JMA 30-year Dvorak Reanalysis for the Western North Pacific

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1. Introduction

Accurate assessment of temporal variations in tropical cyclone (TC) intensity due to climate change is vital from both scientific and disaster management perspectives. In this context, the 7th International Workshop on Tropical Cyclones (IWTC-VII) emphasized the importance of efforts to produce and interpret homogeneous TC analysis data over long periods to reduce uncertainty in climate change-related TC projection (WMO 2011).

In 2009, the Typhoon Committee formed an expert team to assess changes in the frequency and intensity of TCs in the Western North Pacific (WNP) and to make related suggestions/interpretations for policy makers and the public. The team conducted a review of preferred publications/information available at the time, which were summarized in the Assessment Report on Impacts of Climate Change on Tropical Cyclone Frequency and Intensity in the Typhoon Committee Region (Typhoon Committee, December 2010). The report concluded that differences in best track datasets available for WNP (hereafter, Best track dataset) do not allow for a convincing detection of a long-term trend in regional TC intensity change when compared with variability from natural causes. As a follow-up, a best track consolidation meeting was held in Hong Kong in December 2010 to explore the feasibility of setting up or adopting a homogenous and unified TC Best track. Discussions highlighted numerous challenges to be addressed, including a need to identify factors behind discrepancies among TC warning centers and to promote exchanges of Dvorak CI data for historical TCs if they are available, which may be useful for TC research. Both challenges are related to the Dvorak technique (Dvorak 1975 and 1984), which is used to estimate TC intensity (maximum wind speed and minimum sea level pressure) by statistically correlating TC cloud patterns in satellite imagery with TC intensity. One of the conversion tables from Dvorak CI numbers to maximum sustained winds and minimum sea-level pressure for WNP was developed by Koba et al. (1990 and 1991).

The former investigation on discrepancies among TC warning centers was conducted by the Working Group on Meteorology under the annual operating plan titled Harmonization of Tropical Cyclone Intensity Analysis. The project was completed in 2017, with the final report (titled Comparative study of Dvorak Analysis in the western North Pacific (Koide and Nishimura 2017)) submitted to the Regional Specialized Meteorological Centre (RSMC) Tokyo Technical Review. At the 43rd Session of the Typhoon Committee in February 2011, the Japan Meteorological Agency (JMA) expressed its willingness to initiate 30-year reanalysis of satellite data, and has since reported related progress annually to the Typhoon Committee.

Dvorak reanalysis of TC data for the period from 1987 to 2016 for WNP was completed in 2023. The data used for the Dvorak reanalysis are described in Section 2, the procedures applied (including differences from the original Dvorak technique) are outlined in Section 3, the elements and formats of the provided data are detailed in Section 4,

[1] Retired.

dataset specifications are discussed in Section 5, and a summary is provided in Section 6. Acknowledgements, acronyms and references are also included in the latter part of the paper, and other relevant information is given in the appendices.

2. Data used for 30-year Dvorak reanalysis

2.1 Specifications for geostationary meteorological satellites referenced in reanalysis

Since 1978, JMA has operated numerous geostationary meteorological satellites; the Japan's geostationary meteorological satellites (GMS series), the Multi-functional Transport SATellite series (MTSAT-1R and -2) and the current Himawari-8/9. Data from NOAA's Geostationary Operational Environmental Satellite (GOES-9) were deployed from 2003 to 2005 due to the absence of Japanese geostationary satellite observation of the WNP basin. In the reanalysis reported here, geostationary meteorological satellite data with observation at least once an hour between 1987 and 2016 were used (except from January to February 1987), and all available imagery was used for six-hourly reanalysis. Using satellite data with observation intervals of an hour or shorter ensures appropriate quality in 30-year Dvorak reanalysis, in particular for the earlier years. Satellite specifications (scan frequency, number of bands, spatial resolution, calibration resolution (grayscale)) and related differences are summarized in Table 1.

Table 1. Specifications of geostationary meteorological satellites used in reanalysis

Period (Year/Month/Day)	Satellite	Scan frequency	Number of bands	Spatial resolution	Calibration resolution
1987/1/1～	GMS-3	Every 3 hours (F: 8 times)	Visible:1 Infrared:1	Visible: 1.25 km Infrared: 5 km	Visible: 64 (6 bit) Infrared: 256 (8 bit)
1987/3/1～		Every hour (F: 11 times, N: 13 times)			
1989/1/5～		Every hour (F: 24 times)			
1989/12/14～	GMS-4				
1995/6/13～	GMS-5		Visible: 1 Infrared: 3		
2003/5/22～	GOES-9		Visible: 1 Infrared: 4	Visible: 1 km Infrared: 4 km (Water Vapor: 8 km)	Visible: 1,024 (10 bit) Infrared: 1,024
2005/6/28～	MTSAT-1R	Every 30 minutes (F: 24 times, N: 20 times, S: 4 times)		Visible: 1 km Infrared: 4 km	Visible: 1,024 Infrared: 1,024
2010/7/1～	MTSAT-2				
2015/7/7～	Himawari-8	Every 10 minutes (F: 142 times)	Visible: 3 Near-infrared: 3	Visible: 0.5 km (B03), 1 km (B01, B02)	Visible: 2,048 (11 bit) Near-infrared:

			Infrared: 10	Near-infrared: 1 km (B04), 2 km (B05, B06) Infrared: 2 km	2,048, Infrared: 16,384 (14 bit) (B07), 4,096 (12 bit) (B10 - B15), : 2,048 (B08, B09, B16)

* F: full-disk observation; N: Northern Hemisphere observation; S: Southern Hemisphere observation

** B: band

2.2 Utilization of low-earth-orbit satellite data

For reanalysis from 2003 onward, microwave image data observed by low-earth orbit (LEO) satellite were referred to when applicable. The different microwave image data used during the reanalysis period may affect the accuracy of TC intensity analysis, but exact quantitative evaluation of related effects cannot be made in general. In this context, LEO satellite imagery enables certainty reinforcement in reanalysis based on geostationary orbit (GEO) satellite data. In cases where a TC eye was detectable for individual corresponding cloud patterns, and where the TC center location could be estimated (e.g., from rain band curvature), reanalysis referred to microwave imagery for TC center position estimation. Microwave imagery was also referred to in TC intensity analysis for identification of cloud systems during the development stage, including distinguishing CCC patterns (not applied in this reanalysis) from CDO patterns. Asano et al. (2008) described how RSMC Tokyo uses microwave image data in TC analysis. This reanalysis was based on 36.0—37.0 GHz and 85.0—89.0 GHz imagery.

Table 2. Low-earth orbit (LEO) satellites and frequencies of microwave channels used in reanalysis

LEO satellite	Onboard instruments	Frequency used in reanalysis
Aqua	Advanced Microwave Scanning Radiometer-EOS (AMSR-E)	36.5, 89.0 GHz
TRMM	TRMM Microwave Imager (TMI)	85.5 GHz
GCOM-W	Advanced Microwave Scanning Radiometer-2 (AMSR2)	36.5, 89.0 GHz
GPM	GPM Microwave Imager (GMI)	36.5, 89.0 GHz
DMSP	Special Sensor Microwave Imager (SSMI) Special Sensor Microwave Imager/Sounder (SSMIS)	37.0, 85.0 GHz
NOAA (-15, 16, 17, 18, 19)	Advanced Microwave Sounding Unit-B (AMSU-B)	89.0 GHz
Suomi-NPP	Advanced Technology Microwave Sounder (ATMS)	88.0 GHz
Metop (-A, -B, -C)	Microwave Humidity Sounder (MHS)	89.0 GHz

2.3 Production of satellite imagery from meteorological satellite data for reanalysis

Reanalysis was based on images projected on an orthogonal latitudinal-longitudinal square grid transformed from full-disk satellite imagery. Preliminary studies showed that sampling errors generally seen with such conversion were smaller when the resolution was at least three times higher than the original. The geostationary satellite imagery in the analysis was sampled in every 2 km and LEO satellite microwave imagery every 4 km in consideration of disk resources and other factors. The Dvorak technique was used to estimate TC intensity from average depictions for every six hours, and the influence of sampling errors on the reanalysis was therefore low.

Points to note:

- Appendix 1 shows color scale thresholds for brightness temperature in the Enhanced IR (EIR) imagery used for reanalysis.
- With IR, I2 (approx. 12 μm) and I4 (approx. 3.8 μm) images, differential S1 images (IR minus I2) and S2 (I4 minus IR) images are produced for analysis of TC centers and TC cloud patterns.
- The imagery used in Dvorak analysis depends on the satellite observation/scan schedule. For example, analysis for 00 UTC generally involves the use of images for which observation starts between 2320 and 2350 UTC and is completed by 0000 UTC.

3. Dvorak reanalysis

Dvorak reanalysis is primarily conducted using the techniques described in Dvorak (1975 and 1984) with still and animated infrared (IR), visible (VS), S1 and S2 imagery for TC center and intensity analysis. The reanalysis reported here was performed for TCs recorded in the RSMC Tokyo Best track data (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/trackarchives.html) from Early-stage Dvorak analysis period (see Subsection 3.1) when TCs were trackable via their characteristics. Accordingly, the reanalysis start and end times differ from those of the Best track dataset, and no extra-tropical transition was considered.

The first four authors of this paper, who are skilled in Dvorak analysis, performed core analysis along with two other meteorological experts. Two steps were taken; one expert was responsible for the analysis while another for result verification. Data consistency throughout the 30-year period was double-checked at the final stage by the first author.

JMA introduced the Cloud Grid Information Objective Dvorak Analysis technique (named “CLOUD”) into the operation in the 2010s (Kishimoto et al. 2013). However, CLOUD was not used in this reanalysis because GMS-4 had not obtained water vapor (WV) image which is necessary for the analysis by CLOUD.

The following subsections describe the specific methods applied for TCs in the early stages and provide details of the reanalysis. Otherwise, the work was conducted in accordance with the original Dvorak technique (Dvorak 1975 and 1984).

3.1 Early-stage Dvorak analysis

Since 2001, JMA has used the approach described by Tsuchiya et al. (2000), for analysis of TCs in the early development stage (referred to here as Early-stage Dvorak analysis (EDA)) and updated its criteria in 2008 based on

Kishimoto (2008). In the reanalysis reported here, this technique was applied to data from 1987 onward exclusively for tropical disturbances that developed to tropical storm intensity or higher as specified below.

- In EDA, the T-number was set as 0.5 when any four of the following conditions were satisfied, and as 1.0 if all five were satisfied:
  - A convective cloud system had persisted for at least 12 hours.
  - The cloud system had a CSC defined within a diameter of 2.5° latitude or less.
  - The CSC had persisted for at least six hours.
  - The cloud system had a dense cloud area of –31°C or below within 2.0° latitude from the CSC.
  - The dense cloud area was at least 1.5° in diameter.
- For the EDA period, the MET number is set as 9.9. Dvorak regulations on the 12-hour persistence of the CI number are not applied. The CI number is the same as the T number at all times during the EDA period.
- If any of these five conditions are not met during the EDA period, both the T-number and the CI number decrease. Dvorak analysis was applied when the T number reached 1.5 in this analysis. The analysis method for the TC does not revert to EDA even if it weakened to tropical depression.
- Without going to the details here, data for the EDA period are described in three different ways due to the multiple software versions used in the reanalysis. Checking of the cloud patterns applied to CSC analysis (cloud pattern) and intensity analysis (DT pattern) allows determination of which one applies.

3.2 Miscellaneous

The reanalysis reported here adhered to the original Dvorak T-number constraints. For TCs with a clear TC eye and clear cloud patterns, intensities up to peak values were re-analyzed as far as the beginning of TD formation so that the DT number could be adopted at the peak period within these constraints. When TC development exceeded the Dvorak standard intensification and the peak intensity was maintained for at least six hours, the earliest peak time could be analyzed using the PT number and subsequent times using the DT number, so that, the peak intensity was analyzed with the DT number whenever possible while satisfying the Dvorak constraint of the final T-number. As per Dvorak technique, the possible maximum changes of final T number in the previous 6, 12, 18, and 24 hours are based on whether the value at the analysis time was greater than or equal to 4.0, both during the intensification and weakening stages.

Other notable differences from the original Dvorak technique:

- If the TC eye is relatively small, the image production process (Subsection 2.3) may cause sampling errors. To combat this, TC eye temperature is defined as the warmest grayscale temperatures covering 25% or more of the TC eye size by integration from the warmest to the colder scales (Appendix 1).
- MET number evaluation is based on still satellite image differences between the analysis time and 24 hours before, and on animated satellite images from 6 hours before each time.
- As per Koba et al. (1989), the CI number is lowered to match the decrease in the T number at landfall. For another rule, the CI number for a TC making a landfall within 12 hours from when T number starts to decrease is lowered by the same decrease as T number. This rule is continuously applied to the decaying TC for 24 hours after the TC moves back to the sea.

- The CCC pattern was not applied in this reanalysis, as a series of changes in cloud patterns from formation to dissipation was apparent and it can be identified as BAND or CDO pattern by animation.
- For tropical cyclones moving westward from western longitudes, reanalysis over the relevant area was also conducted for T and CI number analysis relating to arrival in eastern longitudes. For information on locations and intensities of disturbances at western longitudes, see the analysis provided by RSMC Honolulu for the central Pacific Ocean.

4. JMA Dvorak reanalysis data and format

4.1 Data and format

The JMA Dvorak reanalysis dataset includes following elements, as described in Appendix 2:

- Analysis time [UTC]
- Latitude/longitude [0.01°]
- Cloud pattern (for CSC analysis)
- DT pattern (for TC intensity analysis), DT number
- MET trend, MET number
- PT type, PT number
- Final T selection (from DT, MET or PT)
- Final T number
- CI number
- Landfall flag (1: sea; 2: land; 3: period of landing effect; 4: after period of landing effect)

4.2 Online resources

JMA's RSMC Tokyo – Typhoon Center website (https://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/RSMC_HP.htm) provides instructions for application of reanalysis data, terms of use, disclaimer information and other content.

5 Reanalysis dataset specifications

The reanalysis project was started in 2012 to produce the most consistent dataset possible for the entire 30-year period, particularly focusing on TC peak intensity. It should be noted that year-to-year differences in geostationary meteorological and LEO satellite data for original full-disk resolution may have caused slight variations in TC intensity for eye pattern. In addition, the presence or absence of the LEO satellite data may affect TC center position accuracy. The extent of related effects on reanalysis data consistency require further clarification.

Discrepancies between the reanalysis and the Best track dataset should also be noted. In some cases, the maximum lifetime CI number for TCs was 1.5 in reanalysis, even though TCs with TS intensity or above were targeted. The start and end times of the reanalysis also differed from the Best track dataset (Section 3) in relation to the sources of the analysis data. While the reanalysis was based on satellite imagery alone, Best track was obtained from all available data, including in-situ observations in addition to satellite imagery. Accordingly, reanalysis data and the Best track dataset are not comparable.

As such, despite JMA's focus on consistency in reanalysis for the entire period, the technical limitations inherent in the achievement of complete consistency and homogeneity for the dataset should be considered.

6. Summary

JMA's Dvorak reanalysis of TC data for WNP is a world-first in consistent analysis on TC intensity for the period from 1987 to 2016. The resulting data are expected to support related analysis of long-term trends and variability against today's background of climate change.

Afterword

The authors are very grateful to Vernon Francis Dvorak, who passed away in September 2022, for developing the Dvorak method in the 1970s and 1980s, which is foundation for this reanalysis. His work brought significant advances in meteorology, and the technique remains standard in TC intensity estimation by WMO RSMCs and NMHSs worldwide. The approach is particularly useful for accurate estimation of intensity over vast ocean basin areas where observation data are scarce. Dvorak's work has contributed greatly to TC disaster mitigation both in Japan and around the world, and should be fully recognized for its role in meteorology today.

Acronyms

AMSR: Advanced Microwave Scanning Radiometer
AMSU: Advanced Microwave Sounding Unit
ATMS: Advanced Technology Microwave Sounder
CCC: Central Cold Cover
CDO: Central Dense Overcast
CI: Current Intensity
CSC: Cloud System Center
DMSP: Defense Meteorological Satellite Program
DT: Data T number (used for Dvorak analysis)
EDA: Early stage Dvorak Analysis
EIR: Enhanced infrared
EOS: Earth Observing System
GCOM-W: Global Change Observation Mission – Water
GOES: Geostationary Operational Environmental Satellite
GMS: Geostationary Meteorological Satellite
GMI: GPM Microwave Imager
GPM: Global Precipitation Measurement
IR: Infrared
IWTC: International Workshop on Tropical Cyclones
JMA: Japan Meteorological Agency
MET: Model Expected T Number (used for Dvorak analysis)
Metop: Meteorological Operational satellite
MHS: Microwave Humidity Sounder
MTSAT-1R: Multi-functional Transport SATellite – 1 Replacement
NMHS: National Meteorological and Hydrological Service
NOAA: National Oceanic and Atmospheric Administration
PT: Pattern T number (used for Dvorak analysis)
RSMC: Regional Specialized Meteorological Centre
S1/S2: 1st difference image/ 2nd difference image
SSMIS: Special Sensor Microwave Imager/Sounder
Suomi-NPP: Suomi National Polar-orbiting Partnership
TC: Tropical Cyclone
TMI: TRMM Microwave Imager
TRMM: Tropical Rainfall Measuring Mission
UTC: Coordinated Universal Time
VS: Visible
WMO: World Meteorological Organization
WNP: Western North Pacific

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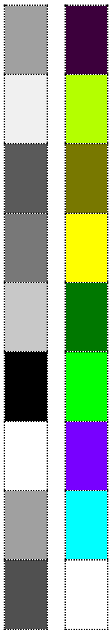
Appendix 1

Gray shading for brightness temperature in enhanced infrared (EIR) imagery



Gray shading (original Dvorak)		→	JMA reanalysis thresholds
WMG (Warm Medium Gray)	≥ +9 °C	→	≥ +9.0 °C
OW (Off White)	+9 °C ≥ ≥ –30 °C	→	+9.0 °C > ≥ –30.5 °C
DG (Dark Gray)	–31 °C ≥ ≥ –41 °C	→	–30.5 °C > ≥ –41.5 °C
MG (Medium Gray)	–42 °C ≥ ≥ –53 °C	→	–41.5 °C > ≥ –53.5 °C
LG (Light Gray)	–54 °C ≥ ≥ –63 °C	→	–53.5 °C > ≥ –63.5 °C
B (Black)	–64 °C ≥ ≥ –69 °C	→	–63.5 °C > ≥ –69.5 °C
W (White)	–70 °C ≥ ≥ –75 °C	→	–69.5 °C > ≥ –75.5 °C
CMG (Cold Medium Gray)	–76 °C ≥ ≥ –80 °C	→	–75.5 °C > ≥ –80.5 °C
CDG (Cold Dark Gray)	–81 °C ≥	→	–80.5 °C >

TC eye temperature in JMA Dvorak reanalysis

- Since the brightness temperature scale used for TC eye temperature in the original Dvorak technique related to the warmest point, some may apply the highest brightness temperature for the TC eye even if only one or two pixels are detected. However, as the brightness temperature of each image pixel is known to depend on various factors (e.g., image conversion errors, digital noise from scanning, sensor resolution differences), TC eye temperature in this reanalysis was defined from the warmest grayscale temperatures covering 25% or more of the TC eye size by integration from the warmest to colder scales.

  Examples

TC eye brightness temperature percentage			->	Adopted
WMG (25%),	OW (25%),	DG (50%)	->	WMG
WMG (5%),	OW (20%),	DG (75%)	->	OW
WMG (5%),	OW (10%),	DG (85%),	->	DG

Appendix 2

JMA Dvorak reanalysis data format

<u>File name</u>

***TYnumber_TCname*.csv**

Sample: T8701_Orchid.csv

TYnumber: T plus 4-digit identification number for a named TC with Beaufort-scale mean sustained wind speeds of 8 or more (34 kt-)

TCname: ESCAP/WMO Typhoon Committee TC name for the western North Pacific and the South China Sea from 2000 onward. TCs were named by the US before 2000 and omitted if there was no English name.

<u>Data</u>

Header line (first row, fixed)

Sample(fixed): Year,Month,Day,Hour,Latitude,Longitude,Cloud Pattern,DT pattern,DT number,MET tendency,MET number,PT type,PT number,Final T selection,Final T number,CI number,Landfall flag

Data lines (second and subsequent rows)

Sample: 2002,07,10,06,25.04,122.68, Curved Band, BAND, 2.5,+0.0,2.5,A,2.5,DT,2.5,2.5,1

#	Format	Element	Expected string
1	AAAA	Year of Analysis time (UTC)	-
2	BB	Month of Analysis time (UTC)	-
3	CC	Day of Analysis time (UTC)	-
4	DD	Hour of Analysis time (UTC)	-
5	EE.EE	Latitude (0.01˚)	-
6	FFF.FF	Longitude (0.01˚)	-
7	G..G	Cloud pattern	-
8	H..H	DT pattern	-
9	I.I	DT number	-
10	±J.J	Met tendency	-
11	K.K	Met number	-
12	L	PT type	A, B or C
13	M.M	PT number	-
14	NN|NNN	Final T selection	DT, MET or PT
15	O.O	Final T number	-

16	P.P	CI number	-
17	Q	Landfall flag	1, 2, 3 or 4

Note:

- For low-level cloud vortex (LCV) pattern, the DT number is set as 9.9 for the missing value and DT pattern is set as “UNDEFINE”.
- Missing DT numbers and MET numbers are set as 9.9.