Intensification of Typhoon Danas (1324) Captured by MTSAT
Upper Tropospheric Atmospheric Motion Vectors

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Abstract

This study exemplifies a capability of upper tropospheric Atmospheric Motion Vectors (AMVs) derived from successive imagery of MTSAT-2 images to detect the intensification of Typhoon Danas (1324). The evolution of the wind field around the cloud top captured by the AMVs revealed two remarkable features: increases of radial outflow, representing secondary circulation in the form of the two convective bursts (CBs), and increases of tangential winds after the first CBs and during the second CBs. It is suggested that the updrafts and latent heat release associated with the first CBs induced increases of lower tropospheric convergence and absolute angular momentum. This preconditioned the axisymmetrization and increase in tangential velocity and inertial stability during the second CBs that led to tropical cyclone (TC) intensification. These results show that upper tropospheric AMVs can be used to detect the primary and secondary circulations, including CBs, during the intensification phase of the TC.

1. Introduction

For disaster prevention and mitigation, it is important to observe and forecast tropical cyclone (TC) intensification accurately. An important focus of such efforts is the dynamics of the TC inner core, where tangential winds reach their maximum strength and the strong updrafts composing the secondary circulation are found (Holland and Merrill 1984; Smith et al. 2009; Houze 2010). TC inner core is generally defined as the area within a radius 2–3 times the radius of maximum wind (RMW). Deep convection in developing TCs often takes the form of “convective bursts (CBs)” (Riehl and Malkus 1961), the characteristics of which have been studied by using satellite observations (Steranka et al. 1986; Jiang 2012). The CBs precondition the establishment of TC inner core by inducing axisymmetrization, which leads to TC intensification (Miyamoto and Takemi 2013).

The updrafts associated with deep convection in the TC inner core enable large upward mass fluxes and the transport of absolute angular momentum from the boundary layer to the upper troposphere (Sawada and Iwasaki 2007; Rogers 2010). Bryan and Rotunno (2009), based on a simulation using a non-hydrostatic model, examined the trajectory of an air parcel passing through the position of maximum wind speed in a TC. They showed that the parcel moved upward along the isopleths of absolute angular momentum and entropy (Supplement 1). This finding supports the idea that a large absolute angular momentum is transported from the surface to the upper troposphere, leading to vertical development of TC cyclonic vortex around the inner core (e.g., Frank 1977).

The temporally dense satellite observations which are acquired by the recent technological advances are useful for tracking clouds associated with various meteorological phenomena. Atmospheric Motion Vectors (AMVs) are wind vectors obtained by tracking clouds or water vapor patterns in consecutive satellite images. If AMVs can be used to detect the primary and secondary circulations of a TC and thereby identify wind patterns characteristic of TC intensification, then they have the potential to provide us with unprecedented knowledge about TC intensification.

The purpose of this study is to exemplify the use of upper tropospheric AMVs for the detection of TC intensification in a case study of Typhoon Danas (1324), which struck the Japanese islands in October 2013 (Fig. 1). We focused on the evolution of the primary and secondary circulations, including CBs, during the intensification phase of the TC.

2. Data and method

2.1 Data

For computing AMV data and detecting CBs, we used imagery data of the infrared (IR1: wavelength, 10.8 µm) and water vapor (WV; wavelength, 6.8 µm) channels of the Multifunctional Transport Satellite -2 (MTSAT-2). Further, the convective rainfall area was detected by using the polarization-corrected temperature of the 91-GHz channel (PCT91) (Spencer et al. 1989) of the Special Sensor Microwave Imager/Sounder (SSMIS) onboard Defense Meteorological Satellite Program (DMSP) polar-orbiting satellites (Hawkins et al. 2008).

For the analysis of the atmospheric parameters related to TC intensification, we used the Japanese 55-year reanalysis dataset (JRA-55; Kobayashi et al. 2015), the coordinate system of which has a spatial resolution of 1.25° of latitude and longitude. To investigate conditions of the oceanic environment, we used the Merged Satellite and in-situ data Global Daily Sea Surface Temperature (MGDST) (Kurita et al. 2006) and daily Tropical Cyclone Heat Potential (TCHP) data derived from the Multivariate Ocean Variational Estimation (MOVE) System (Usui et al. 2013).

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Fig. 1. Track of Typhoon Danas (1324) and SST (contours, °C) and SST anomalies (color scale, °C) relative to the 1981–2010 average on 4 October 2013. Black and white circles show the location of Danas at 0000 UTC and 1200 UTC. Green circles show the track while Danas was a tropical depression.
We used best-track data from the Regional Specialized Meteorological Center Tokyo (http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/bestrack.html) for the center positions and intensities of the TC, and we produced hourly data by linear interpolation.

2.2 AMV derivation

We computed upper tropospheric AMVs at 0000, 0600, 1200, and 1800 UTC from the MTSAT-2 imagery of the IR1 and WV channels by using the AMV derivation scheme of the Meteorological Satellite Center (MSC) of the Japan Meteorological Agency (JMA) (Oyama 2010). In this scheme, the wind vectors for the operational 6-hourly AMV derivations are calculated by tracking high-level clouds such as cirrus clouds in imagery acquired at 15-min intervals by the cross-correlation matching technique. AMV data from both channels with a Quality Indicator (QI) (Holmlund 1998) greater than 0.3 were used complementarily to maximize the AMV data coverage. The target box used for the tracking process was a square of 16 image pixels (image pixel size of IR and WV channels is 4 km at nadir) on a 0.25° latitude × 0.25° longitude grid. The AMVs were assigned to the cloud-top height, which was computed from brightness temperature (TB) data of IR1 and WV channels in the target box with reference to the first-guess field (6-hour forecast) of the JMA’s Global Spectral Model, which has a horizontal resolution of 20 km. Most of the AMV data over the TC area are assigned to pressure levels between 100 and 250 hPa.

Oyama (2015) compared upper tropospheric AMVs with rawinsonde wind data within a radius of 600 km from the centers of 16 TCs that occurred during 2011–2013 and found a vector difference of 6.7–7.5 m s\(^{-1}\) and a bias of −0.8 to −0.5 m s\(^{-1}\). Oyama (2015) attributed the departure of the AMVs from the sonde winds mainly to the collocation and derivation errors, which may be increased by large temporal and spatial variations of the TC wind field.

2.3 Detection of convective bursts

Convective activity within Danas was investigated by using MTSAT-2 TB (IR1) data, which show the cloud-top temperatures of deep convective clouds. The averaged TB within a radius of 200 km from the TC center was used for detecting CBs.

2.4 Analyses of the TC’s upper tropospheric wind field and rainfall asymmetry

We calculated two wind vector components from the upper tropospheric AMVs to represent the primary and secondary circulations of the TC around the cloud top. The maximum tangential wind (hereafter UMaxWind) was determined as the maximum of the azimuthal mean tangential wind in six annuli within a radius of 300 km from the TC center, and the maximum radial wind (hereafter UMaxOutflow) was determined as the maximum of the azimuthal mean radial wind in the same six annuli (Fig. 2). To assess the impact of the TC center determination error on UMaxWind and UMaxOutflow, we computed UMaxWind and UMaxOutflow using the circulation center determined from the upper tropospheric AMVs in place of the best-track data. We confirmed that the impact was small, at least during the development and mature stages of the TC, when the rotation maximum could be roughly specified from the AMVs (with average position errors about 0.6 degrees). The averaging procedure used to derive UMaxWind and UMaxOutflow may mitigate the impact of a TC center determination error. We recognized that evaluation of the impact is difficult for TC stages with very weak cyclonic circulation and large environmental winds such as jets because the rotation center cannot be determined. The impact should be investigated further by using data from other TCs.

We also investigated the azimuthal wavenumber components of the convective rainfall area near the TC center by using PCT91 data (e.g., Ueno 2007), which reflect the rainfall asymmetry. An area with low PCT91 values generally corresponds to an area of deep convection, where large microwave scattering occurs because of the presence of ice particles. We defined the calculation area as a circle with a radius of 150 km around the TC center (Supplement 2).

2.5 Derivation of inertial stability

As a measure of the robustness of the TC inner core, we diagnosed inertial stability as follows (Schubert and Hack 1982).

\[
\text{Inertial stability} = r^2 \frac{\partial M}{\partial r},
\]

where \( r \) is the radius from the TC center and \( M (= r V + f r^2/2) \) is the tangential wind component at radius \( r \) and \( f \) is the Coriolis parameter) is the absolute angular momentum. The value of inertial stability near the TC center increases as the tangential velocity in the inner core increases. We computed inertial stability using the azimuthally averaged tangential components of upper tropospheric AMVs (Fig. 2) in this study.

2.6 Analysis of atmospheric conditions

Vertical wind shear (VWS) is known to negatively influence TC intensity (Kaplan and DeMaria 2003). In this study, VWS was defined using JRA-55 as the wind difference between 200 hPa and 850 hPa levels, averaged over the area within a radius of 600 km from the TC center. In addition, high convective available potential energy (CAPE) is known to be favorable for TC intensification (Miyamoto and Takemi 2013). CAPE was computed using JRA-55 and averaged over the areas within radii of 200, 300, and 400 km from the TC center.

3. Results

3.1 Typhoon Danas (1324) and atmospheric and oceanic environments

Danas formed near the Mariana Islands at 0600 UTC on 4 October 2013 (Fig. 1), and its maximum sustained wind (MSW) increased rapidly at a rate of 12.8 m s\(^{-1}\) day\(^{-1}\) between 0000 UTC 5 October and 0000 UTC 6 October. The TC reached its mature stage with a MSW of 46 m s\(^{-1}\) and central pressure of 935 hPa at 0000 UTC on 7 October 2013 (Fig. 3a). The strong winds that accompanied Danas (10-min average, 37.6 m s\(^{-1}\); gust, 53.5 m s\(^{-1}\)) caused immense damage to houses and infrastructures on Yoronjima Island which the TC passed very near.

Danas moved over an area of the ocean with SST higher than 27°C (Fig. 1) and TCHP larger than 100 kcal cm\(^{-2}\) (not shown) during its development phase (4–7 October). It is suggested that
this relatively high SST and TCHP which exceeded the threshold of about 80 kcal cm\(^{-2}\) (Wada 2015) were favorable for TC intensification. VWS was small (< 5 m s\(^{-1}\)) during the development stage (Fig. 3b), indicating that it did not negatively influence the TC intensity.

### 3.2 Characteristics of the TC wind field captured by AMVs

We investigated CBs by examining temporal changes in the previous 12 hours of UMaxWind, UMaxOutflow, and TB (IR1) averaged within a radius of 200 km from the TC center (Fig. 3c). The time window of 12 hours was determined by taking account of the duration time of the convective bursts, that is, 9 hours or longer (Steranka et al. 1986). Two distinct CBs, one from 0200 UTC to 1100 UTC 4 October (hereafter CB1) and the other from 0000 UTC to 1300 UTC 5 October (hereafter CB2), were recognized by a sudden drop of TB (IR1) by about 30 K. CB2 from 0000 UTC to 1300 UTC 5 October (hereafter CB2), were 0200 UTC to 1100 UTC 4 October (hereafter CB1) and the other or longer (Steranka et al. 1986). Two distinct CBs, one from CB1 and CB2, the low TB (IR1) area expanded outward with time, which may imply outward propagating gravity waves induced by the deep convections (Dunion et al. 2014) or the outward expansion of cirrus clouds from the inner core.

The tangential winds within radii of 50 and 200 km differed remarkably between CB1 and CB2 (Fig. 5b): The tangential winds at radii of 50 and 200 km were greater (about 10 m s\(^{-1}\)) during CB2 than during CB1 (about 5 m s\(^{-1}\) in 12 hours). In contrast, during CB2, the azimuthal wavenumber 1 component first increased steeply in the early CB2 period, and then it decreased, accompanied by increase of UMaxWind at a rate of about 5 m s\(^{-1}\) in 12 hours (Figs. 3b and 3c). The wavenumber 1 component peak in the early CB2 period was associated with the formation of a rainband with PCT91 colder than 160 K on the southern side of the TC (Supplement 2). These findings imply that during CB2 Danas was forming its inner-core, consisting of eyewalls and inner rainbands, and the TC was intensifying. The inertial stability computed from the upper tropospheric AMVs increased drastically between radii of 50 and 100 km after CB2 (Fig. 3d). The wavenumber 2 variations were similar to those of the wavenumber 1 component, but their amplitudes were very small. The wavenumber 1 component peak at 1800 UTC 7 October corresponds to the asymmetric rainfall distribution that formed as the TC approached the middle latitude jet.

During both CB1 and CB2, CAPE was high around the TC center. However, the CAPE value within a radius of 200 km was less during CB2 than it was during CB1 (Fig. 4). Nevertheless, UMaxWind increased at a higher rate during CB2 (about 6 m s\(^{-1}\) in 12 hours) than during CB1 (about 5 m s\(^{-1}\) in 12 hours). This situation indicates that during CB2 there were conditions other than high CAPE that were favorable for inducing TC intensification, that is, the formation of the inner core. The formation of the inner core during CB2 is also implied by a larger increase rate of UMax-Outflow in 12 hours during CB2 (about 5 m s\(^{-1}\)) than that during CB1 (1.5–2.0 m s\(^{-1}\)) (Fig. 3c). Additional studies, including high-resolution numerical simulations, are needed to determine more precisely the role of CAPE in the intensification of Danas because the horizontal resolution of the JRA-55 data used to compute CAPE may be too coarse to analyze the detailed inner-core dynamics.

In radius–time cross section shown in Fig. 5, CB1 and CB2 appear as TB (IR1) values colder than −60°C within a radius of 200 km (Fig. 2). During both CB1 and CB2, the low TB (IR1) area expanded outward with time, which may imply outward propagating gravity waves induced by the deep convections (Dunion et al. 2014) or the outward expansion of cirrus clouds from the inner core.

The tangential winds within radii of 50 and 200 km differed remarkably between CB1 and CB2 (Fig. 5b): The tangential winds near the TC center were very weak during CB1 (which can also be seen in Fig. 6a), suggesting that Danas had low inertial stability during this period (Fig. 3d). After CB1, between 1200 UTC and 1800 UTC 4 October, the tangential winds increased temporarily (Figs. 5b and 6b). In contrast, during CB2, the tangential wind increased drastically from 5 to 10 m s\(^{-1}\) or more, and its peak shifted outward (Fig. 5b), indicating expansion of inner core size during CB2. By the end of CB2, Danas had acquired axisymmetric cyclonic circulation accompanied by strong radial outflows (Figs. 5c, 6c, and 6d).
capable of representing radial outflows induced by the CBs. The radial outflow peaked at around 0000 UTC 8 October, when the TC approached the middle latitude jet.

The results obtained in this study suggest the following scenario: Updrafts and latent heat release associated with CB1 induced intensifications of the lower tropospheric convergence and absolute angular momentum. Thus, CB1 produced conditions favorable for the formation of the TC inner core, which facilitates the following upward transport of large angular momentum and upward mass fluxes. Subsequently, CB2 increased the axisymmetrization and inertial stability of the TC, leading to the rapid intensification of Danas.
4. Discussion

This study presented evidence from upper tropospheric AMVs and satellite observations of convective clouds and rainfall for the intensification of Typhoon Danas (1324) in association with CBs. It was suggested that the formation of the TC inner core, which was indicated by increases of radial outflow during CB1 and CB2 and increases of tangential winds after CB1 and during CB2 around the cloud top, has been closely related to the accumulation and consumption of CAPE. These features, together with axisymmetrization and rapid intensification, are consistent with the results of idealized numerical experiments (Miyamoto and Takemi 2013). As future works, more researches on the response of the upper tropospheric winds to the lower tropospheric winds are necessary since it could vary depending on the robustness of the upper tropospheric winds to the lower tropospheric winds.

Acknowledgements

This study used MTSAT-2 imagery and ancillary data from JMA/MSC for computing AMVs. The authors are grateful to Kazuki Shimoji and Masahiro Hayashi of JMA/MSC for providing these data. Our gratitude is extended to Dr. Nasuno and two anonymous reviewers for their many valuable comments that helped to improve this paper. A part of this study was supported by JSPS-KAKENHI Grant-Number 15K05292.

Edited by: T. Nasuno

Supplements

Supplement 1: The trajectory (bold black line) of an air parcel passing through the location of the maximum wind speed (black dot) in relation to (a) entropy (contour interval, 10 J kg\(^{-1}\) K\(^{-1}\)) and (b) absolute angular momentum (contour interval, 0.2 \(\times\) 10\(^{6}\) m\(^{2}\) s\(^{-1}\)) in a simulated tropical cyclone (Fig. 4 of Bryan and Rotunno (2009)).

Supplement 2: Spatial distributions of PCT91 in a 8° latitude \(\times 8°\) longitude box at the center of Typhoon Danas (1324) during the formation and development stages. The circle with a radius of 150 km at the center of each panel denotes the area used for computing the azimuthal wavenumber components.

References


Manuscript received 28 January 2016, accepted 6 May 2016