the warm core in TD0405 and TD0706 appears at 36 h in the middle and upper troposphere. When the warm core reaches the sea surface to strongest warm core in situ, the original warm core in the upper troposphere has been weakened. After that the warm core is declined apparently either in the middle and upper troposphere or near the sea surface. The disagreement between the time when the warm core appears in the upper and the lower troposphere may also suppress the further development of TDs.

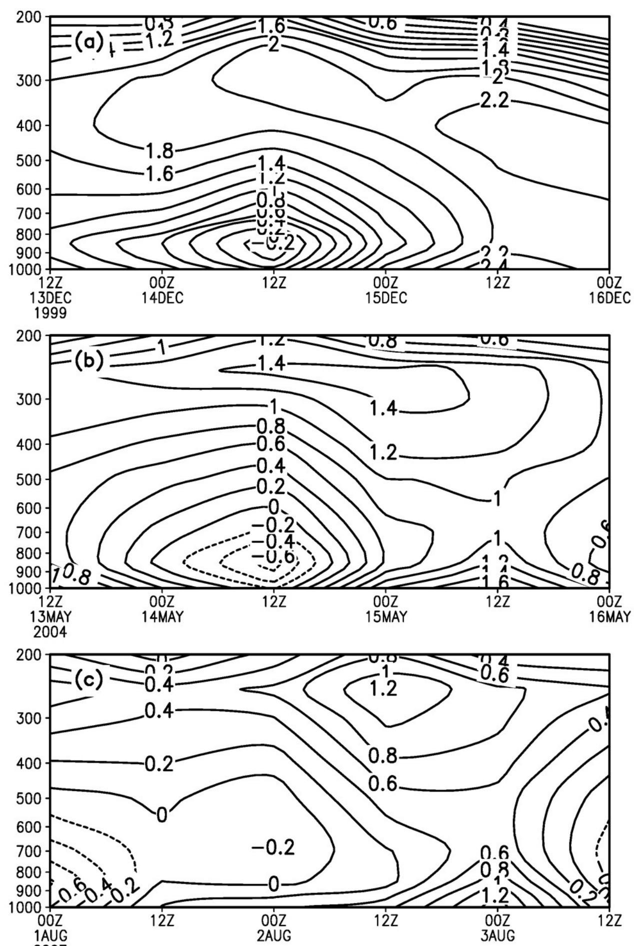


Figure 7. Pressure-time cross section of the non-developing TDs over the SCS (units: K. a: TD9933, b: TD0405, c: TD0706).

3.2 *Developing TDs over the SCS*

To examine the difference of thermal structure between the developing and non-developing TDs over the SCS, we select another 3 TDs originating from the middle and upper troposphere over the SCS. All of them can develop to Tropical Storm (TS) or even stronger, so that they have uniform official name, that is Usagi in the early August of 2001, Mekkhala in the middle of September of 2002 and Maysak in the early November of 2008 (Table 1).

Figure 8 presents the pressure-time cross section of temperature deviation in the centers of the 3 developing TDs over the SCS. It is indicated that the cold or warm core is weak in the TD center near the sea surface in the beginning. And the warm core is strong at 250 hPa in the upper troposphere, then it is developing downward gradually. The warm core in TD center arrives near the sea surface at 48 h when the warm core reaches its maximum near the sea surface and in the upper troposphere. The warm core structure is maintained till 60 h. For the TD Usagi, the evident positive temperature deviation is above 500 hPa with no cold or warm core near the sea surface. At 12 h a negative temperature deviation appears below 750 hPa with its minimum near 850 hPa, while the strong positive temperature deviation is near 250 hPa. Then the warm core in the middle and upper troposphere is extending downward to the sea surface from 12 h to 48 h. And the warm core near the sea surface is strongest at 48 h, accompanied by a positive temperature deviation center with its value of 1.6℃. Then the warm core is strongest in the upper and lower troposphere at this moment. The temperature deviation is greater than 0.8℃ from the sea surface to the top of troposphere at 60 h (Fig.8a). In addition, the positive temperature deviation in the center of TD Mekkhala is above 600 hPa from 0 h to 24 h. The evident positive temperature deviation is located near 250 hPa, whereas the negative temperature deviation controls the low layers. The mid-upper-layer warm core in TD is developing downward from 24 h to 48 h, and the warm core near the sea surface is strongest at 48 h. In the meantime a positive temperature deviation maximum is situated between 450-300 hPa, implying the strongest warm core in the upper troposphere. The strong positive temperature deviation still exists in the whole troposphere at 60 h (Fig.8b). As to the TD Maysak, the cold core is near the sea surface, and the warm core is above 600 hPa initially. The large positive temperature deviation is near 250 hPa. The warm core in TD is expanding and strengthening downward from the middle and upper troposphere to the sea surface during the 12-48 h period. And the warm core is strongest near the sea surface at 48 h, accompanied by a positive temperature deviation center with its value of 1.8℃. Also the warm core has reached its maximum near the sea surface and in the middle and upper troposphere by now. The warm core in the upper and lower troposphere does not disappear until 60 h (Fig.8c).

Generally, the 3 developing TDs are featured by the downward developing of warm core in the middle and upper troposphere. When the warm core near the sea surface is strongest, the counterpart in the upper

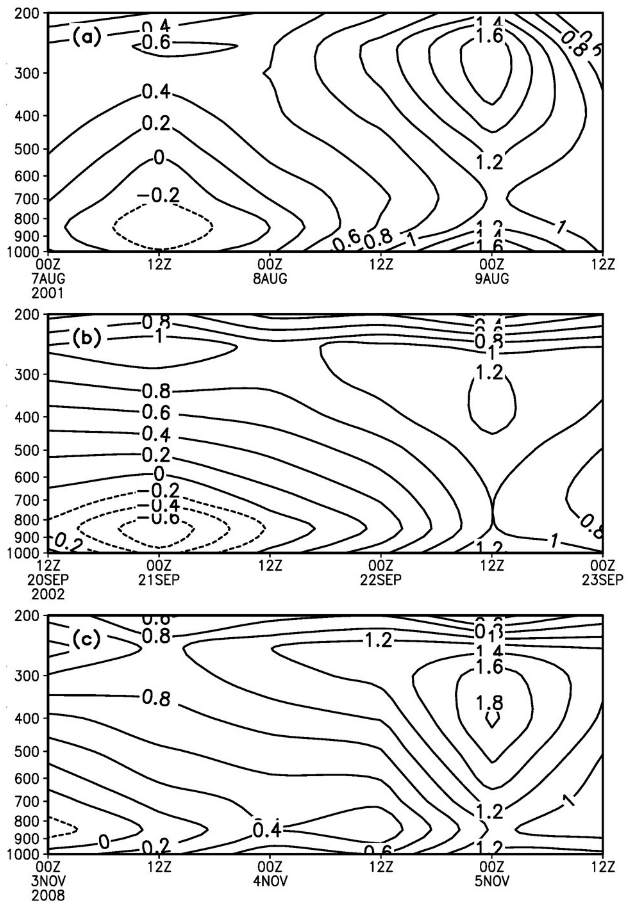


Figure 8. The same as Fig.7, but is about the 3 developing TDs over the SCS (units: K, a: Usagi, b: Mekkhala, c: Maysak).

troposphere is also enhanced abruptly. Thus the warm cores in the upper and lower troposphere are intensified to reach their maximum simultaneously. After that, the thermal structure in vertical is maintained, implicating the further development of TDs. However, the in-phase strengthening of warm core in the upper and lower troposphere does not exist during the evolution of warm core in the non-developing TDs.

4 CONCLUSIONS

The AMSU is advantaged by high spatial resolution and its ability to detect the temperature and humidity penetrating clouds. In this paper, we conduct the Antenna Pattern Correction and the limb adjustment on the data observed by AMSU-A L1B of NOAA-15 polar orbit satellite to invert the air temperature by the linear regression and the horizontal stepwise correction. The inverted temperature is distributed on 40 isobaric surfaces from 1,000–0.1 hPa with a horizontal resolution of 0.5°×0.5°. And then the case study shows that the inverted temperature can depict the detail structure of warm core in TCs.

The downward extending TDs over the SCS are divided into two categories: one is for the developing TDs, and the other is for the non-developing TDs. Each category has 3 samples. The temperature inverted from AMSU-A data indicates that all the downward extending TDs are characterized by the existence of cold core in the lower troposphere and the downward developing of warm core from the middle and upper troposphere to the sea surface. When the warm core reaches the sea surface, the local warm core appears. In the developing TDs, when the warm core appears near the sea surface, an upper warm core is also enhanced to produce the evident positive temperature deviation in the whole troposphere. However, such process does not exist during the evolution of non-developing TDs over the SCS.

Considering the scarce records over the ocean, it may be helpful to predict the TD development via analyzing the evolution of warm core structure in TDs based on the satellite observation in the practical monitor and forecast.

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