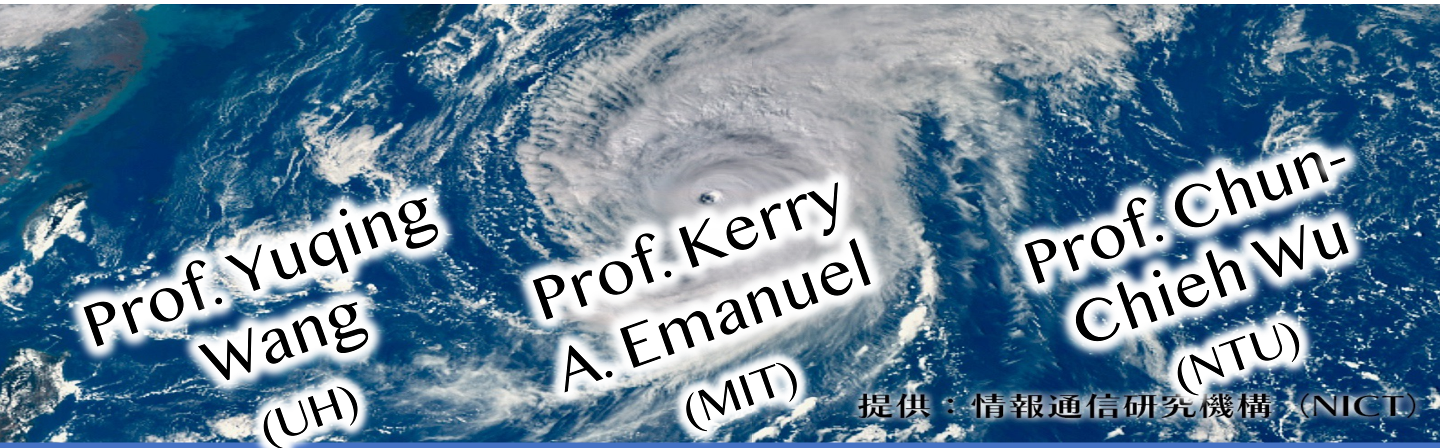
Typhoon Science and Technology Research Center

IWTRC 2023 YOKOHAMA

ABSTRACTS (SESSION 2)



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Ocean interaction and the intensity evolution of two high-impact super typhoons: Hagibis (2019) and Haiyan (2013)

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Devastating Japan in October 2019, Supertyphoon (STY) Hagibis was an important typhoon in the history of the Pacific. A striking feature of Hagibis was its explosive RI (rapid intensification). In 24 h, Hagibis intensified by 100 kt, making it one of the fastest-intensifying typhoons ever observed. After RI, Hagibis's intensification stalled. Using the current typhoon intensity record holder, i.e., STY Haiyan (2013), as a benchmark, this work explores the intensity evolution differences of these 2 high-impact STYs.

We found that the extremely high pre-storm sea surface temperature reaching 30.5°C, deep/warm pre-storm ocean heat content reaching 160 kJ cm^{-2}, fast forward storm motion of ~8 m s^{-1}, small during-storm ocean cooling effect of ~ 0.5°C, significant thunderstorm activity at its center, and rapid eyewall contraction were all important contributors to Hagibis's impressive intensification. There was 36% more air-sea flux for Hagibis's RI than for Haiyan's.

After its spectacular RI, Hagibis's intensification stopped, despite favorable environments. Haiyan, by contrast, continued to intensify, reaching its record-breaking intensity of 170 kt. A key finding here is the multiple pathways that storm size affected the intensity evolution for both typhoons. After RI, Hagibis experienced a major size expansion, becoming the largest typhoon on record in the Pacific. This size enlargement, combined with a reduction in storm translational speed, induced stronger ocean cooling that reduced ocean flux and hindered intensification. The large storm size also contributed to slower eyewall replacement cycles (ERCs), which prolonged the negative impact of the ERC on intensification.

Reference:

Lin, I-I*, Robert F. Rogers*, Hsiao-Ching Huang, Yi-Chun Liao, Derrick Herndon, Jin-Yi Yu, Ya-Ting Chang, Jun A. Zhang, Christina M. Patricola, Iam-Fei Pun, Chun-Chi Lien, A Tale of Two Rapidly-Intensifying Supertyphoons: Hagibis (2019) and Haiyan (2013), *Bulletin of the American Meteorological Society*, Vol. 102, No. 9, E1645–E1664, Sep. 2021. https://doi.org/10.1175/BAMS-D-20-0223.1

Lin, I-I*, Suzana J. Camargo, Chun-Chi Lien, Chun-An Shi, James P. Kossin, Poleward migration as global warming's possible self-regulator to restrain future western North Pacific Tropical Cyclone's intensification. *npj Clim Atmos Sci* **6**, 34, Apr. 2023. https://doi.org/10.1038/s41612-023-00329-y

Joint research between TRC and NTT on typhoon prediction method using atmospheric and oceanographic observation data

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NTT Corporation (hereinafter, "NTT") and Yokohama National University ("YNU") have concluded a joint research contract on "Research into methods of typhoon forecasting using ocean-atmosphere observation data over maritime areas." The project aims to improve the accuracy of typhoon forecasting by enabling the observation of typhoons in real-time using NTT's ultra-wide-area ocean-atmosphere observation technology, taking advantage of the respective strengths of both NTT and YNU, which established Japan's only research institute dedicated to the study of typhoons, the Typhoon Science and Technology Research Center (hereinafter, "the TRC") in 2021.

As typhoons become ever more devastating due to the global warming, the question of how Japan as a typhoon-prone country can defend its safety and security in terms of this threat to its citizens' lives and property is becoming a social challenge of great import. Unfortunately, despite the various disaster prevention and mitigation measures put in place, there seems to be no end to the damage caused by typhoons. To achieve a breakthrough in this situation, we must provide typhoon forecasting information as quickly and as accurately as possible to mitigate the damage caused by these disasters.

Researchers at TRC will not only work on the observation and forecasting of typhoons, but will also look ahead to experimental endeavors that aim to look beyond mitigation of the damage caused by typhoons and to make use of typhoons' energy, with various research themes underway that are connected with controlling typhoons or using their power to generate electricity. NTT, meanwhile, aims to develop a sensing system that can communicate with low-earth-orbit satellites and high-altitude platform stations (HAPSs) floating above the earth at high altitudes, with the aim of integration with NTT's Space Integrated Computing Network project. In this joint research project, NTT's ocean-atmosphere observation data obtained from the areas directly affected by typhoons will be incorporated into the TRC's typhoon forecasting model, and the contribution that this makes to improving the accuracy of forecasting will be verified.

TRC aims to become a global leader by pushing forward innovative research that uses typhoons as a source of "benefits" rather than merely positioning them as "threats". NTT aims to enable observations over a wider area and in real-time, including unexplored areas, using its Space Integrated Computing Network project, enabling low-cost sensing over an ultra-wide area. By making it possible to conduct real-time observation of maritime weather conditions over an ultra-wide area through collaborating with a variety of industries and organizations, NTT will help to develop high-accuracy forecasting of future typhoons as part of environmental and social activities, transforming typhoons into a "benefit" for humanity, and helping to build resilience among the countries of the Pacific Rim.

Digital Typhoon Dataset: 40+ years of satellite images of tropical cyclones for machine learning research

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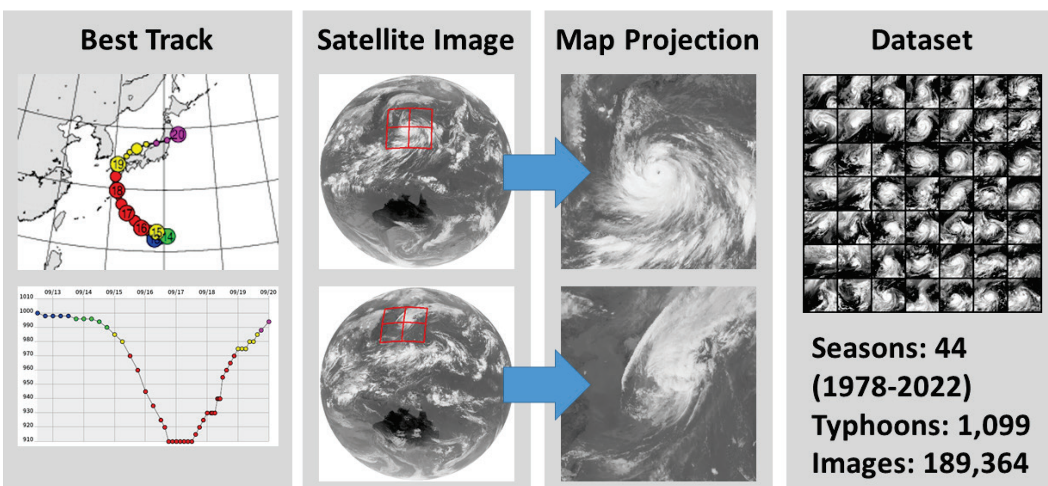
This paper presents the official release of the Digital Typhoon dataset, the longest typhoon satellite image dataset for 40+ years aimed at benchmarking machine learning models for long-term spatio-temporal data. To build the dataset, we developed a workflow to create an infrared typhoon-centered image for cropping using Lambert azimuthal equal-area projection referring to the best track data. We also address data quality issues such as inter-satellite calibration to create a homogeneous dataset. To take advantage of the dataset, we organized machine learning tasks by the types and targets of inference, with other tasks for meteorological analysis, societal impact, and climate change. The benchmarking results on the analysis, forecasting, and reanalysis for the intensity suggest that the dataset is challenging for recent deep learning models, due to many choices that affect the performance of various models. This dataset reduces the barrier for machine learning researchers to meet large-scale real-world events called tropical cyclones and develop machine learning models that may contribute to advancing scientific knowledge on tropical cyclones as well as solving societal and sustain ability issues such as disaster reduction and climate change. The figure below illustrates a part of the processes of creating the dataset.



Digital Typhoon is a project started in 1999 to create a typhoon dataset for machine learning and a web-based platform for digging into the long-term multimodal typhoon database. It offers not only satellite data but also other time-series data such as weather warning information, ground observations, weather charts, and disaster records. Since then, it has evolved into one of Japan's most popular typhoon websites, with an annual page view of more than 20 million. A future direction would be to expand machine-readable datasets so that AI can augment traditional methods for analysis and forecasting.

The dataset is publicly available at http://agora.ex.nii.ac.jp/digital-typhoon/dataset/

Civilian aircraft ability to monitor tropical cyclone intensity

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Tropical cyclone (TC) intensity is important information for accurate weather forecasting to reduce natural disasters. The central pressure of a TC is usually estimated using satellite images, although recent studies point out that satellite estimates contain errors that hinder understanding of long-term changes in TC intensity. Accurate in-situ measurements of pressure and temperature in the eye are thought to be achievable only by military aircraft capable of withstanding severe turbulence. Using a small civilian jet, we demonstrate that by flying in the upper troposphere, we can safely fly into the eye of an intense TC and accurately estimate its central pressure using temperature profile. We have entered the eye of an intense TC 16 times in the northwestern Pacific, but we never encountered strong turbulence. Based on aircraft and ground-based observations, we found that the mean temperature anomaly in the eye from the lower to upper troposphere is highly correlated with the central pressure (Fig. 1). This result is a new perspective compared to previous studies that focused on the maximum temperature anomaly in the upper troposphere. This result suggests that if the temperature profile inside the eye can be accurately obtained using a geostationary satellite in the future, it will be possible to accurately monitor TC intensity at short intervals (~15 minutes).

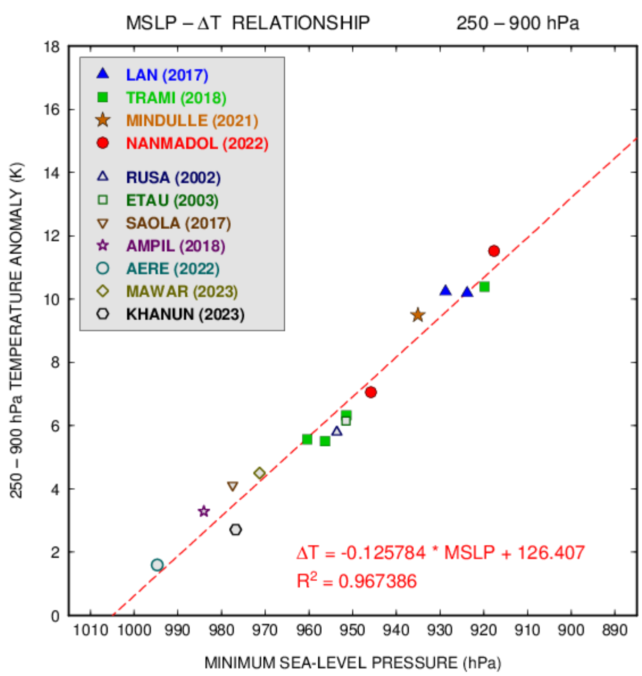

Fig. 1 Relationship between the minimum sea-level pressure and the mean temperature anomaly between 250 and 900 hPa. Closed symbols are the case obtained by dropsondes released from the aircraft while open symbols are the case obtained by radiosondes launched from the Ryukyu Islands in Japan.

Wind distribution in the eye of tropical cyclone revealed by a novel atmospheric motion vectors derivation

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Atmospheric motion vectors (AMVs), calculated by tracking clouds in image sequences captured by geostationary meteorological satellites, are useful for diagnosing the wind distribution of tropical cyclones (TCs). Lower-level clouds in the eye of a TC reflect the winds near the top of the atmospheric boundary layer, where wind speed is maximized. Using a cloud tracking method, Horinouchi et al. (2023) successfully calculated AMVs around the eye of a TC from a research-based 30-sec interval observation conducted by Himawari-8 satellite. Additionally, it was found that calculating AMVs in the lower-level eye region without any TC-specific processing is challenging with the usual 2.5-min observations by Himawari-8/9. Therefore, more elaborated methods are required to achieve this.

In this study, we developed a novel TC-specific cloud tracking method that explicitly considers TC rotation using template matching with cross-correlation. Initially, we create counter-rotated image sequences (rotated in the opposite direction of the TC's lower-wind direction) with preset multiple angular velocities. Cloud tracking using template matching is then performed within a narrow search range in each image sequence. The AMVs that pass a quality control are used as candidate estimates. The estimates with the highest cross-correlation coefficient at each spatiotemporal grid are used as tentative estimates. The candidates that have large differences from surrounding tentative estimates are iteratively rejected, and the tentative estimates are also updated. The final AMVs are determined when the update process stops.

By employing this method, we obtained AMVs with high spatiotemporal resolution for typhoons Haishen (2020), Nanmadol (2022), and Lan (2017). In the comparison with dropsonde observations, which are considered to be the most reliable, the AMVs obtained from the 2.5-min interval images in the eye of Lan (Nanmadol) are evaluated to have the root-mean-square errors of 2.2 (1.2) m/s for tangential velocity and 1.5 (2.5) m/s for radial velocity. As asymmetric motions in the obtained AMVs in the eye, transient azimuthal wavenumber-1 features are identified in all three TCs. These features are believed to be the algebraically growing wavenumber-1 disturbances, which transport angular momentum inward and accelerate the eye rotation with a long time period. In the case of Lan, the angular velocity in the eye increased by approximately 1.5 times within 1 hour. This short-term increase is further examined. Visualization of lower-level vorticity in the eye and angular momentum budget analysis suggest that angular momentum transport associated with mesovortices may have played an important role in the increase of tangential wind and the homogenization of angular velocity in the eye of Lan.

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Three-dimensional Fujiwhara effect

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When two or more tropical cyclones (TCs) coexist within a certain area, they interact with each other. This interaction is known as the Fujiwhara effect as Fujiwhara (1921, 1922, 1923, 1931) discovered the rotational and attractive effect for binary vortices in his laboratory experiment. Although many studies have been carried out using two-dimensional barotropic models, they lack diabatic heating, which can potentially modify the TC track when the vertical wind shear (VWS) of the horizontal wind creates an asymmetric structure (Yamada et al. 2016).

Thus, we conducted a set of idealized three-dimensional simulations of binary TCs on an *f* plane with diabatic heating. A pair of upper-tropospheric anticyclonic and lower-tropospheric cyclonic circulations are generated by the system of binary TCs owing to their outflows that have a Rossby's deformation radius and primary circulation, respectively. These circulations served as the VWS for each TC, causing an asymmetric structure and weakening. The asymmetric structure of diabatic heating of each TC in the idealized simulations modifies TC tracks. The maximum diabatic heating is directed to the rear left side, looking down at the counterpart TC. It resists counterclockwise and approaching motion due to advection. This effect is particularly evident when the separation distance is greater than 8 degrees in latitude. It is because horizontal advection becomes more important when binary TCs are closer. These recent studies have introduced a new three-dimensional perspective on the interaction of binary TCs.

We also verify the existence of these three-dimensional effects in the western North Pacific using the best track and ERA5 reanalysis data. The TC motion was found to deviate systematically from the steering flow. The direction of deviation is clockwise and repelling with respect to the midpoint of the binary TCs with a separation distance of more than 1000 km. The large-scale upper-level anticyclonic and lower-level cyclonic circulations serve as the VWS for each TC in a manner consistent with the idealized simulations. The VWS of a TC tends to be directed to the rear-left quadrant from the direction of the counterpart TC, where the maxima of rainfall and diabatic heating are observed. The potential vorticity budget analysis shows that the actual TC motion is modulated by the diabatic heating asymmetry that offsets the counterclockwise and approaching motion owing to horizontal advection when the separation distance of the binary TCs is 1000–2000 km. With a small separation distance (<1000 km), horizontal advection becomes significant, but the impact of diabatic heating asymmetry is not negligible. The abovementioned features are robust, while there are some dependencies on the TC intensities, size, circulation, duration, and geographical location.

Secondary eyewall formation in sheared tropical cyclones

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Previous studies have shown that relatively higher (but not extreme) vertical wind shear is more favorable for secondary eyewall formation (SEF). This study investigates the physical processes regarding SEF in sheared tropical cyclones (TCs) using numerical simulations. It is found that diabatic cooling of the stratiform clouds in the downwind sector of outer rainbands leads to descending inflow. The inflow results in supergradient winds at the upper levels of the boundary layer, forcing local convergence and ascent. Along with conditional instability, convection can develop on the inward edge of the descending inflow. Simultaneously, shear-induced inner rainbands tend to exist in the downshear quadrants and propagate radially outward. As the inner rainbands approach the edge of the inner core, they interact with the convection mentioned above and gradually become axisymmetrized, eventually forming a secondary eyewall. A potential vorticity tendency budget further indicates that the contribution of eddy potential vorticity flux convergence associated with the spiral rainbands is comparable to that of symmetric potential vorticity flux convergence during the secondary eyewall formation. In addition, symmetric radial advection of absolute vorticity is the leading cause of the secondary tangential wind maximum related to the secondary eyewall, while eddy radial advection of absolute vorticity plays a secondary role.

Formation mechanism of TC secondary eyewall by numerical experiments: Role of dry air inflow from the middle and upper troposphere and cooling by evaporation and sublimation

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An eyewall replacement cycle is often seen in tropical cyclones, when a secondary eyewall forms outside the inner eyewall, and the inner eyewall disappears. Although this cycle significantly affects the intensity of tropical cyclones, the mechanisms of secondary eyewall formation (SEF) are diverse, and most are complementary. Some studies have suggested that dry air inflow and diabatic cooling may be important in SEF via the mesoscale descending inflow (MDI). Here, we use numerical experiments to investigate the role of the middle and upper tropospheric dry inflow in SEF. Idealized experiments were conducted using the plane version of the Nonhydrostatic Icosahedral Atmospheric Model. The control experiment produced SEF with a dry air inflow in the middle and upper troposphere and associated MDI. In sensitivity experiments, in which the water vapor in the middle and upper troposphere was increased in the outer areas of the tropical cyclone, SEF was hindered and slowed down. These results reveal the two distinct processes of SEF: the angular momentum transport by MDI and the unbalanced dynamics in the boundary layer.

The figure highlights the radius-height cross-sections of the azimuthally averaged profiles of the tangential wind, radial wind, and radial component of the agradient force for the control experiment (top) and the deviations of the sensitivity experiment to the control experiment. In (b), the middle- and high-level inflow and the associated MDI emerged at the beginning phase of SEF at 116h. In (c), the agradient force component at around 1-2 km invokes SEF near a radius of 200 km by the unbalanced dynamics in the boundary layer. In the sensitivity experiment, the water vapor is increased in the middle and high-level inflow, and the MDI region, and the middle- and high-level inflow weakens (e) due to reduced evaporation and sublimation. The inward angular momentum transport is reduced, and the agradient force becomes weaker near the SEF region (f). This effect delays the onset of SEF.