Is the Number of Tropical Cyclone Rapid Intensification Events in the Western North Pacific Increasing?

Udai Shimada¹, Munehiko Yamaguchi¹, and Shuuji Nishimura²

¹Meteorological Research Institute, Tsukuba, Japan
²Matsuyama Local Meteorological Office, Ehime, Japan

Abstract

Japan Meteorological Agency (JMA) best track data indicate that the number of rapid intensification (RI) tropical cyclone events in the western North Pacific increased from 1987 to 2018. To clarify whether this increase is due to climatological changes or qualitative changes in the data, the long-term trend of RI events in JMA operational Dvorak data, which have been used as the first guess for best track analysis, was investigated. Because the JMA Dvorak analysis procedure has remained almost unchanged since 1987, the temporal homogeneity of the Dvorak data is expected to be much better than that of the best track data. The results showed no discernible trend in Dvorak-based RI events over the 32 years. Although the frequency distribution of 24-h intensity changes slightly in the Dvorak analysis, that of the best track data changed significantly; as a result, the frequency of best track-based RI events increased after 2006. JMA started using microwave satellite imagery for best track analysis in 2006. This change likely affected the temporal homogeneity of the best track data. These results suggest that the increase in best track-based RI events was due mainly to qualitative changes related to advances in observational techniques.

(Citation: Shimada, U., M. Yamaguchi, and S. Nishimura, 2020: Is the number of tropical cyclone rapid intensification events in the western North Pacific increasing? SOLA, 16, 1–5, doi:10.2151/sola.2020-001.)

1. Introduction

Forecasting rapid intensification (RI) events in tropical cyclones (TCs) is essential for mitigating TC-related disasters. Most intense TCs undergo RI (e.g., Kaplan and DeMaria 2003), and the resulting violent winds and storm surges can cause devastating damage to human communities. However, all presently existing numerical and statistical models have, to a greater or lesser extent, difficulty predicting RI (e.g., Langlade et al. 2018). In particular, the timing of RI is hard to predict, which is a concern because even a small difference in the predicted timing of RI can lead to large intensity forecast errors. Additionally, in light of the changing climate, it is crucial for disaster preparedness, prevention, and mitigation to improve our understanding of TC activity from a climatological perspective, in particular whether the annual numbers of intense TCs (e.g., Emanuel 2005; Kamahori et al. 2006; Kossin et al. 2007, 2013; Elsner et al. 2008; Song et al. 2010; Mei and Xie 2016; Knutson et al. 2019) and RI occurrences (e.g., Balaguru et al. 2018) are increasing.

There is a discrepancy in the long-term RI occurrence trend between best track datasets for the western North Pacific (WNP). According to best track data from the Japan Meteorological Agency (JMA), both the number of TCs that underwent RI and the RI occurrence frequency increased from 1989 to 2015 (Ito et al. 2016; Fudeyasu et al. 2018). In contrast, best track data from the Joint Typhoon Warning Center (JTWC) indicate that the number of TCs that experienced RI during the active TC season (July to November) decreased slightly from 1989 to 2015 (Zhao et al. 2018, see their Fig. 2b). This discrepancy suggests that the trend in RI occurrence reflects not only climatological changes but also qualitative changes in the best track data. To examine TC activity from a long-term climatological perspective using best track data, a quality check is needed to remove potential artifacts resulting from changes in observing techniques. In the WNP where aircraft reconnaissance is rare, it is critical to understand what observations and estimation techniques were employed to construct the best tracks, which are used as basic information in all TC-related research, for appropriate interpretation of the research findings.

Temporal inhomogeneity in the best track data, if present, might severely affect the skill of statistical-dynamical models such as the Statistical Hurricane Intensity Prediction Scheme (SHIPS, DeMaria and Kaplan 1994; DeMaria et al. 2005) and the RI index (Kaplan et al. 2010, 2015). Statistical-dynamical models that predict intensity changes or RI probabilities are constructed by using best track data and environmental conditions derived from atmospheric and oceanic reanalysis data. At present, the JMA version of the RI index does not have sufficient skill for RI prediction because the forecast RI probabilities provided by the RI index mainly do not correspond to observed frequencies (i.e., they do not concentrate along the 1-1 line of a reliability diagram; Shimada 2019). To improve the accuracy of the RI index, it is necessary to investigate the properties of the best track data used to construct the index, as well as to add new predictors and to develop a new methodology.

How can changes in RI occurrence in best track data due to climatological changes be discriminated from those due to artificial qualitative changes? In this study, we examined RI occurrences in operational Dvorak analysis (Dvorak 1984) data produced by JMA from 1987 (Meteorological Satellite Center/JMA 2004). JMA uses the Dvorak analysis data as a first guess for estimating best track intensity, and then modifies the first guess based on other observations (i.e., satellite products and surface observations) so that best track intensities are consistent with weather chart analysis (see details in Kishimoto 2011, Regional Specialized Meteorological Center Tokyo 2012, and Kunitsugu 2012). JMA started to perform operational Dvorak analysis using the enhanced infrared (EIR) method in 1987 (Akashi et al. 1988; Fujita and Hagiwara 2000), and the procedure has remained almost unchanged since then. Thus, Dvorak intensity estimates are more consistent in time than best track intensities and are better suited for trend analysis even with their large uncertainties (e.g., Koba et al. 1991; Martin and Gray 1993; Velden et al. 2007). If we assume that the Dvorak procedure is temporally homogeneous, we can use Dvorak intensity estimates for trend analysis. If there are differences in RI occurrence trends between the JMA best track and Dvorak intensities, then the best track trends could include artifacts from changes in estimation methods. If trends in the two datasets are consistent, we have more confidence that temporal changes in estimation methods have not affected best track trends. The purpose of this study is to examine whether the number of RI occurrences increased in response to climatological changes or not during the period from 1987 to 2018.
2. Data and methodology

We used JMA Dvorak intensity (i.e., Current Intensity (CI) numbers) data and JMA best track intensity (i.e., maximum wind speed, Vmax) data from the WNP for the period from 1987 to 2018. We adopted intensity data that are at least tropical storm strength (CI ≥ 2 and Vmax ≥ 34 kt). The Dvorak data were operationally produced by JMA in real time. Additionally, we used JTWC best track data from 1987 to 2017 for comparison. Unfortunately, five TCs that occurred during the study period were not included in the Dvorak dataset. We were able to include four of the missing TCs in the dataset by performing additional Dvorak analyses because their satellite datasets were available to us. Therefore, the only TC not included in this study was Typhoon Orchid (1987). We describe later how we dealt with this omission.

We defined RI as follows:
1) in JMA Dvorak analysis data, a CI number increase of at least 2 over a 24-h period, or
2) in best track data, a Vmax increase of at least 30 kt over a 24-h period.

Dvorak intensity is initially expressed as a CI number, which is then converted to Vmax. In the JMA Dvorak analysis, a CI number increase of 2 is equivalent to a Vmax increase of 28–30 kt (Table 1). Additionally, if Vmax or the CI number remained the same during the first or last 6-h period that satisfied the RI definition, that period was excluded from the RI period to determine the onset and duration of RI. As a result, the RI period of some TCs was only 18 h. In this study, each successive period satisfying the definition of RI was counted as one RI “event”; this definition of event is the same as that used by Tao et al. (2017). Thus, it was possible for a TC to experience two or three RI events during its lifetime. This counting method was adopted to capture multiple RI events in long-lived TCs.

In total, we identified 176 RI events in the JMA best track data and 289 events in the JMA Dvorak data. The missing typhoon, Typhoon Orchid (1987), experienced one RI event, according to the best track data. Therefore, we decided to add one more event to the number of Dvorak-based RI events in 1987. We believe that the addition of four TCs to the Dvorak dataset and the lack of data for one TC did not affect the conclusions of this study.

3. Results and discussion

The annual number of best track-based RI events tended to increase over the 32 years, whereas the annual number of Dvorak-based RI events exhibited no long-term trend (Fig. 1). The difference in the annual number of events between the best track and Dvorak datasets was relatively large in the 1990s (6 on average), but small during the last 10 years of the study period (2 on average).

To examine why the number of RI events differed between the datasets and why the magnitude of the difference changed, we compared the annual mean increase in the CI number with the annual mean increase in Vmax during the first 24 h of Dvorak-based RI events (Fig. 2). Because in the Dvorak technique, intensity changes over 24 h are constrained (ΔCI number ≤ 2.5) (Dvorak 1984, Cangialosi et al. 2015), the annual mean increase in the CI number remained unchanged (2.1 on average). In contrast, annual mean Vmax noticeably increased around 2006. For TCs that met the Dvorak-based RI definition, annual Vmax increases were, in general, 20–25 kt from 1987 to 2005, but 25–30 kt from 2006 to 2018. Because a CI-number increase of 2 can be converted into 25 or 30 kt by using the JMA conversion table (Table 1), the results presented in Fig. 2 suggest that, in general, the Dvorak intensity increases were discounted by 5 kt before 2006 when the best track intensities were estimated. Consequently, the annual number of Dvorak-based RI events was much greater than that of best track-based RI events before 2006, but the difference between the datasets became smaller after 2006.

Next, we examined changes in the frequency distributions of 24-h intensity changes in the Dvorak and best track datasets after 2006 (Fig. 3). In the Dvorak dataset, the standard deviation of CI-number changes was 0.98 from 1987 to 2005 and 1.02 from 2006 to 2018. The difference in the variance was small, although...
whether that change stemmed from climatological variations or of Vmax changes of more than 25 kt (i.e., the frequency of RI) from 2006 to 2018. This difference was so large that the frequency deviation of Vmax changes was 13.5 from 1987 to 2005 and 15.7 it was statistically significant at the 95% confidence level in a Vmax changes (kt) in the best track dataset.

Fig. 3. Frequency distributions of 24-h intensity changes during 1987−2005 and 2006−2018: (a) CI-number changes in the Dvorak dataset; (b) Vmax changes (kt) in the best track dataset. it was statistically significant at the 95% confidence level in a two-sided F test. In contrast, in the best track dataset, the standard deviation of Vmax changes was 13.5 from 1987 to 2005 and 15.7 from 2006 to 2018. This difference was so large that the frequency of Vmax changes of more than 25 kt (i.e., the frequency of RI) greatly increased after 2006. Although there was a slight change in the RI frequency in the Dvorak data, we were unable to judge whether that change stemmed from climatological variations or modifications in how the Dvorak technique was implemented at JMA.

What caused the significant trend in the annual number of RI events in the JMA best track data? The history of observations used for best track intensity estimation (Table 2) shows that JMA started using microwave satellite imagery in 2006. Moreover, around 2006, the availability of satellite-derived ocean surface wind data was enhanced and JMA started to implement Dvorak re-analysis for best track analysis. The use of these new observations could likely lead to changes in the quality of Dvorak intensities.

Best track analysts can use microwave satellite imagery to check whether an eye pattern selected by the Dvorak technique is valid because TC eye patterns are sometimes unclear in infrared satellite imagery and, in particular, a pseudo-eye pattern may be observed. In general, the RI period corresponds to the time when the cloud pattern transitions from a central dense overcast (CDO; i.e., no eye) pattern to an eye pattern. Our examination indicated that 92% of Dvorak-based RI onsets occurred when the CI number was 2−4 (not shown), before the eye pattern appeared. With a CDO pattern, the maximum potential CI number is 5.0, but if an eye pattern is selected within 6−12 h, then the CI number can rapidly reach 6.0 or 6.5, leading to RI. Thus, the magnitude of the increase in the CI number depends greatly on the timing of the (subjective) selection of an eye pattern. Nowadays, it is well known, based on knowledge gained through microwave satellite imagery, that an eyewall forms before it is visible in infrared satellite imagery (e.g., Velden et al. 2006; Olander and Velden 2019). Earlier, however, there were not enough observations that could support the selection of an eye pattern and the resultant RI. Thus we infer that, before 2006, the Dvorak intensity increases were discounted when best track intensities were estimated to avoid potential overestimation. After 2006, in contrast, the selection of an eye pattern became reliable with the use of microwave imagery. Best track analysts could adopt the Dvorak intensity as the best track intensity. In addition, ocean surface wind observations and Dvorak reanalysis data might have enhanced confidence in the Dvorak intensity.

In light of these considerations, the increasing trend in the annual number of RI events in the JMA best track data can be attributed, at least in part, to qualitative changes in the data related to advances in observational techniques. We should recognize that best track data represent the “best analysis” according to the knowledge of TCs and all observations available at the time. Available observations reflect the accuracy and temporal and spatial resolutions of the measurement techniques used. Changes in measurement techniques and procedures used to create the JMA best tracks must be addressed when developing/validating statistical models or performing trend analysis. Other best track datasets also contain temporal inhomogeneities due to advances in observation techniques, as has been pointed out previously (e.g., Chu et al. 2002; Harper et al. 2008; Torn and Snyder 2012; Schreck et al. 2014).

For comparison, we examined RI events derived from JTWC best track data (Fig. 4). The number of RI events in these data, like the number of JMA’s Dvorak-based RI events, remained unchanged over 32 years. This result is also consistent with the findings of Zhao et al. (2018), who studied RI TCs occurring in the WNP from July to November during 1979−2015. The number of JTWC RI events was generally greater than the number in JMA’s Dvorak analysis. This is partly because JTWC’s Dvorak analysis tends to increase CI numbers faster than JMA’s Dvorak analysis does (Nakazawa and Hoshino 2009) and also because in the conversion table used by JTWC (Table 1), Vmax increases much faster for CI numbers greater than 3.0 than it does in the JMA table.

Instead of the annual number of events, it is worthwhile to examine changes in the ratio of RI TCs to all TCs, because the annual number of TCs decreased over the 32 years (Fig. 5). The

| Year | Description |
|------|-------------|
| 1987 | Operational Dvorak analysis (using the enhanced infrared (EIR) method) in real time begins at the Meteorological Satellite Center, JMA |
| 1995 | Use of Geostationary Meteorological Satellite 5 (GMS-5) data (including water vapor and split window bands) begins |
| 2000 | Use of Quick Scatterometer Mission (QuikSCAT) data (ocean surface winds) begins |
| 2005 | Use of Multifunction Transport Satellite 1R (MISAT-1R) data, observed at 30-min intervals, begins |
| 2006 | Use of microwave satellite imagery obtained from the Aqua Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), and the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager Sounder (SSMIS) series (Nishimura et al. 2007) begins |
| 2007 | Use of Advanced Scatterometer (ASCAT) data (ocean surface winds) from Meteorological Operational satellite A (MetOp-A) begins |
| 2009 | Use of high-resolution Himawari-8 data observed at 10-min intervals (Bessho et al. 2016) begins |
| 2015 | Use of ocean-surface wind data derived from atmospheric motion vectors (AMVs) (Meteorological Satellite Center/JMA 2019) begins |
frequency of best track–based RI events increased measurably. Track intensity increases changed greatly, with the result that the increases over 24 h showed a slight change, whereas that of best creases. After 2006, the frequency distribution of Dvorak intensity in Dvorak-based RI events over the 32 years. Before 2006, best ical change or artifacts. The results showed no discernable trend seen in the JMA best track data could be attributed to climatological 4. Conclusion

We investigated Dvorak-based RI events of TCs in the WNP from 1987 to 2018 to clarify whether the increase in RI events seen in the JMA best track data could be attributed to climatological changes or artifacts. The results showed no discernable trend in Dvorak-based RI events over the 32 years. Before 2006, best track intensity increases during the first 24 h of Dvorak-based RI events were smaller by ~5 kt compared with Dvorak intensity increases. After 2006, the frequency distribution of Dvorak intensity increases over 24 h showed a slight change, whereas that of best track intensity increases changed greatly, with the result that the frequency of best track–based RI events increased measurably after that date.

In 2006, JMA started using microwave satellite imagery for best track analysis, which allowed analysts to confirm the validity of the cloud pattern selected in the Dvorak technique. Confirmation of eyewall formation in microwave imagery gave the analysts confidence in the selection of an eye pattern. We infer that the use of microwave imagery promoted the adoption of the Dvorak intensity as the best track intensity after 2006. Therefore, the increase in RI events seen in the best track data since 2006 was mainly due to procedural changes at JMA. It should be noted, however, that because the annual number of TCs decreased over the 32 years, the proportion of RI TCs relative to the total number of TCs increased by 5% even in the Dvorak analysis data. We found temporal inhomogeneity in the JMA best track data and identified its cause. However, our results do not diminish the value of JMA best track data. Rather, they demonstrate that because JMA conducts best track analysis by using all observations and knowledge of TCs available at the time, the quality of its analysis has improved along with advances in observation techniques and our understanding of TCs.

Acknowledgments

The opinions in this paper are those of the authors and should not be regarded as official views of JMA. We are deeply grateful to our colleagues at JMA who provided the historical Dvorak analysis data. We also acknowledge JTWC for their best track data. The helpful comments from two reviewers are appreciated. This work was supported by MEXT KAKENHI grant 19K14797.

Edited by: K. Cheung

References

Akashi, S., H. Koba, T. Harada, and T. Ichinari, 1988: Comparison between visible and enhanced infrared analyses by Dvorak’s method for tropical cyclone intensity estimation (in Japanese). J. Meteor. Soc. Japan, 66, 181–196.

Balaguru, K., G. R. Foltz, and L. R. Leung, 2018: Increasing magnitude of hurricane rapid intensification in the central and eastern tropical Atlantic. Geophys. Res. Lett., 45, 4238–4247, doi:10.1029/2018GL077597.

Bessho, K., and co-authors, 2016: An introduction to Himawari-8/9 – Japan’s new generation geostationary meteorological satellites. J. Meteor. Soc. Japan, 94, 151–183, doi:10.2151/jmsj.2016-009.

Bhatia, K. T., G. A. Vecchi, T. R. Knutson, H. Murakami, J. Kossin, K. W. Dixon, and C. E. Whitlock, 2019: Recent increases in tropical cyclone intensity rates. Nature Commun., 10, 635.

Cangialosi, J., T. Kimberlain, J. Beven, and M. DeMaria, 2015: The validity of Dvorak intensity change constraints for tropical cyclones. Wea. Forecasting, 30, 1010–1015, doi:10.1175/WAF-D-15-0028.1.

Chu, J.-H., C. R. Sampson, A. S. Levine, and E. Fukada, 2002: The joint typhoon warning center tropical cyclone best-tracks, 1945–2000. Naval Research Laboratory Tech. Rep. NRL/MR/7540-02-16, 28 pp. (Available online at https://www.metoc.navy.mil/jtwc/products/best-tracks/cb-bt-report. html, accessed 04 September 2019).

DeMaria, M., and J. Kaplan, 1994: A Statistical Hurricane Intensity Prediction Scheme (SHIPS) for the Atlantic basin. Wea. Forecasting, 9, 209–220, doi:10.1175/1520-0434(1994)009<0209:ASHIPS>2.0.CO;2.

DeMaria, M., M. Mainelli, L. K. Shay, J. A. Knaff, and J. Kaplan, 2005: Further improvements to the Statistical Hurricane Intensity Prediction Scheme (SHIPS). Wea. Forecasting, 20, 531–543, doi:10.1175/WAF862.1.

Dvorak, V. F., 1984: Tropical cyclone intensity analysis using satellite data. NOAA Tech. Rep., 11, 45 pp.

Elsner, J. B., J. P. Kossin, and Y. H. Jagger, 2008: The increasing

Fig. 4. Annual number of RI events in the JTWC best track data (green) compared with the annual number of JMA’s Dvorak-based RI events (red). The thin green line is a regression line fitted to the JTWC data.

Fig. 5. Percentages of best track–based (blue) and Dvorak-based (red) RI TCs relative to the number of all TCs (green bars) for each year from 1987 to 2018. The straight blue and red lines are regression lines fitted to the best track and Dvorak-based data, respectively. The straight green line is a regression line fitted to the number of TCs.
intensity of the strongest tropical cyclones. *Nature*, **455**, 92–95.

Emanuel, K. A., 2005: Increasing destructiveness of tropical cyclones over the past 30 years. *Nature*, **436**, 686–688.

Fudeyasu, H., K. Ito, and Y. Miyamoto, 2018: Characteristics of tropical cyclone rapid intensification over the western North Pacific. *J. Climate*, **31**, 8917–8930, doi:10.1175/JCLI-D-17-0653.1.

Fujita, Y., and T. Hagiwara, 2000: Typhoons, analysis and prediction. *Meteor. Res. Notes*, **197**, 1–75 (in Japanese).

Harper, B. A., S. A. Stroud, M. McCormack, and S. West, 2008: A review of historical tropical cyclone intensity in northwestern Australia and implications for climate change trend analysis. *Aust. Meteor. Mag.*, **57**, 121–141.

Ito, K., 2016: Errors in tropical cyclone intensity forecast by RSMC Tokyo and statistical correction using environmental parameters. *SOLA*, **12**, 247–252, doi:10.2151/sola.2016-049.

Kamahori, H., N. Yamazaki, N. Mannoji, and K. Takahashi, 2006: Variability in intense tropical cyclone days in the western North Pacific. *SOLA*, **2**, 104–107, doi:10.2151/sola.2006-027.

Kaplan, J., and M. DeMaria, 2003: Large-scale characteristics of rapidly intensifying tropical cyclones in the North Atlantic basin. *Wea. Forecasting*, **18**, 1093–1108, doi:10.1175/1520-0434(2003)018<1093:LCRTIO>2.0.CO;2.

Kaplan, J., M. DeMaria, and J. A. Knaff, 2010: A revised tropical cyclone rapid intensification index for the Atlantic and East Pacific basins. *Wea. Forecasting*, **25**, 220–241, doi:10.1175/2009WAF2222280.1.

Kaplan, J., and co-authors, 2015: Evaluating environmental impacts on tropical cyclone rapid intensification predictability utilizing statistical models. *Wea. Forecasting*, **30**, 1374–1396, doi:10.1175/WAF-D-15-0032.1.

Kishimoto, K. 2011: JMA best track data. Second IBTrACS Workshop, Hawaii, USA, WMO (Available online at ftp://eclipse.ncdc.noaa.gov/san1/ibtracs/workshop/SecondWorkshop/12-Tuesday/April-12-1340-JMA%20best%20track-Kishimoto.pptx, accessed 24 November 2019).

Koba, H., S. Osano, T. Hagiwara, S. Akashi, and T. Kikuchi, 1991: Relationship between the CI-number and central pressure and maximum wind speed in typhoons. *Geophys. Mag.*, **44**, 15–25.

Kossin, J. P., K. R. Knapp, D. J. Vimont, R. J. Murnane, and B. A. Harpar, 2007: A globally consistent reanalysis of hurricane variability and trends. *Geophys. Res. Lett.*, **34**, L04815, doi:10.1029/2006GL028836.

Kossin, J. P., P. L. Olander, and K. R. Knapp, 2013: Trend analysis with a new global record of tropical cyclone intensity. *J. Climate*, **26**, 9960–9976, doi:10.1175/JCLI-D-13-00262.1.

Knutson, T., and co-authors, 2019: Tropical cyclones and climate change assessment: Part 1. Detection and attribution. *Bull. Amer. Meteor. Soc.*, **100**, 1987–2007, doi:10.1175/BAMS-87-9-1195.

Kunitsugu, M., 2012: Tropical cyclone information provided by the RSMC Tokyo-typhoon Center. *Tropical Cyclone Research and Review*, **1**, 51–59, doi:10.6057/2012TCRR01.06.

Langlade, S., and co-authors, 2018: Intensity change: operational perspectives. * Ninth Int. Workshop on Tropical Cyclones, Hawaii, USA, WMO* (Available online at https://www.wmo.int/pages/prog/arep/wrwp/tmr/documents/WT9-Subtopic_3-3.pdf, accessed 04 September 2019).

Martin, J. D., and W. M. Gray, 1993: Tropical cyclone observation and forecasting with and without aircraft reconnaissance. *Wea. Forecasting*, **8**, 519–532, doi:10.1175/1520-0434(1993)008<0519:TCOAFW>2.0.CO;2.

Mei, W., and S. P. Xie, 2016: Intensification of landfalling typhoons over the northwest Pacific since the late 1970s. *Nat. Geosci.*, **9**, 753–757.

Meteorological Satellite Center, Japan Meteorological Agency, 2004: *Analysis and Use of Meteorological Satellite Images, Tropical Cyclones*, 135 pp. (Available online at https://www.data.jma.go.jp/mscwdb/ja/prod/pdf/book/book_neteikisho.pdf, accessed 04 September 2019).

Meteorological Satellite Center, Japan Meteorological Agency, 2019: *AMV-based Sea-surface Wind for Tropical Cyclone Monitoring* (Available online at http://www.data.jma.go.jp/mscw/en/product/product/awind/monitor/awind.php, accessed 04 September 2019).

Nakazawa, T., and S. Hoshino, 2009: Intercomparison of Dvorak parameters in the tropical cyclone datasets over the western North Pacific. *SOLA*, **5**, 33–36, doi:10.2151/sola.2009-009.

Nishimura, S., and co-authors, 2007: Analysis of Tropical Cyclones with Microwave Satellite Imagery. *Meteorological Satellite Center Technical Note*. **49**, 91–125 (in Japanese) (Available online at https://www.data.jma.go.jp/mscw/technote/msc techrep49-7.pdf, accessed 04 September 2019).

Olander, T. L., and C. S. Velden, 2019: The advanced Dvorak technique (ADT) for estimating tropical cyclone intensity: update and new capabilities. *Wea. Forecasting*, **34**, 905–922, doi:10.1175/WAF-D-19-0007.1.

Region Specialized Meteorological Center (RSMC) Tokyo, 2012: Operational tropical cyclone analysis by RSMC Tokyo, Japan. Appendix C, *Proc. the International Workshop on Satellite Analysis of Tropical Cyclones*, 34–43 (Available online at https://library.wmo.int/doc_num.php?explnum_id=6291, accessed 24 November 2019).

Schreck, C. J., K. R. Knapp, and J. P. Kossin, 2014: The impact of best track discrepancies on global tropical cyclone climatologies using IBTrACS. *Mon. Wea. Rev.*, **142**, 3881–3899, doi:10.1175/MWR-D-14-00021.1.

Shimada, U., 2019: RI index. *Technical Reports of the Meteorological Research Institute, 82*, 31–38 (in Japanese) (Available online at http://www.mri-jma.go.jp/Publish/Technical/DATA/VOL_82/4.pdf, accessed 04 September 2019).

Song, J., Y. Wang, and L. Wu, 2010: Trend discrepancies among three best track data sets of western North Pacific tropical cyclones. *J. Geophys. Res.*, **115**, D12128, doi:10.1029/2010JD013058.

Tao, C., H. Jiang, and J. Zawislak, 2017: The relative importance of stratiform and convective rainfall in rapidly intensifying tropical cyclones. *Mon. Wea. Rev.*, **145**, 795–809, doi:10.1175/MWR-D-16-0316.1.

Torn, R. D., and C. Snyder, 2012: Uncertainty of tropical cyclone best-track information. *Wea. Forecasting*, **27**, 715–729, doi:10.1175/WAF-D-11-00085.1.

Velden, C., and co-authors, 2006: The Dvorak tropical cyclone intensity estimation technique: A satellite-based method that has endured for over 30 years. *Bull. Amer. Meteor. Soc.*, **87**, 1195–1210, doi:10.1175/BAMS-87-9-1195.

Velden, C. S., D. Herndon, J. Kossin, J. Hawkins, and M. DeMaria, 2007: Consensus estimates of tropical cyclone (TC) intensity using integrated multispectral (IR and MW) satellite observations. *Joint 2007 EUMETSAT Meteorological Satellite/15th Conf. on Satellite Meteorology and Oceanography, Amsterdam, the Netherlands, EUMETSAT–Amer. Meteor. Soc.* (Available online at http://www.ssec.wisc.edu/meetings/jointmetsat2007/pdf/valden_sacoon.pdf, accessed 4 September 2019).

Zhao, H., X. Duan, G. b. Raga, and P. Klotzbach, 2018: Changes in characteristics of rapidly intensifying western North Pacific tropical cyclones related to climate regime shifts. *J. Climate*, **31**, 8163–8179, doi:10.1175/JCLI-D-18-0029.1.