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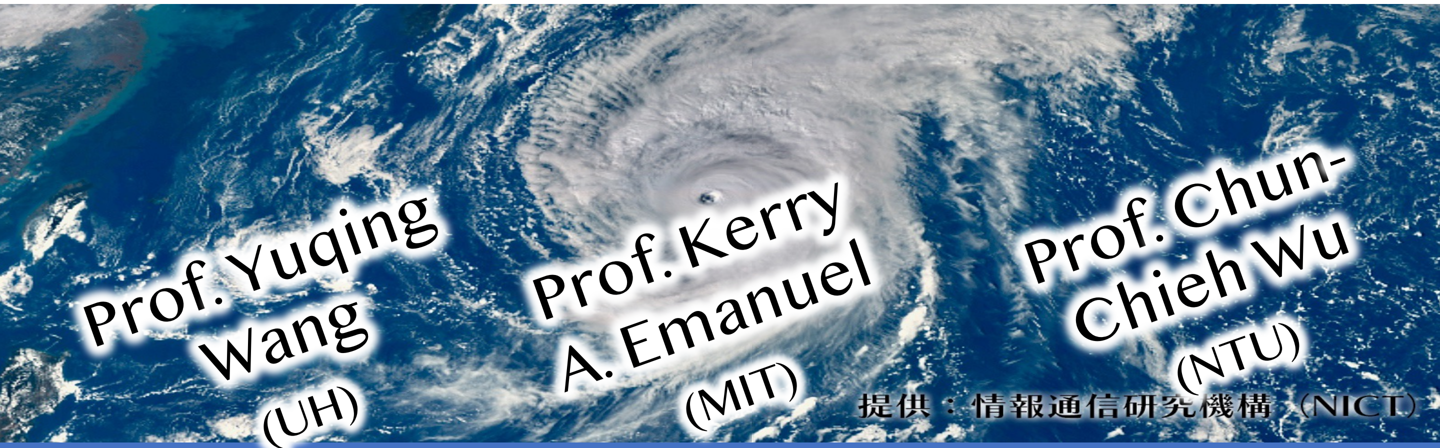
IWTRC 2023 YOKOHAMA

ALL ABSTRACTS



The 1st International Workshop of the Typhoon Science and Technology Research Center

IWTRC

November 8-9, 2023 on-site
Yokohama National University, Japan

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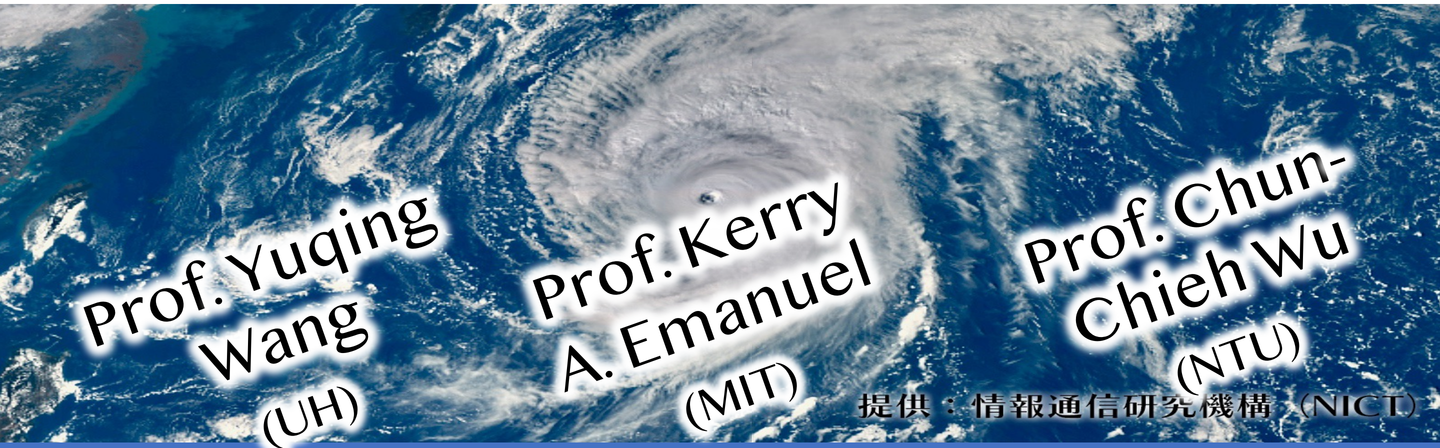
ABSTRACTS (KEYNOTES)



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The challenge of estimating long-term tropical cyclone risk

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1. The nature of long-term natural hazard risk

Natural hazards cause enormous destruction and dislocation worldwide. Long-term records of such hazards show that their average annual loss (AAL, the total damage over the long record divided by the number of years in the record) tends to be dominated by "100-year events", those events with an annual probability of about 0.01. Societies are usually well adapted to events that are somewhat more frequent, while rarer events, though individually more destructive, are too infrequent to dominate the AAL. Large problems arise when, owing to climate change, events that used to be very rare become less so (e.g. 250-year events becoming 50-year events).

This presents two important problems for estimating long-term hazard risk. First, robust estimates of 100-year events require at least 1,000 years of data, which we almost never have. This requires us to "regionalize" risk… a 100-year event for a specific location maybe a 10-year event for a large enough region around it, and so we may be able to robustly estimate the latter. But translating regional risk to local risk requires us to assume homogeneity of risk over the region. This assumption is often dubious…e.g. earthquakes are concentrated along fault lines, heavy rains are often focused on topographic features, and storm surge magnitude depends sensitively on the local shape of the coast and the near-shore bathymetry.

The second problem, particular to meteorological hazards, is that, owing to climate change, historical statistics have largely ceased to be relevant to current risk. For this reason, it is imperative that risk be estimated from physics, including physics-based numerical models, rather than exclusively from historical statistics. Yet most extant decision making, including the pricing of insurance, continues to be modeled on inadequate and often irrelevant historical statistics. The estimation of risk it far too important to be left to statisticians and desperately requires input from scientists specializing in the physics and numerical modeling of the hazards.

2. Physical risk modeling

An obvious way to estimate long-term weather hazard risk under a changing climate is to employ global climate models. The numerical requirements, however, are daunting. Many weather hazards, including severe local storms, are not currently resolvable by climate models, and even well-resolved phenomena, such as large-scale blocking patterns – responsible for prolonged heat waves and droughts – are not handled particularly well by today's models. Even if they were, one would have to perform thousands of years of simulations to capture the rare events that dominate AAL, and do so with many different models to account for model errors and biases.

Phenomena unresolved by global models (e.g. severe local storms) must either be downscaled – by driving high-resolution local and/or regional models with the global model output, or predicted using statistical or AI-type algorithms applied to the global model fields. The latter technique is risky because the algorithms must be trained on past data that may not adequately reflect climate change. To take a concrete example, climate change effects on severe convective storms are currently assessed by noting changes in large-scale correlates – e.g. wind shear and convective available potential energy – explicitly predicted by global climate models. Such assessments are not necessarily informed by a deep understanding of the physics underlying the changes in the large-scale correlates.

3. Tropical cyclone risk modeling

There is by now a large literature on the direct simulation of tropical cyclones by global models; see the review papers by Knutson et al. (2019, 2020). The global models used have horizontal grid spacing ranging from about 15 km to as much as 120 km. Many inferences have been made using such models in spite of the fact that even the finest resolution of these do not adequately resolve tropical cyclones. We know from observations, theory, and highly specialized tropical cyclone models (e.g. Rotunno et al. 2009) that the all-important eyewall has dimensions of order 10 km and requires grid-spacings of a few kilometers for numerical convergence. The more intense tropical cyclones have even more stringent resolution requirements. Consequently, assessments based directly on today's global climate models may prove to be ill-founded.

Alternatives to direct simulation of tropical cyclones by global models include deterministic and deterministic/statistical downscaling. In the first approach, fine-scale regional models are either embedded within the global model, providing two-way interaction, or driven offline by the global model output. In the second approach, statistics of the global fields (e.g. monthly mean thermodynamics and means and variances of winds) are used to drive simplified models of genesis, tracks and intensity.

In this paper, I will use the particular downscaling method developed by the author and his collaborators (Emanuel et al. 2008) to illustrate how appropriately constructed tropical cyclone downscaling from global reanalyses and climate models can be used to help estimate current and future risk from these storms. Broadly, the track model is a beta-and-advection model driven by time series of winds at two levels in the troposphere, synthesized from the global model or reanalysis daily winds such that the monthly means and covariances among the different wind components at the two levels are always correct, and that the power spectrum follows geostrophic turbulence scaling. The intensity model is the Coupled Hurricane Intensity Prediction System (CHIPS; Emanuel et al. 2004), an axisymmetric coupled ocean-atmosphere model phrased in a coordinate system for which the radial coordinate is the square root of the absolute angular momentum. This yields very high resolution (~ 1 km) in the all-important eyewall region while using relatively few computational models. Wind shear effects are parameterized such as to optimize real-time intensity forecasts (Emanuel and Rappaport 2000). The thermodynamic components, including the potential intensity and upper ocean thermal structure, are provided by monthly mean output of the climate model. Genesis is simulated by space-time random seeding of the global fields with weak proto-vortices. Most of these fail to develop, owing to having been placed in unsuitable large-scale environments; those that do are regarded as constituting the tropical cyclone climatology for the reanalysis or global model used to drive the algorithm. Random seeding has been shown to work well provided the seeds are weak enough (Emanuel 2022) and when applied to reanalyses, the algorithm produces realistic intensity probability distributions, track and genesis distributions, seasonal cycles, and ENSO-induced variability (e.g. Emanuel et al. 2008). That an independent seed climatology does not appear to be necessary is consistent with the results of Patricola et al. (2018) and Danso et al. (2022).

Tropical cyclone events generated using this or other downscaling methods can be used to drive hydrodynamic storm surge models (e.g. Lin et al. 2010) to assess surge risk, and rain associated with the tropical cyclones (Feldmann et al. 2019) can be used to drive hydraulic flood models (Bates et al. 2021) to assess tropical cyclone freshwater flood risk.

4. From physical hazards to long-term risk

Quantifying the statistics and physical characteristics of weather hazards is half the battle. The other half is turning hazard risk into economic and social risk and conveying those risks to those who need to know them. This second step is as unknown to most weather and climate scientists as the first step is to insurers, politicians, emergency managers, and other users of risk information. We need to educate a new generation of scientists who are well acquainted with both these endeavors.

To illustrate what can be done with sufficiently large sets of tropical cyclone events under a changing climate, we used the aforementioned technique to generate 6,200 tropical cyclone events that affect the eastern U.S., driven by output from each of 8 global climate models over each of the periods 1984-2014, and 2070-2100 under a middle-of-the-road greenhouse gas emissions scenario (SSP3-7.0). The total number of tracks was therefore close to 100,000. We then used these synthetic hurricane events to estimate damage to a large portfolio of insured property aggregated over 12,968 zip codes, assigning all the value in each zip code to the geographical centroid of that zip code. The fraction of total insured value (TIV) destroyed in each zip code was estimated by applying an idealized wind damage function (Emanuel et al. 2012) to the peak wind experienced during each hurricane event at each zip code centroid. The TIV of this portfolio is close to \$2 trillion.

The annual exceedance probability of damage to this portfolio of insured property is shown in Figure 1; note that the damage is on a log scale.

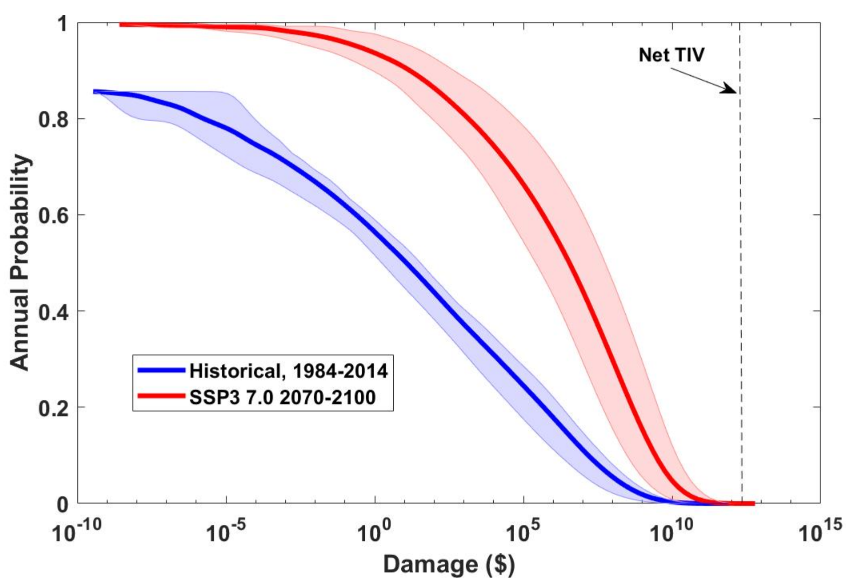

Fig. 1: Annual exceedance probability of damage exceeding the amount shown on the abscissa. The Total Insured Value (TIV) of this portfolio, shown by the vertical dashed line at right, is about \$2 trillion. The solid curves show the multi-model means and the shading denotes the 5th and 95th quantiles among the 8 models. Blue is for the historical period and red is for the end of the 21st century.

The multi-model median annual damage, with an exceedance probability of 0.5, is only $12 for the historical period, showing high levels of adaptation to the climate of the past, but rises to $3.5 million by the end of this century, still a tiny fraction of the TIV.

Figure 2 shows the same data displayed a different way. On the ordinate we now have the exceedance probability multiplied by the corresponding damage itself, representing the loss density. The area under these curves gives the Average Annual Loss (AAL). The multi-model mean AAL for the historical period is $536 million, and for the end of the century is $4.1 billion. By comparing figures 1 and 2 it can readily be seen that the main contributions to the AAL are by exceedingly rare events, with average return periods of more than 450 years in the historical climate and more than 100 years in the climate of the end of this century. Note also the extremely large uncertainty in AAL, indicated by the spread among the climate models downscaled (red shading in figure).

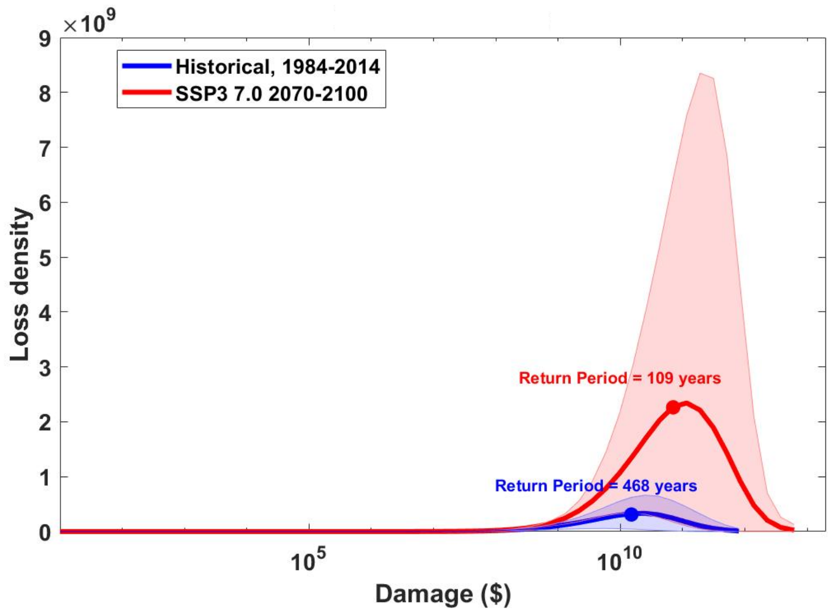

Fig. 2: Loss density ($) corresponding to Fig. 1, produced by multiplying the exceedance probability by the damage associated with it. The area under the curves is the average annual loss (AAL). The return periods of the main contributors to the AALs are indicated. As in Fig. 1, blue corresponds to the historical period and red to the end of this century.

It is important to recognize that statistics like those shown in the two figures are only examples of quantities that are of interest to risk assessors. With large numbers of synthetic tropical cyclone events, it is possible to estimate a wide variety of quantities that may be of interest but not calculable from limited historical data. For example, one can create a large number of realizations (say, 1,000) of 100-year time series of total annual losses in a changing climate by randomly drawing from each year's set of synthetic events, according to the average annual frequency for that year. From this, it is possible to calculate the probability of business failure, considering, for example, the random and climate-forced (e.g. ENSO-related) clustering of events. This would be a desirable statistic even in a stationary climate.

5. Summary

Historical records are too short to make accurate assessments of the long-term risk of most natural hazards, and climate change renders obsolete such assessments of weather-related hazards. In the case of tropical cyclones, climate models are too coarse to use directly to assess tropical cyclone risk, even though many research groups have done just that. Downscaling is perhaps the only viable option at this point, but suffers from the absence of two-way interaction, neglecting the possible feedback of tropical cyclones on climate. Those acquainted with tropical cyclone physics and modeling can make important contributions to social welfare by learning to convert the hazard risk into social risk and developing better ways of communicating the social risk. When that risk is effectively communicated to populations, both directly and through taxes and insurance premiums, citizens can make more informed judgements about climate action.

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The roles of wind-induced surface heat exchange in secondary eyewall formation, rapid intensification and size of tropical cyclones

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Abstract

In this lecture, we plan to review a series of recent studies examining the roles of surface heat fluxes, particularly in relation to the wind-induced surface heat exchange (WISHE; Emanuel 1989) mechanism, in (i) secondary eyewall formation (SEF), (ii) rapid intensification (RI), and (iii) size of tropical cyclones (TCs). Numerical experiments, in which the surface wind used for the surface flux calculations is capped at varying magnitudes and at different radial intervals, have been performed to investigate the role of WISHE in TC structure and intensity change.

(i) The Dynamics of SEF will first be reviewed through the works of Wu et al. (2012), Huang et al. (2012), and Huang et al. (2018), followed by major findings from Cheng and Wu (2018). To examine the sensitivity of SEF to the WISHE mechanism, the surface wind used for the calculation of surface heat fluxes is capped at several designated values and at different radial intervals. When the heat fluxes are moderately suppressed around and outside the SEF region observed in the control experiment, sensitivity experiments show that the formation of the outer eyewall is delayed, and the intensity of both eyewalls is weaker. When the heat fluxes are strongly suppressed in the same region, SEF does not occur. In contrast, suppressing the surface heat fluxes in the storm's inner-core region has limited effect on the evolution of the outer eyewall. This study provides important physical insight into SEF, indicating that the WISHE mechanism plays a crucial role in SEF.

(ii) The study of RI by Chang and Wu (2017) will be reviewed, and then results from Cheng and Wu 2020 will be discussed. Sensitivity experiments with capped surface fluxes and reduced WISHE exhibit delayed RI and weaker peak intensity, while WISHE could affect the evolutions of TC both before and after the onset of RI. Before RI, more WISHE leads to faster increase of equivalent potential temperature in the

lower levels, resulting in the eruption and the axisymmetrization of the convection (especially in the lower levels). In addition, TCs in experiments with more WISHE reach a certain intensity level earlier, before the onset of RI. During the RI period, more surface heat fluxes cause more efficient intensification in a TC, leading to a stronger peak intensity, a more significant and deeper warm core in the TC center, and the axisymmetrization of convection in the higher levels. In both stages, different levels of WISHE alter the thermodynamic environment and convective-scale processes. With WISHE, a consequent development in the convective activity is identified, resulting in a stronger secondary circulation and increased diabatic heating. Within the inner-core region, deeper inflow increases the transport of angular momentum from the outer radii, leading to faster spin-up of the tangential circulation. In all, the important role of the WISHE feedback in RI, both during the pre-RI stage and during the RI period, is highlighted. In the case of Typhoon Megi (2010), a weaker WISHE effect delays the RI onset time, and the simulated storm therefore has a weaker peak intensity. A stronger WISHE effect leads to a faster increase of low-level equivalent potential temperature and thus higher convective instability, resulting in more frequent and stronger convective activity and faster TC intensification rates. The simulated storm can therefore reach a stronger peak intensity, and establish a stronger and deeper TC warm core.

In a separate study (Peng and Wu 2020), the RI of Typhoon Soudelor (2015) was simulated using a full-physics model. To investigate how the outer-core surface heat fluxes affect TC structure and RI processes, a suite of numerical experiments were performed by suppressing surface heat fluxes between various radii. It was found that a TC would become much weaker when the surface heat fluxes are suppressed outside the radius of 60 or 90 km (the radius of maximum surface wind in the control experiment at the onset of RI is roughly 60 km). However, interestingly, the TC would experience stronger RI when the surface heat fluxes are suppressed outside the radius of 150 km. For those sensitivity experiments with capped surface heat fluxes, the members with greater intensification rate show stronger inner-core mid- to upper-level updrafts and higher heating efficiency prior to the RI periods. Although the outer-core surface heat fluxes in these members are suppressed, the inner-core winds become stronger and extract more ocean energy from the inner core. Greater outer-core low-level stability in these members results in aggregation of deep convection and subsequent generation and concentration of potential vorticity inside the inner core, thus confining the strongest winds therein. The above-mentioned findings are also supported by partial-correlation analyses, which reveal the positive correlation between the inner-core convection and subsequent 6-h intensity change, and the competition between the inner-core and outer-core convections (i.e., eyewall and outer rainbands).

In all, suppression of the WISHE mechanism within the radial interval from 1 to 2.5 times the inner-core size effectively hinders the RI in the case of a simulated Typhoon Soudelor (2015). In contrast, suppression of the WISHE process outside of this radial interval slightly facilitates RI due to the suppressed/concentrated convective activities in the outer-core/inner-core region.

(iii) Shen et al. (2021) attempted to understand how surface heat fluxes in different storm regions affect TC size. The Advanced Research Weather Research and Forecasting (ARW-WRF) model (version 3.5.1) was used to simulate Typhoon Megi (2016). A series of numerical experiments were carried out, including a control simulation and several sensitivity experiments with surface heat fluxes suppressed in different TC regions (to mimic the reduction of the WISHE feedback in the inner and/or outer core). The results showed that with surface heat fluxes suppressed in the entire domain, the TC tends to be smaller. Meanwhile, the TC size is more sensitive to the surface heat flux change in the outer core than to that in the inner core. Suppressing surface heat fluxes can weaken the rainbands around the suppressed area, which in turn slows down the secondary circulation. When the surface heat flux is suppressed in the inner-core region, the weakening of the secondary circulation associated with the diminished inner rainbands is limited to the inner core region, and only slightly affects the absolute angular momentum import from the outer region, thus having negligible impact on TC size. However, suppression of surface heat fluxes in the outer-core region leads to less active outer rainbands and a more substantial weakening of the secondary circulation. This results in less absolute momentum import from the outer region, and in turn, a smaller TC.

In all, while suppression of the WISHE mechanism in the whole outer-core region constricts the size of Typhoon Megi (2016), the same degree of suppression on WISHE in a narrow ring region (3 - 4 *RMW, radius of maximum wind) results in a lager TC. In the former case, suppression of surface heat fluxes in the outer-core region leads to less active outer rainbands and a more substantial weakening of secondary circulation, resulting in less import of absolute momentum and in turn a smaller TC. In the latter case, the TC expansion is attributed to enhanced convection near the outer edge of the ring, where the boundary layer inflow decelerates and the low-level convergence.

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A Unified Time-Dependent Theory of Tropical Cyclone Intensification and Its applications: Current Status and Future Directions

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Upon the genesis of a tropical depression under favorable environmental conditions, such as high sea surface temperature (SST) and high heat content in the uppermost ocean layer, and weak vertical wind shear, the cyclonic low-pressure system may develop into a tropical cyclone (TC). In the absence of detrimental environmental effects, a TC often experiences a phase of rapid intensification associated with an increase in near-surface maximum wind speed of more than 15 m s^{-1} per day, before it reaches its maximum intensity. Over the past five decades or so, many efforts have been devoted to conceptualizing the physical mechanisms that are responsible for TC intensification. Each of the proposed mechanisms describes a kind of positive feedbacks and can give a qualitative explanation for TC intensification processes to some extent. However, none of the concepts can provide a quantitative measure of the intensification rate of a TC.

Unlike the maximum potential intensity (MPI), i.e., the maximum intensity a TC may reach under given favorable environmental conditions (Emanuel 1986, 1997), the TC intensification rate may depend on the intensity of the TC itself, the radial location of diabatic heating, and both the inner- and outer-core structures of the TC vortex. Although two time-dependent equations for TC intensification rate have been proposed under various assumptions in the literature (Emanuel 2012; Ozawa and Shimokawa 2015), neither of them can capture the intensity-dependent TC intensification rate in observations (Xu and Wang 2015, 2018).

A fundamental advancement in recent years has been the development of a unified time-dependent theory of TC intensification, which can capture the major features of TC intensification in both observations and full-physics model simulations (Wang et al., 2021a,b, 2022, 2023). In particular, with the introduction of environmental factors, the unified theory can be used to understand the impact of various environmental factors on TC intensity change in observations and to perform real-time TC intensity forecasts. The theory also provides a basis for understanding and evaluating impact of climate change on TC intensification. In this lecture, the current status will be given and the future directions in this line will be briefly discussed.

There are two versions in the literature: one is energetically based and the other is dynamically based. The energetically based theory considers a TC vortex as an unsteady Carnot heat engine. Namely, instead of a balance between the power generation and power dissipation for a steady-state heat engine assumed for the TC MPI (Emanuel 1997), the power generation during the intensification stage is larger than the power dissipation, the power gain will then be used to increase the kinetic energy of the TC system.

$$\int\int \rho \frac{\partial}{\partial t}\left(\frac{1}{2}\left|\vec{V}\right|^2\right) r dr dz = E\int \rho \epsilon C_k \left|\vec{V}\right| (\kappa_o^* - \kappa_a) r dr - \int \rho C_D \left|\vec{V}\right|^3 r dr, \qquad (1)$$

where a TC is assumed to be axisymmetric, r is radius, C_k, C_D are the surface exchange coefficient for enthalpy and momentum, respectively, ρ is the air density near the surface, $\left|\vec{V}\right|$ is the near-surface wind speed, κ_o^* the saturated enthalpy of the ocean surface at a given SST (T_S), κ_a the enthalpy of the atmosphere near the surface, $\varepsilon = (T_s - T_0)/T_s$ is the thermodynamic efficiency of the heat engine with T_0 being the outflow temperature, E is the dynamical efficiency, namely the percentage of the potential energy being converted to kinetic energy (Wang et al. 2021a). Note that $|\vec{V}|$ on the rhs of Eq. (1) represents the near-surface wind speed, while that on the lhs represents wind speed in the inner-core column.

Considering the fact that the intensification of a TC is dominated by the increase in wind speed (kinetic energy) near the RMW, the integration of Eq. (1) can be approximated by

$$H\bar{\rho}\bar{V}\frac{\partial \bar{V}}{\partial \tau} = E\rho_0 \varepsilon C_k V_{max}(\kappa_o^* - \kappa_a)_{rm} - \rho_0 C_D V_{max}^3, \quad (2)$$

where H is the scale height of the inner-core column, the change with time τ means the change following the RMW, overbar means the corresponding column mean, ρ_0 the air density near the ocean surface, and V_{max} is the maximum near-surface wind speed at the RMW, namely the TC intensity by definition. Eq. (2) can be simplified to

$$\frac{\partial V_{max}}{\partial \tau} = \frac{\alpha C_D}{h}\left(EV_{mpi}^2 - V_{max}^2\right), \quad (3)$$

here $\alpha/h = \rho_0/(\bar{\rho}H\mu^2)$, with $\mu = \bar{V}/V_{max}$, the column mean total wind speed scaled by the maximum near-surface wind speed, α is introduced so that the rescaled height parameter h is equivalent to the depth of the well-mixed boundary layer in the inner core ($\sim 2000m$). We will see from the dynamically based theory below that α is similar to the reduction factor of the near-surface wind speed from the boundary layer depth-mean wind speed, which ranges between 0.7~ 0.8. The MPI (V_{mpi}) in (3) is given by

$$V_{mpi} = \sqrt{\frac{C_k}{C_D}\varepsilon(\kappa_o^* - \kappa_a)|_{r_m}}. \quad (4)$$

The dynamical efficiency E in Eq. (3) needs to be determined to make the time-dependent theory closed. Since the steady-state TC intensity should be equal to its MPI given all favorable environmental conditions, the dynamical efficiency E should be 1.0 for a steady-state solution. However, when the TC is very weak, the Rossby radius of deformation is large and the dynamical efficiency of the heat engine much be very low as implied from the balanced dynamics (Schubert and Hack 1982). As a result, $E \to 0, as\ V_{max} \to 0$. Based on calibration of results from both idealized full-physics numerical simulations and TC best-track data, E can be expressed as a function of relative intensity (Wang et al., 2021b) given below

$$E = \left(V_{max}/V_{mpi}\right)^{3/2}, \quad (5)$$

The above energetically based time-dependent equation of TC intensification can also be obtained based on dynamics (Wang et al., 2021b). In a slab boundary layer, the tangential wind and entropy budget equations for an axisymmetric TC vortex can be written as

$$\frac{\partial V_b}{\partial t} + u_b\frac{\partial M_b}{r\partial r} = -\frac{C_D}{h}|\vec{V}|V_T, \quad (6)$$

$$\frac{\partial s_b}{\partial t} + u_b\frac{\partial s_b}{\partial r} = \frac{C_k}{h}|\vec{V}|(s_0^* - s_b), \quad (7)$$

where M_b, V_b and u_b are the depth-averaged AAM, tangential, and radial wind velocities in the boundary layer, which has a depth of h, $|\vec{V}|$ and V_T are the total wind speed and the tangential wind speed near the sea surface, respectively, s_0^* and s_b are the saturated entropy at the underlying SST and the well-mixed air entropy in the slab boundary layer. Note that the horizontal diffusions of both tangential wind and entropy are neglected although they may be important across the eyewall in strong TCs.

Since the TC intensification is defined as the rate of change in the near-surface wind speed following the RMW (r_m), all terms in Eqs. (6) and (7) should be evaluated following the RMW. Because of the large radial entropy gradient and strong inflow and the highly elevated entropy flux across the RMW, the local change in entropy near the RMW is relatively small. Therefore, a thermodynamic quasi-equilibrium near the RMW can be assumed, and thus Eq. (7) can be approximated as

$$u_b \frac{\partial s_b}{\partial r}|_{rm} = \frac{C_k}{h}\left|\vec{V}\right|(s_0^* - s_b)|_{rm}. \quad (8)$$

Combining Eqs. (6) and (8) gives

$$h\frac{\partial V_b}{\partial \tau} = -\frac{1}{r_m}\frac{\partial M_b}{\partial r} C_k\left|\vec{V}\right|(s_0^* - s_b)/\frac{\partial s_b}{\partial r} - C_D|V|V_T. \quad (9)$$

Note that in Eq. (9), τ is used instead of t because the budget and all variables are now evaluated following the RMW. Since the total wind speed at the RMW is close to the tangential wind speed, we can assume $\left|\vec{V}\right| \approx V_T = V_{max}$. We further assume $V_{max} = \alpha V_{b,m}$, where α is the reduction factor from the depth-averaged boundary layer wind speed to the near-surface wind speed at the RMW, which is roughly between 0.7~0.8 based on observations. With these approximations, Eq. (8) can be rewritten as

$$\frac{\partial V_{max}}{\partial \tau} = \frac{\alpha}{h}\left[-\frac{1}{r_m}\frac{\partial M}{\partial s}\bigg|_{b,r_m} C_k V_{max}(s_0^* - s_b)|_{r_m} - C_D V_{max}^2\right]. \quad (10)$$

The continuity at the top of the boundary layer requires $\frac{\partial M}{\partial s}\Big|_{b,r_m} \cong \frac{\partial M}{\partial s}\Big|_{h,r_m}$. Therefore, Eq. (10) can be closed if $\frac{\partial M}{\partial s}\Big|_{h,r_m}$ can be determined. Following Emanuel (1986), we assume that the TC vortex in the free atmosphere above the boundary layer is axisymmetric and in thermal wind balance, If both s and M are assumed to be conserved along streamlines, the s and M surfaces are congruent, or equivalently the state of moist-neutral eyewall ascent is along M surfaces (Emanuel, 1986), we have

$$\frac{1}{r^3}\left(\frac{\partial r}{\partial p}\right)_M = \frac{1}{2M}\frac{\partial s}{\partial M}\left(\frac{\partial T}{\partial p}\right)_s, \quad (11)$$

If we integrate Eq. (12) along a trajectory of moist-neutral ascent (constant M and s surface) starting from the RMW at the top of the boundary layer (r_m, h) to the point at a large radius (r_0) in the upper tropospheric outflow where the trajectory becomes essentially horizontal and tangential wind becomes zero, we can have (Bryan and Rotunno 2009b)

$$\frac{dM}{ds}\bigg|_{h,r_m} = -\frac{T_b - T_0}{M_{h,r_m}\left(\frac{1}{r_m^2} - \frac{1}{r_0^2}\right)}, \quad (12)$$

where T_b is air temperature at (r_m, h), T_0 is the air temperature at the outer radius r_0 in the outflow. Note that although the assumption of moist-neutral convection in the eyewall is a good approximation for a strong TC, this is often not satisfied during the TC intensification stage. Namely, the M and s surfaces would not be congruent but intersect, especially (Peng et al., 2018). Therefore, an *ad hoc* parameter A can be introduced into Eq. (12), thus we have (Wang et al., 2021b)

$$\frac{\partial M}{\partial s}\bigg|_{b,r_m} \cong \frac{\partial M}{\partial s}\bigg|_{h,r_m} = -A\frac{T_b - T_0}{M_{h,r_m}\left(\frac{1}{r_m^2} - \frac{1}{r_0^2}\right)}, \quad (13)$$

where A denotes the extent to which the M surface is parallel to the s surface, which should satisfy $0 \le A \le 1$ considering $(\partial M/\partial s)_{h,r_m} \le 0$. A should be close to 1.0 when the eyewall convection reaches a nearly moist-neutral state with the M and s surfaces being almost congruent as in Eq. (12), while it is close to zero in the early incipient stage when V_{max} is close to zero and the M and s surfaces are nearly orthogonal (Peng et al., 2018). Substituting Eq. (13) into Eq. (10) and using the approximations of ($T_b \approx T_s$), $V_{b,rm} \approx V_{max}$, and $(k_0^* - k_B) \approx T_s(s_0^* - s_b)$, Eq. (10) can be simplieid to

$$\frac{\partial V_{max}}{\partial \tau} = \frac{\alpha C_D}{h}\left(AV_{mpi}^2 - V_{max}^2\right), \tag{14}$$

where again V_{mpi} is the MPI defined in Eq. (4).

Mathematically, Eq. (14) is identical to Eq. (3) except that *E* is replaced by *A*. Although the parameter *A* introduced in the dynamically based theory and the dynamical efficiency *E* in the energetically based theory have different physical meanings, they both are nondimensional and thus share the same dependence on relative intensity as given in Eq. (5) as demonstrated by Wang et al. (2021b) and Xu and Wang (2022). Since the *ad hoc* parameter *A* measures the extent to which the *M* and *s* surface are confluent in the eyewall updraft, it is termed the ventilation parameter (Wang et al., 2021b). Namely a smaller *A* indicates a larger intersection angle between *M* and *s* surfaces. In this case, less potential energy is converted to kinetic energy, with a smaller dynamical efficiency. Substituting Eq. (5) into either Eq. (3) or Eq. (15), we can have

$$\frac{\partial V_m}{\partial \tau} = \frac{\alpha C_D}{h} V_{mpi}^2 \left[\left(\frac{V_m}{V_{mpi}}\right)^{3/2} - \left(\frac{V_m}{V_{mpi}}\right)^2\right], \tag{15}$$

Eq. (15) was derived both energetically and dynamically. The first term on the rhs of Eq. (15) is the intensification potential while the second term is the weakening tendency due to surface friction.

Note that the time-dependent theory above was derived under idealized environmental conditions, and thus it reflects the potential intensification rate (PIR) a TC vortex can reach with a given favorable thermodynamic environment. The theory can reproduce well the intensity evolution of TCs in idealized, full-physics model simulations (Wang et al., 2021b) and capture the observed PIR of real TCs (Xu and Wang, 2022). The theory has been extended to include the contribution of dissipative heating and the thermodynamic expansion of the boundary layer inflow to TC intensification (Wang et al., 2022; 2023). In general, both effects increase with increasing TC intensity.

Although the theory was obtained for a TC in a quiescent environment, it can be extended to include the detrimental environmental dynamical effects by introducing an environmental dynamical efficiency or environmental ventilation parameter (Wang et al., 2021b). In this case, the first term in Eq. (15) should be multiplied by such an efficiency or ventilation parameter (*B*), which is always less than 1.0. In this case, Eq. (15) can be revised to

$$\frac{\partial V_{max}}{\partial \tau} = \frac{\alpha C_D}{h} V_{mpi}^2 \left[B\left(\frac{V_{max}}{V_{mpi}}\right)^{3/2} - \left(\frac{V_{max}}{V_{mpi}}\right)^2\right]. \tag{16}$$

Physically, the parameter *B* can be considered as the collective detrimental effect of environmental factors, such as vertical wind shear, that ventilate the eyewall entropy both in and above the boundary layer, reducing the extent to which the M and s surfaces are confluent and thus the intensification rate of the TC. If *B* is parameterized using environmental factors and calibrated based on best-track TC data, Eq. (16) can be potentially used for operational TC intensity prediction.

In addition, since many studies have projected an increase in MPI in a warmer future climate, Eq. (16) implies that TCs in a warmer climate may intensify more rapidly. For example, a 5% increase in MPI may lead to a 10.25% increase in TC PIR. Since rapid intensification is still a challenge in current operational forecasts, the increasing intensification rate may make the TC intensity more difficult to predict in the future under global warming as also discussed by Emanuel (2017).

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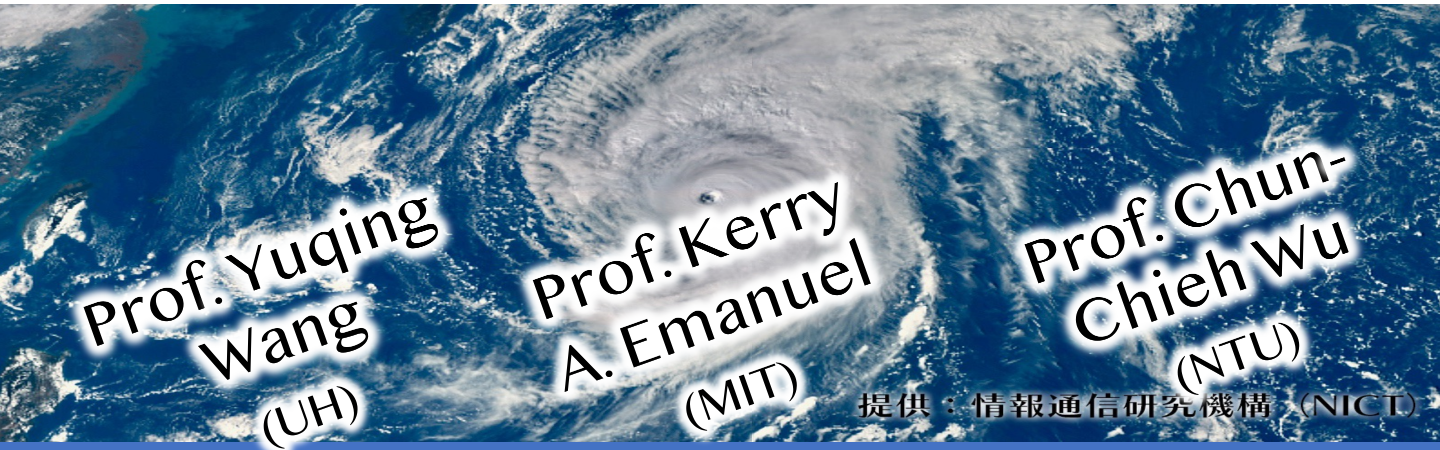
ABSTRACTS (SESSION 1)



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Tropical cyclone characteristics over the western North Pacific stratified by genesis environment

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A tropical cyclone (TC) forms under large-scale environmental conditions favorable for cyclogenesis (TCG), which are generally found where higher sea surface temperatures (SSTs) and supportive largescale flow patterns coexist. Ritchie and Holland (1999) grouped the lower-tropospheric large-scale atmospheric flow patterns contributing to TCG over the western North Pacific (WNP) into five TCG factors: shear line (SL), confluence region (CR), monsoon gyre (GY), easterly waves (EW), and Rossby wave energy dispersion from a preexisting cyclone (PTC). Yoshida and Ishikawa (2013), following their study, developed a method of detecting the five TCG factors, named Typhoon Genesis Score (TGS). The TGS methodology is currently available on TRC's website, providing real-time analysis results. The advantages of releasing real-time TGS results are twofold: 1) differences in the TCG factors that lead to characterization of TCs and 2) differences in the TCG factors could be considered key determinants of whether a TC develops to tropical storm strength.

Fudeyasu and Yoshida (2017) determined the statistical characteristics of TCs over the WNP, stratified by five TCG environmental factors in the summer and autumn during 1979–2013, using TGS. TCs that formed in large-scale flows mainly associated with a GY (hereafter, GY-TCs, and similar terms) tended to develop slowly. The average lifetime maximum intensity of PTC-TCs is larger than those of other factors, due to their longer development stage. On average, TC size of GY-TCs is larger at the TCG time than other TCG factors, whereas those of EW-TCs and PTC-TCs are smaller. These results provide important information for use in disaster prevention.

Using the TGS and early stage Dvorak analysis (EDA) provided by the Japan Meteorological Agency, Fudeyasu et al. (2020) investigated the characteristics and environmental conditions of TCs over the WNP from 2009 to 2017 that dissipated before reaching tropical storm strength (TDs) under unfavorable environmental conditions. We compared TDs with TCs that reached tropical storm strength (TSs) in terms of modulations of the five TCG factors. The environments around TDs were less favorable for development than those around TSs, as there were significant differences in atmospheric (oceanic) environmental parameters between TDs and TSs in the factors of CR, EW, and PTC (SL, GY, and PTC). The environmental conditions for reaching tropical storm strength over their genesis stage, using five factors, can be summarized as follows: higher tropical cyclone heat potential in the SL and GY, weak vertical shear in the CR, wet conditions in the EW, and higher SSTs and an intense preexisting cyclone in PTC. Thus, the development conditions stratified by environmental factors using TGS can be used for operational forecasting.

Counterbalancing impacts from historical anthropogenic aerosols and greenhouse gases on global-scale tropical cyclone genesis potential

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How anthropogenic forcing could change tropical cyclones (TCs) is a keen societal concern owing to its significant socio-economic impacts. However, a global picture of the anthropogenic aerosol and greenhouse gas effect on TCs has not yet emerged. Here we show that anthropogenic aerosol emission can reduce northern hemisphere (NH) TCs, represented by genesis potential index (GPI), but increase southern hemisphere (SH) TCs primarily through altering vertical wind shear and mid-tropospheric upward motion in the TC formation zones using the single anthropogenic forcing experiments from the 14 Coupled Model Intercomparison Project phase 6 (CMIP6) models.

These circulation changes are driven by anthropogenic aerosol-induced NH-cooler-than-SH and NH-increased versus SH-decreased meridional (equator to mid-latitudes) temperature gradients. The cooler NH produces a low-level southward cross-equatorial transport of moist static energy, weakening the NH ascent in the TC formation zones; meanwhile, the increased meridional temperature gradients strengthen vertical wind shear, reducing NH TC genesis. The opposite is true for the SH. The results may help to constrain the models' uncertainty in the future TC projection. Reduction of anthropogenic aerosol emission may increase the NH TCs threat. Further, we quantify the relative contributions of anthropogenic aerosol and greenhouse gas (GHG) to global TCF.

We find that the two forcings have comparable but opposite impacts on GPIs due to their influences on the TC environment, leading to an insignificant change in GPIs in the historical period (1850-2014). Notably, the aerosol radiative forcing's intensity is only about one-third of that of GHG, suggesting a more effective modulation of aerosol forcing on GPIs. The stable global TC frequency during the past decades could be attributable to the similar pace of the two anthropogenic emissions. The results highlight that a reliable global TC projection depends on both the aerosol and GHG emission policies.

Typhoon seasonal forecasting by a high-resolution coupled GCM (NICOCO)

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To mitigate the impact of typhoons, it is needed to precisely predict typhoon activity before the beginning of the typhoon season (June). Some research institutes, operational centres, and insurance companies abroad issue seasonal forecasts of typhoons. In Japan, a part of private weather companies provide an outlook of typhoon activities, but no official seasonal typhoon forecast is issued by JMA.

Dynamical-based typhoon seasonal forecast using conventional coupled GCMs has been intensively examined along with the progress of high-performance computers in the recent couple of decades. However, horizontal resolution is not high enough to represent observed typhoon intensity and some bias correction technique is needed to predict the intensity-related index (e.g., ACE) quantitatively.

Here, we used a 14-km-mesh global nonhydrostatic atmospheric model coupled with a 0.25-deg-mesh global ocean model (NICOCO; an AGCM NICAM coupled with an OGCM COCO) for 10-year (2010-2019) typhoon seasonal forecast experiments. The model is initialized on 20 May of each year and integrated to 1 November. The initial conditions for the atmosphere are made by interpolating the ensemble analysis data of ALERA (the first 5 members only are used because of computational resources). The initial conditions for the ocean are created by driving COCO using JRA-55do. Thus, the ensemble size of the experiments is five and the initial condition for the ocean is common among the ensemble members. We also performed NICAM (atmosphere-only) experiments. For NICAM experiments, the observational SST of OISSTv2.1 is given.

The results show that NICOCO performed better in predicting seasonal (June–October) numbers of typhoons and seasonal ACE than NICAM. For example, the correlation coefficients between simulated and observed seasonal numbers of typhoons are higher in NICOCO experiments (0.41) than that in NICAM experiments (0.31). The absolute value of mean error is lower in NICOCO (–2.18) than in NICAM (3.86). The model showed the best performance in predicting the seasonal number of typhoons in the eastern south part of the WNP (0°–18°N, 140°–180°E), where intense typhoons often form. The correlation coefficients between simulated and observed seasonal (June-October) numbers of typhoons are higher in NICOCO experiments (0.77) than that in NICAM experiments (0.70). For ACE in the eastern south part of the WNP, the correlation coefficient for NICOCO experiments is 0.80 and that for NICAM experiments is 0.67. The correlation coefficient between simulated and observed numbers of typhoons in June–August is higher in NICOCO experiments (0.36) than that in NICAM experiments (0.34). In September–October, however, the correlation is lower in NICOCO (0.24) than in NICAM (0.35). These results demonstrate NICOCO's good performance in typhoon seasonal forecasting.

On the Intensification of Typhoon Damrey with the Monsoon Gyre

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Typhoon Damrey, the first named tropical cyclone (TC) of the year 2000 in the western North Pacific, was embedded in a monsoon gyre (MG) during its intensification period. We explored the mechanisms of its rapid development and the contribution of the MG using a localized, instantaneous energetics diagnostic tool: the multiscale window transform (MWT) and MWT-based multiscale energetics analysis. We used the ERA5 reanalysis dataset to obtain the fields on three temporal scales: TC-scale fields; MG-scale fields; and large-scale background fields. The canonical transfer of kinetic energy from the large-scale background fields to the tropical cyclone was negligible, whereas the MG increased the TC-scale kinetic energy in the precipitation active quadrant and weakened its kinetic energy in the precipitation inactive quadrant. Barotropic canonical transfer therefore did not contribute to the development of this tropical cyclone. Kinetic energy was produced in Damrey mainly through buoyancy conversion and pressure work. In the upper troposphere, the available potential energy converted to TC-scale kinetic energy, but this was mostly offset by the negative work done by the pressure gradient force with the updraught near the eyewall. In the lower troposphere, TC-scale kinetic energy was produced by horizontal pressure work due to the inflow. This new finding helps us to understand the impact of the MG on the TC intensification and the underlying mechanisms governing TC evolution.

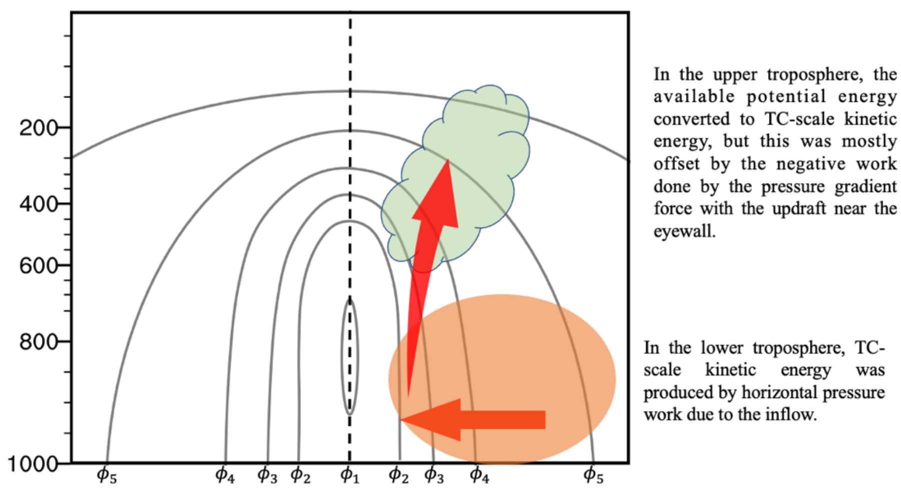

Fig. 1 Schematic diagram of the intensity changes of Typhoon "Damrey" in 2000.

Relationship between tropical cyclone intensity and SST

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The primary importance of the sea surface temperature (SST) to the tropical cyclone (TC) activity is well known. In the western North Pacific (WNP) anomalous SST significantly modulates the TC activity through the atmospheric responses. Occurrences of the intense TCs are the community's major concern. Here we discuss how the SST anomalies affect the frequency and distribution of the TC lifetime maximum intensity (LMI) in the WNP.

We focus on how the modulation of SST in the specific subdomains of the WNP (e.g., tropics, subtropics) can affect the TC LMI, by sensitivity experiments using a global atmospheric model (Nonhydrostatic ICosahedral Atmospheric Model, NICAM[1]) for the 2018 boreal summer season[2],[3]. A horizontal mesh size of 14 km, which marginally resolve TC structure, was employed. Each sensitivity case consists of 24 members.

The 2018 summer is characterized by warm SST anomalies over the central subtropical Pacific, central the eastern Pacific, and south of Japan, and enhanced TC activity in the eastern part of the WNP. By sensitivity experiments removing the subtropical/tropical SST anomalies, it was found that the tropical (subtropical) SST anomalies contribute to the overall TC activity including the occurrence of intense TCs (eastward extension of the occurrence of intense TCs), by maintaining the strong monsoon circulation and associated local Hadly/Walker circulations.

Comparison of the historical pre-TC environment factors between the strong and weak LMI TCs shows that SST and vertical wind shear are the leading two factors in all sensitivity cases. Comparison between the strong and moderate LMI TCs suggests that the middle tropospheric vertical velocity was comparable to the above leading two factors in the cases without subtropical warm SST anomalies. These results highlight common and specific aspects of the impacts of SST anomalies on the TC LMI in the WNP.

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Multi-scale interaction and predictability/controllability of the tropical cyclone intensification

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Predicting tropical cyclone intensity changes, especially the onset of rapid intensification, has been a challenging topic because of its chaotic nature in multi-scale physical process with significant contributions from convective-scale phenomena. The forecast uncertainty in the intensification onset process is particularly limited. This may also indicate the potentials of effective controllability.
In this study, we have explored the contribution of moist convective activity to influence/modify the predictability and variability of TC intensification onset. Our recent investigation in Minamide and Posselt (2022) proposed a Lagrangian-based approach to identify the potential signals of individual convective occurrence. Using the technique, we conducted sensitivity experiments to intervene in specific convective activities within the inner-core of early-stage TCs with convection-permitting Weather Research and Forecasting model (WRF-ARW). The results indicate that the spatiotemporal variability of convective activity had significant impacts on whether early-stage vortex completes precession and initiates RI. Given the strong nonlinearity of the onset process of RI, the advancement of our understanding of the uncertainty sources will provide an insight to explore the TC predictability/controllability.

Reference: Minamide, M., D. J. Posselt, 2022: Using Ensemble Data Assimilation to Explore the Environmental Controls on the Initiation and Predictability of Moist Convection, Journal of the Atmospheric Sciences, doi:10.1175/JAS-D-21-0140.1.

Predictability of the most long-lived tropical cyclone Freddy (2023) during its westward journey through the southern tropical Indian Ocean

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In 2023, Storm Freddy emerged as the most long-lived tropical cyclone (TC) in record, lasting 35 days over the southern tropical Indian Ocean and spanning both weather and sub-seasonal to seasonal time ranges. The primary objective of this study is to understand the factors contributing to the poor predictability of Freddy in forecasts spanning over two weeks. This holds significant importance as our understanding about the ability of the numerical models to predict long-lived TCs remains limited. Using over 7000 global ensemble forecasts from five global Numerical Weather Prediction centers and a high-resolution regional model, we identified three key factors contributing to the limited predictability of Freddy: the strength of the Mascarene High, the position of Storm Dingani (2023), and the size of Freddy. In large track-error results of the global forecasts and regional simulations for Freddy, the strength of the Mascarene High was underestimated, Dingani was located further northeast, and Freddy was either too large or too small. Our investigation emphasizes the crucial role played by the interaction between the TC and multi-scale systems in TC forecasts. This is meaningful for the improvement of Numerical Weather Prediction models to deal with extreme TC events in the future.

Large eddy simulation of entire tropical cyclone for entire development period

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We have realized a large eddy simulation (LES) of an entire tropical cyclone with time integration longer than 100 hours, which can cover the entire development period from an initial disturbance. In the previous study (Ito et al., 2017), the developed tropical cyclone was interpolated into LES with a grid size of 20000 x 20000 x 60, and only 10 hours of time integration was performed. While the configurations of LES are the same, the state of the art supercomputer "Fugaku" enables to extend the time integration.

A weak vortex is placed as the initial disturbance. The environment exmploys a sounding in the case of Hagibis 2019, which made the rapid intensification The simulated tropical cyclone starts to develop 72 hours after the initiation. After about 100 hours, the simulated tropical cyclone strengthens to ~920 hPa (Fig. 1), which is indicated by the maximum potential intensity.

As similar to the previous LES, the developed TC reveal various fine-scale structures in both the boundary layer and the eyewall cloud (Fig. 2). Temporal evolution of the simulated TC is investigated. Significant temporal variations are found in outer rainbands, azimuthal wave number of significant pattern of eyewall, boundary layer height, and so on.

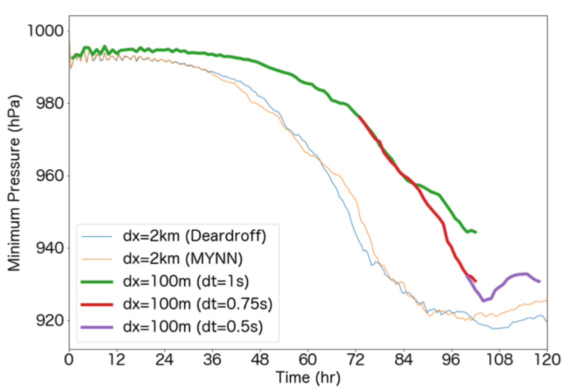

Figure 1: Time series of the minimum surface pressure of simulated tropical cyclone. Both LES (dx=100m) and coarser resolution (dx=2km) results are shown

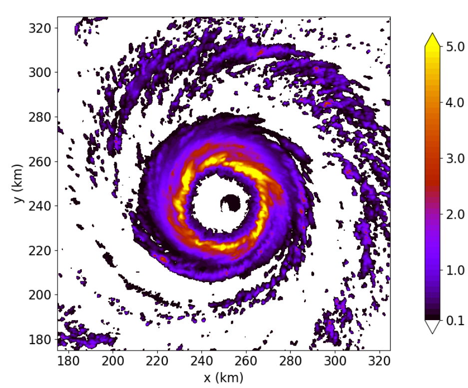

Figure 2: Mixing ratio of hydrometer (g/kg) in the horizontal plane at the height of 39 m in LES at 103 hours after the initiation.

Reference

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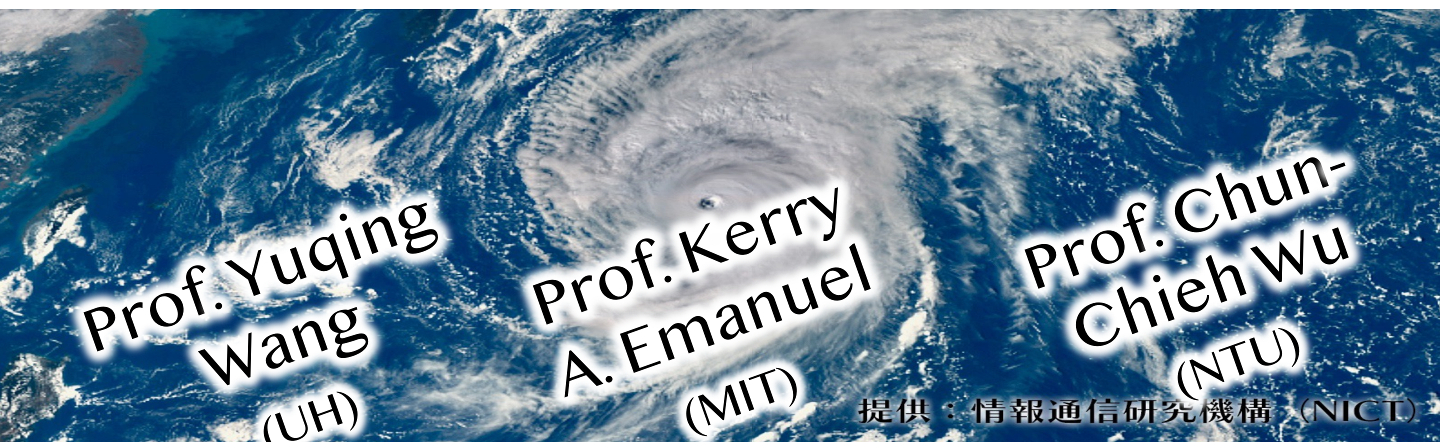
ABSTRACTS (SESSION 2)



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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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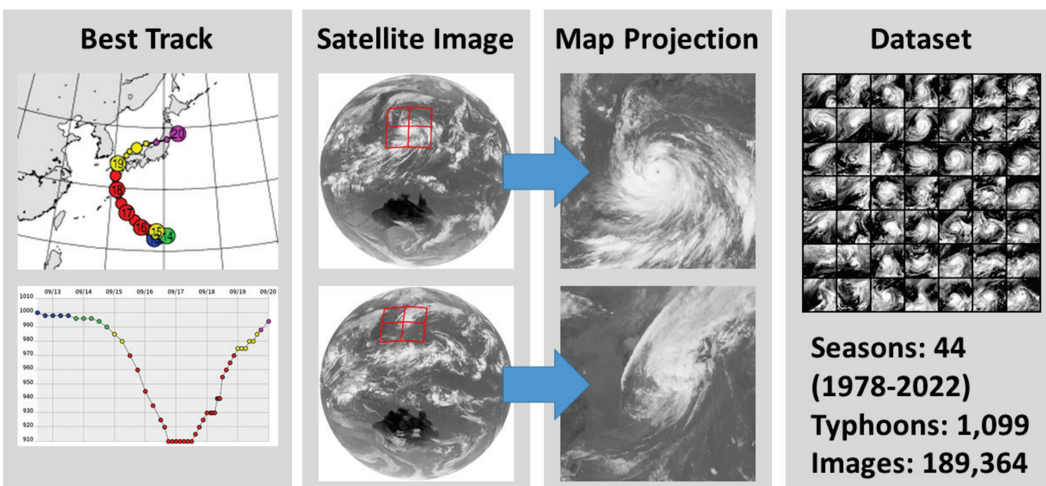
This paper presents the official release of the Digital Typhoon dataset, the longest typhoon satellite image dataset for 40+ years aimed at benchmarking machine learning models for long-term spatio-temporal data. To build the dataset, we developed a workflow to create an infrared typhoon-centered image 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).

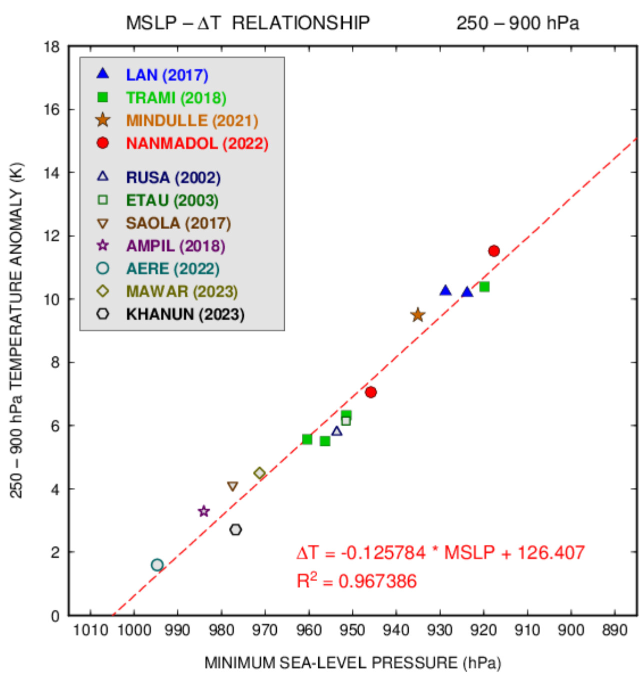

Fig. 1 Relationship between the minimum sea-level pressure and the mean temperature anomaly between 250 and 900 hPa. Closed symbols are the case obtained by dropsondes released from the aircraft while open symbols are the case obtained by radiosondes launched from the Ryukyu Islands in Japan.

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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[2]*Department of Physics and Earth Sciences, University of the Ryukyus, Nishihara, Japan;*
[3]*Typhoon Science and Technology Research Center, Yokohama National University, Yokohama, Japan;*
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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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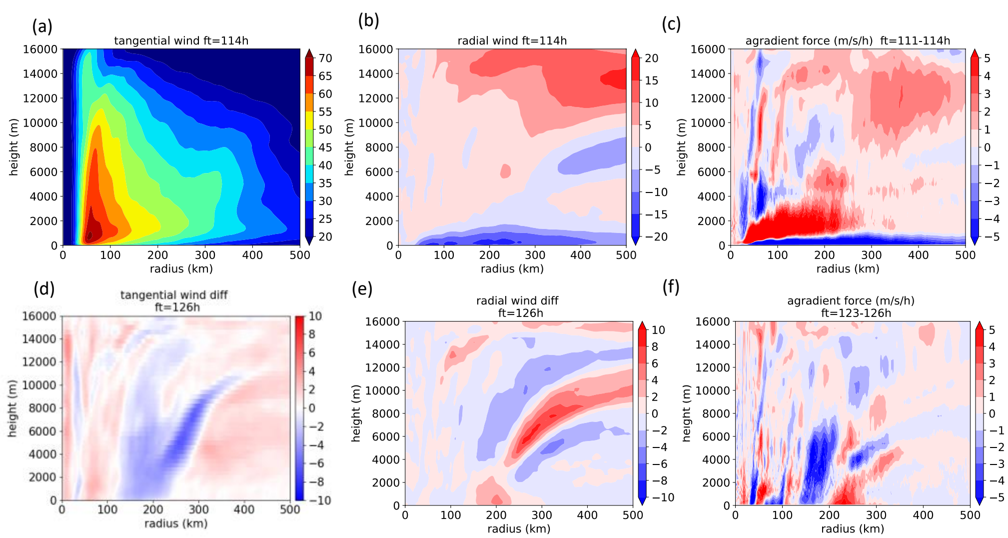
An eyewall replacement cycle is often seen in tropical cyclones, when a secondary eyewall forms outside the inner eyewall, and the inner eyewall disappears. Although this cycle significantly affects the intensity of tropical cyclones, the mechanisms of secondary eyewall formation (SEF) are diverse, and 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.



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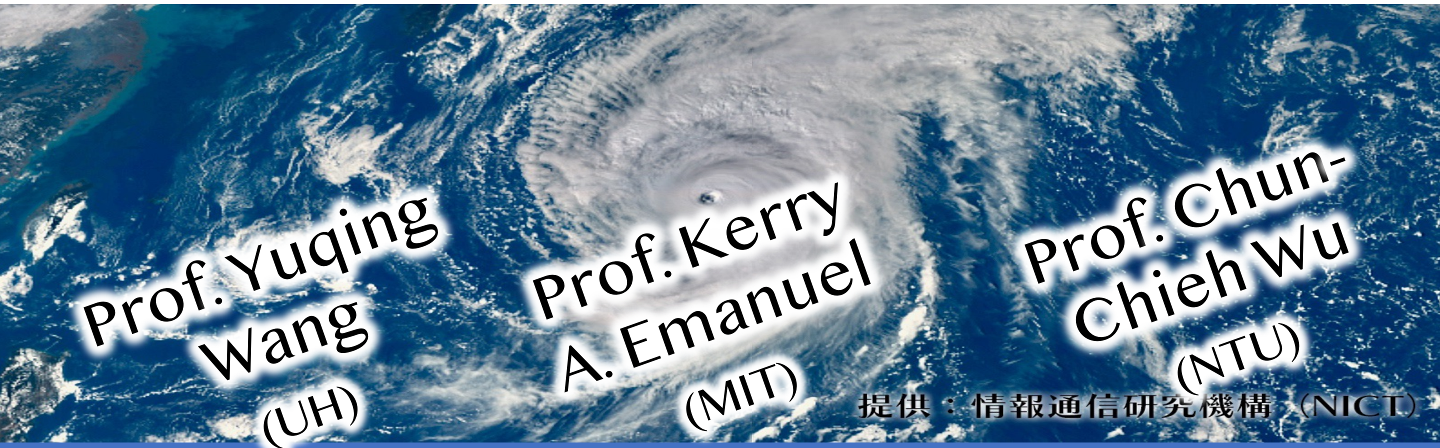
ABSTRACTS (SESSION 3)



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Impact of urbanization on precipitation associated with typhoon landfall

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Previous studies have shown that urbanization can affect the convection, and hence precipitation over or near cities through the modification of land cover characteristics, and the generation of anthropogenic heat and aerosols. Since the last few decades, more and more cities have developed along the East Asia coast, with some of them merging to become the so-called megacities. The question is whether and how urbanization associated with these megacities would modify the precipitation intensity of typhoons that make landfall near these large city clusters.

An observational analysis of the precipitation associated with typhoons making landfall along the South China coast indicates that in recent years, heavier precipitation appears to be more common. In a modeling study, changing the land-surface characteristics of the megacity area to an urban setting also leads to heavier rainfall over the megacity from just before landfall to after landfall through the processes of higher sensible heat flux and stronger surface convergence. If the aerosol concentration is also changed, not only does higher precipitation occur over the megacity, the outer rainbands also develop more vigorously due to the increase of cloud condensation nuclei in these rainbands, and hence ice-phase processes. Modeling studies using different typhoons yield similar results.

These results suggest that in predicting precipitation associated with typhoon landfall near megacities using numerical weather prediction models, the representation of the land use along the coast is very important. In addition, incorporation of aerosol concentration into the models will likely contribute to better predictions.

Energy cascading during typhoon and calm weather scenarios over urban atmosphere

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In urban environments, the intricate interplay of diverse motion scales, ranging from small-scale turbulent activities near the surface to mesoscale atmospheric circulation patterns, exerts substantial influence over energy transfer and dissipation within the atmosphere. Accurate weather prediction and the development of sustainable urban areas hinge on unraveling these interactions. The urban landscape, marked by high concentrations of buildings, roads, and infrastructure, departs significantly from natural surfaces like forests, resulting in disparities in heat absorption and emission. This divergence disrupts the urban-rural energy equilibrium, leading to distinctive energy cascades over urban regions. Although past research has predominantly explored the impact of urban-scale environmental changes on local weather patterns, there remains a critical knowledge gap regarding energy cascading from the broader mesoscale to the smallest turbulent scale due to alterations in the grid-to-urban scale environment. Our study aims to bridge this gap by utilizing CUBE LES to model complex urban geometries and employing Immersed Boundary Methods (IBM). We will investigate LES simulations under diverse wind conditions, including Calm and Typhoon scenarios, as they interact with the urban canopy. Our approach dissects energy scales within urban contexts into distinct spatial and temporal modes, thus deepening our understanding of energy transfer and dissipation mechanisms. Specifically, we seek to identify the fundamental scales of energy transfer, offering insights into scale interactions and enhancing our capacity for severe weather prediction in urban environments.

Historical trends of tropical cyclones and related compound hazards along the coastline of Vietnam

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The concept of compound hazards refers to the simultaneous occurrence or rapid succession of multiple hazards within a specific area. These can pose greater risks than individual hazards and may result in more significant economic losses. In this study, we considered three types of hazards: TCs, high temperatures, heavy rainfall, and their combinations, i.e. compound hazards. A temperature hazard (rainfall hazard) is identified if the maximum temperature (rainfall amount) of a given day exceeds the 95th percentile of all daily values recorded over the study period. A location is exposed to a TC hazard on a given day if the distance from that location to the TC center is less than 250 km.

We computed the number of hazards over 10 selected stations along the coastline of Vietnam for the period 1980–2018. The TC track data were sourced from the International Best Track Archive for Climate Stewardship (IBTrACS), and daily maximum temperature and daily accumulated rainfall were obtained from the Vietnam Meteorological and Hydrological Administration (VMHA).

The results indicate that the average annual number of TCs affecting most stations has decreased slightly, while the number of rainfall (temperature) hazards exhibits inhomogenous trends across the stations. The annual number of compound hazards shows statistically significant increasing trends over three out of 10 stations, and is insignificant over the remaining seven stations. The increasing trend in the number of compound hazards is largely contributed to by the increase in temperature hazards. At the seasonal scale, compound hazards usually occur from March to November, primarily associated with temperature hazards in the first half of the year and with TCs and rainfall hazards in the later months. The peak of the sum of the individual hazards occurs at a different time than the peak of the compound hazards, suggesting that the compound hazard analysis may provide additional information for resilience and adaptation management planning.

Keywords: Tropical cyclones, compound hazards, historical trends, Vietnam

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Observing system simulation experiments toward objective analysis of tropical-cyclone intensity by assimilation of satellite-based cloud-tracking winds in the typhoon inner core

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Tropical-cyclone intensity estimation at tropical-cyclone warning centers around the world is mainly performed by a statistical method of the Dvorak technique with cloud patterns from satellite imagery. Compared with hurricane intensity estimation with available aircraft observations, the typhoon intensity estimation relatively relies on the Dvorak technique after operational aircraft reconnaissance entering the storm center ceased in 1987. After new-generation geostationary meteorological satellites such as Himawari-8/9 and GOES-R were launched, high-frequency observations (with 1- or 2-minute intervals) over limited areas including typhoons were available. Recently, some studies proposed new techniques to track horizontal motions of cloud top at the mesoscale using continuous images from the high-frequency observation. The cloud tracking quantitatively estimates spatiotemporal distributions of the horizontal wind near the cloud-top height including meso-vortices associated with shallow cumuli within the typhoon eye. By combining the cloud-tracking winds with data assimilation procedures, we considered the possibility of an objective typhoon intensity estimation (i.e., an assimilation-based objective analysis for typhoon).

In this study, we examine the availability of the cloud-tracking winds for the typhoon objective analysis. We use a nonhydrostatic atmosphere model and data-assimilation system (SCALE-LETKF) to perform observing system simulation experiments (OSSEs) for a real typhoon after the mature stage. Assimilated virtual observation data are produced by vertically averaging axisymmetric tangential winds over a specified layer at every 4-km radius from the vortex center in a (true) numerical simulation. We designed one experiment without any assimilations (i.e., free run) and three experiments with assimilating cloud-tracking observations in different areas, (Case1) inside the radius of maximum wind speed (RMW) in the lower troposphere, (Case2) at radii with outflows in the upper troposphere, and (Case3) both Case1 and Case 2. Note that the winds at the RMW are not included in the virtual observations because the geostationary-satellite-based cloud tracking is not available at the RMW in general. We performed identical (non-identical) twin experiments by producing the virtual observation data from the SCALE (a different model from SCALE) simulation.

In the identical twin experiments, the overdevelopment of the typhoon vortex in the free run was suppressed by assimilating the cloud-tracking winds and the vortex structure in the assimilation run resembled the true vortex. The observations in the eye (Case1) suppressed the eyewall contraction associated with overdevelopment in the free run. The results suggest that the cloud-tracking winds can be effective for the objective typhoon intensity estimation. In the non-identical twin experiments, the results were qualitatively similar to the identical experiments. However, the tangential wind at around the RMW, where the cloud tracking is not available, in the non-identical experiments was still stronger than that in the true vortex. This feature might be due to the difference in the configuration such as boundary-layer processes and evolution of sea surface temperature between the numerical models used to produce the virtual observation data.

Exploring the controllability of chaotic systems through deep reinforcement learning

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Chaotic systems are inherently sensitive to perturbations, which makes them highly unpredictable, and yet the same sensitivity enables highly efficient control. This intriguing nature of chaotic systems have led to the successful modulation of chaotic flows, stabilization of heart arrhythmias, and recently, it has been proposed to utilize the chaos to mitigate extreme weather. One of the core challenges in controlling chaotic systems is to identify an effective control strategy which tells the timing, location, and type of perturbations (e.g., cloud seeding) aimed at achieving control objectives (e.g., weakening extreme weather events).

In this study, we explore the potential of deep reinforcement learning (DRL) to identify the control strategies in chaotic systems. DRL, a subset of machine learning, excels in complex decision-making scenarios and has celebrated successes in areas like playing computer games and controlling nuclear fusion plasma. Here we demonstrate that DRL can identify highly efficient strategy to control the Lorenz chaotic systems. When perturbation shapes are restricted, DRL even offers strategies that transcend human intuition — it demonstrates the possibility of suppressing chaos through temporary chaos enhancement. Additionally, we propose a DRL-based controllability metric: the "value of control." This novel metric provides a perspective distinct from traditional metrics such as the Lyapunov exponent. We will present latest progress on this topic during the workshop.

Development of a method for the typhoon weakening based on the chamber and the numerical simulation experiments

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This study aims to examine the feasibility of the typhoon modification from intervening in the cloud microphysical process as a part of "A core research program for Typhoon controlling aiming for a safe and happy society" in the JST Moonshot Goal 8. Various ideas are proposed by the Moonshot project for the typhoon modification, the intervention method currently envisioned in our group is to weaken the deep convection at the center of the typhoon by invigoration of cumulonimbus clouds instead of cumulus at the outer region of the typhoon. To promote deep convection at the outer region of typhoons, seeding with hygroscopic aerosols will increase the number of cloud droplets, shift the size distribution of cloud droplets toward smaller size, and facilitate adiabatic heating in the upper layers.

Our goal is realization of the typhoon modification method, but we necessary test the idea before starting the development of the technique. To properly understand how cloud droplets formation and ice crystal formation processes can be modified by seeding in a typhoon environment, we investigate the aerosol competition through laboratory experiments using a cloud chamber at Japan Meteorological Agency / Meteorological Research Institute, and to reflect the results in a numerical model. The cloud chamber is undergoing modification of the air inlet section and installation of a large heating and humidification system to enable experiments to be conducted under warm and humid conditions.

As a counter part to the chamber experiment, we conducted ideal numerical simulations by changing the number of cloud droplet ranging from 30 to 3000 cm^{-3} using the SCALE regional model developed by RIKEN to understand the detail processes in the microphysical processes when the cloud droplet number is changed. The intensity of simulated typhoon with the large number of the cloud droplet tends to be weak comparing to the simulated typhoon with the small number of the cloud droplet; this is an encouraging result for our idea.

To understand responses in realistic typhoons and examine the modification hypothesis in the microphysical processes when the cloud droplet number is changed from 50 to 2200 cm^{-3}, we conducted real case numerical simulations. The CReSS regional model developed by Nagoya University was used for the real case simulation. The target case is Typhoon Faxai in 2019. The intensity of simulated typhoon with the large number of the cloud droplet tends to be weak comparing to the simulated typhoon with the small number of the cloud droplet. But the response to the cloud droplet number is not linear and much more complicated than that found in the ideal simulations. Further investigation to examine the best method for TC weakening.

Reducing the Intensity of an Approaching Typhoon Forced by an Artificial Cold Pool Using the Stretched Version of a Non-hydrostatic Icosahedral Atmospheric Model (NICAM)

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Tropical cyclones are highly destructive natural disasters that can be very costly, and therefore, is of grave concern to any society. As a part of the Moonshot project of the Typhoon Control Research Aiming For a Safe and Prosperous Society, a series of experiments are conducted using the stretched version of the non-hydrostatic icosahedral atmospheric model (NICAM) with a minimum grid spacing of 1.4km to see the impact an artificial forcing would have on an approaching typhoon. Each experiment has an artificial forcing with a different intensity to induce a cold pool positioned at 27 degrees North Latitude and 138 degrees East longitude in the pathway of typhoon Hagibi. The experiments run for two days (48 hours) prior to landfall in Japan. The intensities provide a constant cooling source of 1K/hr, 2K/hr, 10K/hr and 20K/hr where each are circular in shape with a radius of 50km.

Time evolution of the minimum sea level pressure (slp) reveals that for the first 6 hours the cold pool has no impact on typhoon Hagibi in each of the experiments. From 6 -14 hours there is an impact because the control run (no forcing) has the lowest pressure at all times during this period. Interestingly, the forcings of varying intensities impact the typhoon in the same way during this time period. From 23 hours until the end of the simulation, the forcings that provide a cooling effect of 10K/hr and 20K/hr have a greater and more observable impact than the forcings that provide a cooling effect of 1K/hr and 2K/hr. The cold pool is at its strongest one day (24 hrs) into the simulation. We can see the vertical structure of the cold pool best in the 10K/hr and 20K/hr experiments. There is a strong updraft at the edge of the cold pool which acts as a barrier to the inflowing warm moist air. The experiments for 1K/hr and 2K/hr are not able to show a distinct vertical profile of the cold pool.

To better understand the impact, snapshots of the plane-view of the slp, 10-metre wind speed and the 2-metre temperature values are assessed and the differences evaluated to quantify the impact at specific times. Surprisingly, the range of the differences between the control and the experiment for the slp are similar at the same time interval for all the experiments. This pattern is seen too for the 10-metre wind speed and also the 2-metre temperature. For all experiments, the impact of the cooling is most noticeable one day (24 hours) into the simulation. When the typhoon makes landfall (48 hrs) in Japan, it is not at an appreciable weaken state. The reduction in slp, 10-metre wind speeds and 2-metre temperature is not significant enough and the reduction does not happen throughout the whole typhoon. Wind speeds, convection and precipitation are usually not symmetric in a cyclone because a tropical cyclone tends to be non-axisymmetric. The cooling force for each experiment is only able to weaken the typhoon in certain areas while in other areas there are increases in both the 10-metre wind speed and the 2-metre temperature, and decreases in slp. All indicating that there is no weakening. These results prove that weakening a cyclone will be challenging and using one approach may not be sufficient. Improvements are being made to the forcings.

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Typhoon control and its ELSIs

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The typhoon is a natural phenomenon, which is, at first sight, beyond the control of human beings. However, the climate and weather of our planet are going to have increasingly harsher impacts on human lives and society. As long as we still wish to continue to inhabit the earth, we must find a way to deal with this serious challenge. The typhoon control project under Moonshot Goal 8 proposes one possible—but somewhat dangerous—option for doing this. To make the future control operation happen safely, we should address the possible implications of this activity other than the feasibility of the scientific and technological aspects. These trans-science questions are generally called ethical, legal, and social implications (ELSIs).

This presentation will cover several ELSIs that typhoon control activities would have for society, culture, the environment, and biodiversity if the application of this technology has been agreed on by the year 2050 (the Moonshot target year). We especially focus on (1) the permissibility of controlling nature and (2) the risk of third-party (adverse) influence and discuss them from the humanities and social sciences perspective. The discussion will be based on presumable future and technologically neutral scenarios.

Before examining specific ELSIs, this presentation will explain our team's strategy for struggling with these interdisciplinary and complex questions. We realize that, when discussing the ELSIs of novel technologies, it is important to incorporate a timeline. The maturity of science and technology, as well as the climate and social circumstances, will change the world of the future and people's perceptions. Having said that, novel science and technologies also contain a general feature: **uncertainty**. This applies equally to typhoon control. There is no agreed meaning of "control." The timing, the effect, and the risk of interference with typhoon are still uncertain, and the climate, the intensity of typhoons, and the efficacy of other disaster prevention methods that will exist in 2050 are not sufficiently predictable. This situation can easily lead to the "**technology control dilemma**," meaning that the risks and problems are uncertain at this premature stage, and, when the risks become certain, the technology is already mature and fixed, and it is difficult to reverse it, even when there remain some concerns about it. On the other hand, stalling because of uncertainty could put us in the position of being "too late."

To avoid this situation, our ELSI team and this presentation apply a general approach, providing a comprehensive list of presumable implications of weather control in a broader perspective (a **technologically neutral approach**). This list should help us avoid overlooking important but less obvious issues that should be taken into account. Our team has been continuing to have talks with scientists, specialists in disaster management, communities, and people in other fields. We also have embarked on exchanges in other existing, comparable fields, such as precipitation enhancement and geoengineering (solar radiation modification and carbon dioxide removal). Every new connection gives us new awareness, so the list will be constantly enriched.

Typhoon Science and Technology Research Center

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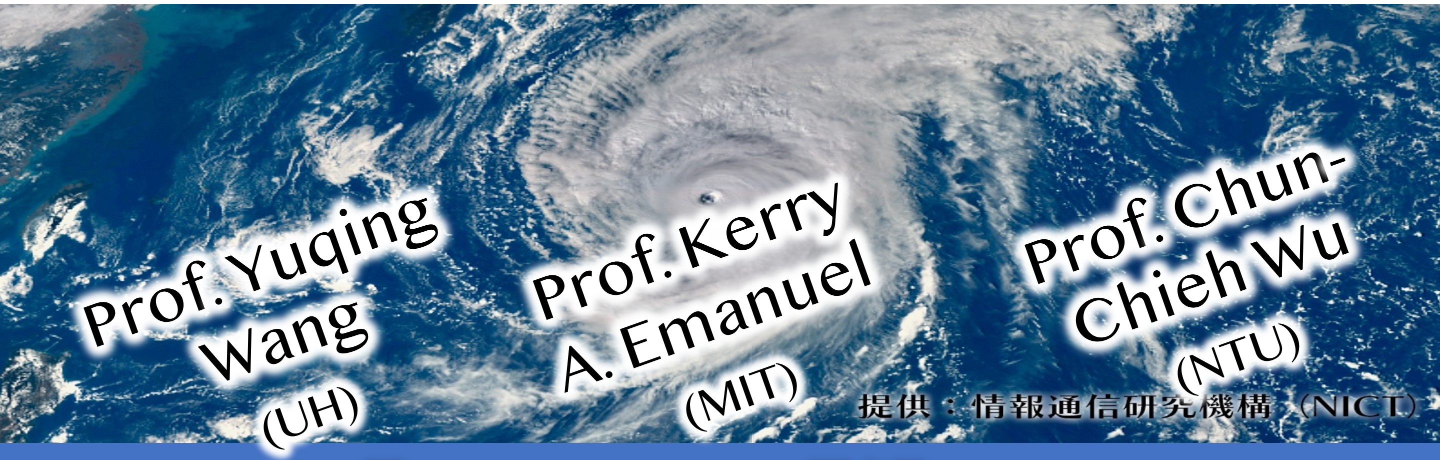
ABSTRACTS (POSTERS)



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Ocean subsurface suppresses tropical cyclone genesis during El Niño

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The vast tropical Pacific is home to the majority of tropical cyclones (TCs) which threaten the rim countries every year. The TC genesis is nourished by warm sea surface temperatures (SSTs). During El Niño, the western Pacific warm pool extends eastward. However, the number of TCs does not increase significantly with the expanding warm pool and it remains comparable between El Niño and La Niña. Here, we show that the subsurface heat content change counteracts the favorable SSTs in the tropical central-north Pacific. Due to the anomalous positive wind stress curl, the 26 °C isotherm shoals during El Niño over this region and the heat content diminishes in the tropical central-north Pacific, even though warm SST anomalies prevail. This negative correlation between SST and 26 °C isotherm depth anomalies is opposite to the positive correlation in the tropical eastern and western Pacific. This is critical because quantifying the dynamics of the subsurface ocean provides insight into TC genesis. The trend in TC genesis continues to be debated. Future projections must account for the net effect of the surface-subsurface dynamics on TCs, especially given the expected El Niño-like pattern over the tropical Pacific under global warming.

Our work has been published in *Nature Communications* recently (https://www.nature.com/articles/s41467-022-35530-9).

Environmental characteristics of western North Pacific tropical cyclone onset in neutral ENSO years

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This study investigates the inter-annual changes in tropical cyclone season onset (TCSO) over the western North Pacific (WNP) in neutral El Niño-Southern Oscillation (ENSO) conditions during 1979–2019. The average TCSO during early TCSO years (~ March 27) is significantly earlier than during late TCSO years (~ June 18). In response to inter-annual changes of TCSO in neutral ENSO years, TC activity shows distinct seasonal features. Although there are no significant differences in total TC counts, more TCs occur in March–May while fewer TCs occur in September–November during early TCSO years. Additionally, TC genesis locations tend to move eastward and equatorward during early TCSO years. These TCs are also found to have stronger lifetime maximum intensities. Changes in seasonal TC activity are closely associated with changes in the large-scale environmental pattern changes, which are driven by the seasonal evolution of sea surface temperature anomalies (SSTAs). Low-level vorticity and mid-level humidity changes are found likely to be the two primary factors inducing the seasonal feature differences between early and late TCSO years. Further analyses suggested that the seasonal evolution of sea surface temperature anomaly patterns over the tropical Indian Ocean and tropical Pacific accompanied by TCSO in neutral years is closely linked to changes in the spring Pacific Meridional Mode. Observational analyses and numerical simulations suggest that the Pacific Meridional Mode mainly causes changes in the low-level large-scale circulation over the tropical WNP via a Rossby wave Gill-type response, thus affects inter-annual variability of TCSO during neutral ENSO years. This response is found to be distinct from the previously documented strong relationship between TCSO and strong ENSO events.

Atmospheric modes fiddling the simulated ENSO impact on tropical cyclone genesis over the Northwest Pacific

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The El Niño-Southern Oscillation (ENSO) is crucial to the interannual variability of tropical cyclone (TC) genesis over the western North Pacific (WNP). However, most state-of-the-art climate models exhibit a consistent pattern of uncertainty in the simulated TC genesis frequency (TCGF) over the WNP when we focus on ENSO years. Here, we analyze large ensemble simulations of TC-resolved climate models to identify the source of this uncertainty. Results show that large uncertainty appears in the South China Sea and east of the Philippines, primarily arising from two distinct atmospheric modes: the "Matsuno-Gill-mode" and the Pacific-Japan-like pattern ("PJ-mode"). These two modes are closely associated with anomalous diabatic heating linked to tropical precipitation bias in model simulations. By conditionally constraining either of these atmospheric modes, we can significantly improve the simulated TCGF, confirming that it is the atmospheric circulation bias in response to tropical precipitation bias that causes the uncertainty in the simulated WNP TCGF.

Influence of the Atlantic Multidecadal Oscillation on the rapid intensification of tropical cyclones over the western North Pacific

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Rapid intensification (RI) of tropical cyclones (TCs), defined as an explosive increase of TC intensity over a short time period exceeding a given threshold (e.g., 30 knots in 24 hours), poses a great challenge to both forecasting and disaster prevention. Some recent studies have documented a significant increase in TC RI magnitude (RIM, measured as the mean intensification rate of all TC RI records in a TC season) over the western North Pacific (WNP) since 1979, and attributed it to the influence of global warming. In this study, results from statistical analysis show that the JTWC TC RIM over the WNP during 1951 2021 exhibits significant interdecadal variability, which is found to be closely related to the Atlantic Multidecadal Oscillation (AMO). During the positive AMO phase, the TC RIM increased over the most of the WNP. And the JMA best-track data verified the impact of AMO on TC RIM. Further analyses indicate that the response of the local thermodynamic conditions to the AMO plays a dominant role in such a relationship. The positive AMO phase favors the large TC RIM over the WNP by producing significant warm sea surface temperature (SST) anomalies, increasing TC heat potential and the mid-tropospheric relative humidity in the main occurrence region of TC RI.

Mechanism analysis revealed how AMO remotely affects the WNP environment, especially the whole basin SST warming on the WNP, and then regulates the interdecadal variation of WNP TC RIM. AMO remotely controls the large-scale environmental conditions and then the RIM over the WNP through modulating the local surface heat fluxes and the Ekman heat transport by the Matsuno-Gill-type response and Walker circulation. Through such a response, the warm SST anomaly over the North Atlantic can lead to the low-level convergence and upper-level divergence over the WNP. On one hand, this results in an increase in cloud cover over the tropical Pacific and thus enhances the longwave radiative flux from the atmosphere to the ocean, resulting in SST warming over the WNP. On the other hand, this induces anomalous surface easterly wind over the tropical WNP, which transports warm water northward by the Ekman heat transport, also contributing to SST warming over the WNP. The results are confirmed by results from the AMO sensitivity experiments in the Decadal Climate Prediction Project Component C in the framework of the Coupled Model Intercomparison Project Phase 6.

Climatology and characteristics of rapidly intensifying tropical cyclones over the North Indian Ocean

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Rapid Intensification (RI) of a tropical cyclone (TC) is defined as an increase in the wind speed by 30 knots within 24 hrs. It is a less understood process, particularly for TCs over the North Indian Ocean. We considered data for the past 39 years (1982-2020) from the JTWC and studied the climatology of TCs to understand the frequency and patterns of rapid intensification and identify the key atmospheric and oceanic factors influencing it. The study aims to enhance our understanding of TC behavior in this region, contributing to improved forecasting and disaster preparedness. We found that, out of 197 cases, 44 TCs (22%) experienced RI. There is a significant increasing trend in RI TCs frequency and duration over the Arabian Sea (AS). Lifetime maximum intensity (LMI) is significantly higher, and genesis to LMI duration is also significantly longer for TCs undergoing RI over the AS. LMI is double for RI TC than for Non RI (NRI) TC. The longer duration to achieve the higher maximum intensity resulted in a longer total lifespan for RI TCs. All TCs reaching a super cyclonic storm category underwent RI and generally, RI onset happens in the depression stage. During the Pre-monsoon season, April and May are the most prominent months for RI over the Bay of Bengal, whereas, the May and June months are prominent over the Arabian Sea. During the Post-monsoon season October and November months are the prominent ones over both the basins.

The composites are prepared to understand the characteristics of RI TCs in contrast to NRI TCs. For the RI TC composite, the period includes 12 hours before and 24 hours after the RI onset. For the NRI TC, we considered 36 hours starting from the initial intensification stage. The analysis shows the RI TCs are embedded in the warm water regions with ocean heat content of 90–100 KJ cm^{-2} and strong latent heat flux transport. RI TCs also have higher positive low-level relative vorticity, higher upper-level divergence, and higher mid-level relative humidity, with higher moisture content around the TC center. Deep clouds with 208K <IRBT < 240K dominate in RI TCs. The total surface rainfall for RI cases is symmetric around the center. RI TCs have higher rainfall fractions with intense surface rain rates for stratiform and convective rainfall during the pre-monsoon. These findings are derived from composite plots, and while they provide valuable insights, they may not be universally applicable to every cyclone, as there could be variations in the favorable parameters leading to rapid intensification of a cyclone.

Keywords: tropical cyclones, North Indian Ocean, rapid intensification, climatology, characteristics

Applying a time-dependent theory of tropical cyclone intensification for predicting tropical cyclone intensity

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Accurate prediction of tropical cyclone (TC) intensity has proven to be a challenging task due to the complex multiscale physical processes involved in TC intensity change. In this study, we developed a new prediction scheme for TC intensity over the western North Pacific (WNP) based on a state-of-the-art time-dependent theory of TC intensity change, namely an energetically based dynamical system (EBDS) model, together with the use of the Long Short-term Memory (LSTM) neural network, or in short, the EBDS_LSTM. In the EBDS model, TC intensity change is controlled by both the internal dynamics determined by the given favorable ocean and atmospheric thermodynamic conditions and the detrimental environmental effect, with the latter being collectively contributed by various environmental factors, such as environmental vertical wind shear. The LSTM neural network is used to predict the environmental dynamical efficiency in the EBDS model. To minimize the issue of limited-data records, we employed transfer learning to train the scheme using the best-track TC data, the global reanalysis data during 1982–2017 and the data from the NCEP (National Centers for Environmental Prediction)'s Global Forecast System (GFS) during 2019–2021, respectively. The developed scheme is evaluated for TC intensity prediction in 2017 using reanalysis data and 2021-2022 using the GFS data. The prediction by the new scheme shows better skill than the official prediction from the China Meteorological Administration and those by other state-of-art statistical and dynamical forecast systems, particularly for long lead-time forecasts.

Comparisons between the predictability of tropical cyclone track forecasts in WNP and ATL basins

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It is well recognized that there has been great improvement in tropical cyclone (TC) track forecasts over the past decades. In recent years, however, the decreasing trend of perceived error (errors between forecasts and observed positions) has flattened out, and some studies suggested that "the approaching limit of predictability for tropical cyclone track prediction is near or has already been reached". Noting that there remains error in best track dataset, the track forecast errors (short for TFE) published by forecast centers are actually not true track forecast errors (short for TTFE). In this study, a recently proposed forecast error analysis method called SAFE was used to estimate the TTFE of tropical cyclone in Western North Pacific (WNP) Ocean. Using several assumptions and just four parameters, a multi-year forecast error model was constructed to describe TTFE behavior of lead time 24-120 h in WNP basin over the TC seasons from 2011 to 2021, and the variation was extrapolated into the future. The results showed that the TC track forecast in WNP has not yet reached the limit of predictability, with an improvement of about two days in 16-17 years. Furthermore, comparing our WNP results with previous studies for Atlantic (ATL) Ocean basin, it was found that the TTFE in WNP grows faster than in ATL. This is probably because TCs in WNP basin have averagely larger size and intensity, resulting in greater difficulty in forecasting the surrounding winds and therefore larger TTFE growth rate.

Factor analysis and prediction of typhoon intensification using explainable AI

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Typhoon discrimination and development prediction using AI technology have been actively carried out in recent years. Deep learning such as convolutional neural networks (CNNs) is mainly used for AI technology. While deep learning provides high prediction accuracy, it has the disadvantage that it is difficult to understand the prediction reasons and to utilize known meteorological knowledge for prediction.

Against this background, this study examines the application of explainable AI (XAI) to prediction of typhoon intensification. XAI is an AI technology that can explain the reasons of judgment or prediction, and in recent years it has been given importance from the viewpoint of ensuring the reliability of prediction results. In this study, we aim to link the predictive reasons for XAI outputs with meteorological knowledge.

In this study, we use Wide Learning as XAI. Wide Learning is an XAI technology developed by Fujitsu that comprehensively discovers hypotheses expressed by combinations of variables and makes predictions based on those hypotheses. In addition to ensuring explainability of AI, it is capable of discovering new knowledge that humans cannot find.

This study uses the dataset of tropical cyclogenesis in a cloud-resolving global atmospheric simulation. Field data in this dataset, such as longwave radiation and sea level pressure, are subjected to principal component analysis and the top principal components are used as variables.

As a first step, a model for determining the state of a tropical cyclone was learned by Wide Leaning. Tropical cyclones have three types: precursor(preTC), tropical cyclone(TC), and extratropical cyclone(exTC). The accuracy of the determination of tropical cyclone types was 78.2% for precision and 76.8% for recall. Many variables such as longwave radiation, sea-level pressure, and east-west wind were identified as the reasons for the prediction of TC.

Then, using the same dataset, a model for predicting rapid intensification(RI) of tropical cyclones was learned by Wide Learning. The accuracy of RI prediction was 78.6% for accuracy and 64.1% for recall, when the central pressure dropped by 10hPa or more after 24 hours. Many variables, such as the principal component of sea level pressure and the within-field variance value, appeared as the reasons for prediction of RI. The variables appearing in the reasons are the features related to RI. In the future, we will improve our understanding of these characteristics and compare them with existing knowledge of meteorology, and examine whether they can provide new knowledge on typhoon development.

Weighted analog intensity prediction (WAIP) guidance for Philippine tropical cyclones: Initial assessment in intensity bifurcation cases

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The performance of the intensity forecasts generated by the bifurcation version of the seven-day Weighted Analog Intensity Prediction technique for the Western North Pacific (WAIP) was evaluated for 13 tropical cyclone (TC) events that occurred within the Philippine Area of Responsibility (PAR) in 2022 using the preliminary best track intensities from the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) as verifying dataset. The method generates a rank-weighted average of intensity evolutions of 16 historical analogs from the 1945-2018 Joint Typhoon Warning Center (JTWC) best track data that closely resemble the PAGASA official track forecast and initial intensity at the time WAIP was run. Furthermore, hierarchical cluster analysis is used to separate analog intensity evolutions into two clusters, provided, that a substantial intensity bifurcation (e.g., threshold intensity difference ≥ 15 kt at each forecast time) is observed.

For the 2022 test cases comprising 105 WAIP intensity forecasts with forecast length of up to 120 hours, the 16-analog WAIP showed generally increasingly negative bias errors with increasing forecast time and root mean square error (RMSE) ranging from 7.5 kt at 12-hour to 23.4 kt at 120-hour. In 36 of 105 WAIP intensity forecasts where substantial intensity bifurcation was observed, there was a considerable improvement in the intensity RMSE relative to the original 16-analog WAIP if an always perfect selection of the correct intensity cluster is made. The "perfect-cluster selection" WAIP forecasts had generally smaller bias errors and lower RMSE across nearly all forecast times, with percent decrease in RMSE ranging from 14.1 to 33.1% relative to those observed in the intensity forecasts from all 16 analogs. While further verification will be performed for TC cases from the 2018 to 2023 seasons, this preliminary evaluation demonstrated the viability of the WAIP as an operational intensity forecast guidance tool within the PAR region compared to the original 10-analog, seven-day WAIP in operational use at PAGASA, especially in intensity bifurcation situations.

Typhoon seasonal forecasting by a high-resolution coupled GCM (NICOCO)

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To mitigate the impact of typhoons, it is needed to precisely predict typhoon activity before the beginning of the typhoon season (June). Some research institutes, operational centres, and insurance companies abroad issue seasonal forecasts of typhoons. In Japan, a part of private weather companies provide an outlook of typhoon activities, but no official seasonal typhoon forecast is issued by JMA.

Dynamical-based typhoon seasonal forecast using conventional coupled GCMs has been intensively examined along with the progress of high-performance computers in the recent couple of decades. However, horizontal resolution is not high enough to represent observed typhoon intensity and some bias correction technique is needed to predict the intensity-related index (e.g., ACE) quantitatively.

Here, we used a 14-km-mesh global nonhydrostatic atmospheric model coupled with a 0.25-deg-mesh global ocean model (NICOCO; an AGCM NICAM coupled with an OGCM COCO) for 10-year (2010-2019) typhoon seasonal forecast experiments. The model is initialized on 20 May of each year and integrated to 1 November. The initial conditions for the atmosphere are made by interpolating the ensemble analysis data of ALERA (the first 5 members only are used because of computational resources). The initial conditions for the ocean are created by driving COCO using JRA-55do. Thus, the ensemble size of the experiments is five and the initial condition for the ocean is common among the ensemble members. We also performed NICAM (atmosphere-only) experiments. For NICAM experiments, the observational SST of OISSTv2.1 is given.

The results show that NICOCO performed better in predicting seasonal (June–October) numbers of typhoons and seasonal ACE than NICAM. For example, the correlation coefficients between simulated and observed seasonal numbers of typhoons are higher in NICOCO experiments (0.41) than that in NICAM experiments (0.31). The absolute value of mean error is lower in NICOCO (–2.18) than in NICAM (3.86). The model showed the best performance in predicting the seasonal number of typhoons in the eastern south part of the WNP (0°–18°N, 140°–180°E), where intense typhoons often form. The correlation coefficients between simulated and observed seasonal (June-October) numbers of typhoons are higher in NICOCO experiments (0.77) than that in NICAM experiments (0.70). For ACE in the eastern south part of the WNP, the correlation coefficient for NICOCO experiments is 0.80 and that for NICAM experiments is 0.67. The correlation coefficient between simulated and observed numbers of typhoons in June–August is higher in NICOCO experiments (0.36) than that in NICAM experiments (0.34). In September–October, however, the correlation is lower in NICOCO (0.24) than in NICAM (0.35). These results demonstrate NICOCO's good performance in typhoon seasonal forecasting.

Relative timing of rapid intensification and rapid contraction of the radius of maximum wind in tropical cyclones

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Based on the balanced vortex dynamics, it has long been known that tropical cyclone (TC) intensification often occurs simultaneously with contraction of the radius of maximum wind (RMW). However, some recent studies have found that rapid contraction (RC) of RMW could precede rapid intensification (RI) of TC in both observations and simulations, and the understanding of the involved dynamics is incomplete.

In this study, this phenomenon is first revisited based on ensemble axisymmetric numerical simulations. Consistent with previous studies, because the absolute angular momentum (AAM) is not conserved following the RMW, the phenomenon cannot be understood based on the AAM-based dynamics. Both budgets of tangential wind and the rate of change in the RMW are shown to provide dynamical insights into the simulated relationship between RI and RC. During the RC stage, due to the weak TC intensity and large RMW, the moderate negative radial gradient of radial vorticity flux and small curvature of the radial distribution of tangential wind near the RMW favor RC but weak diabatic heating far inside the RMW leads to weak low-level inflow and small radial absolute vorticity flux near the RMW and thus a relatively small intensification rate. As RMW contraction continues and TC intensity increases, diabatic heating inside the RMW and radial inflow near the RMW increase, leading to a substantial increase in radial absolute vorticity flux near the RMW and thus the RI. However, the RMW contraction rate decreases rapidly due to the rapid increase in the curvature of the radial distribution of tangential wind near the RMW as the TC intensifies rapidly and RMW decreases.

The analysis above suggests that RC tends to precede RI. To verify it, the statistical relationship between RC and RI is further examined based on the extended best track dataset for the North Atlantic and eastern North Pacific during 1999–2019. Results show that, as expected, for more than ∼65% of available TCs, the time of the peak contraction rate precedes the time of the peak intensification rate, on average, by ∼10–15 h. With the quantitatively defined RC and RI, results show that ∼50% TCs with RC experience RI, and TCs with larger intensity and smaller RMW and embedded in more favorable environmental conditions tend to experience RI more readily following an RC. Among those TCs with RC and RI, more than ∼65% involve the onset of RC preceding the onset of RI, on average, by ∼15–25 h. The preceding time tends to be longer with lower TC intensity and larger RMW and shows weak correlations with environmental conditions. The qualitative results are insensitive to the time interval for the calculation of intensification/contraction rates and the definition of RI. The results from this study can improve our understanding of TC structure and intensity changes.

Helicity evolution during the life cycle of tropical cyclones formed over the North Indian Ocean

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Tropical cyclones (TCs) are violent meso-β scale convections occurring in the atmosphere. The destructive impact of the TCs commensurate to the helicity associated with their evolution. The evolution of helicity of three TCs viz. Fani, Luban, and Ockhi formed over the north Indian ocean have been analyzed in this study. The analysis of kinetic energy density of primary (EP), secondary (ES) circulation and total helicity has shown that TCs showed helical features when the secondary overturning circulation knotted with primary tangential circulation in a moist convective situation. This condition can be considered a starting of the self-sustained helical feedback process. At this time, the core region became a rotation-dominated region that suppressed strain-dominated surroundings. The Okubo-Weiss parameter demonstrates the similar qualitative behavior of deep convection as total helicity. The local maximas in helicity time series commensurate with the changes in tropical cyclones' stages (intensification/dissipation). Therefore, consideration of helicity analysis is essential to analyze the TC intensification and dissipation.

Exploring aerosol effects on tropical cyclone dynamics and cloud microphysics

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Cyclonic storms are relatively common in the Arabian Sea, but extremely severe cyclonic storms, especially in the pre-monsoon season, are rare. Recently, an exceptionally severe cyclonic storm named "Tauktae" occurred from May 14 to 19, 2021 in the Arabian Sea. Climatological records indicate that such a deadly cyclonic storm has not been observed in the last 60 years. Cyclone Tauktae had a devastating impact on the west coast of India. In this analysis, we examined the dynamics and microphysics of Cyclone Tauktae. Additionally, we explored the role of aerosols in influencing the storm's dynamics and cloud microphysics. Our analysis utilized CERES observations for aerosols and the ERA5 reanalysis dataset for dynamics. The primary factors contributing to the intensification of Cyclone Tauktae included unusual warming in the Arabian Sea, significant latent heat release, and the buildup of cyclone heat potential. We also explored additional factors i.e., mixing of aerosols for this cyclone's intensification. As Cyclone Tauktae matured and progressed, it drew in a substantial amount of aerosols from the surrounding region. The northern tail of the cyclone brought in aerosols from the foothills of the Himalayas, while the southern tail pulled them from the Arabian Peninsula. This mixing of aerosols in the environment strengthened cyclone dynamics and cloud microphysics, leading to increased precipitation during its later stages around the time of landfall. This role of aerosols in storm dynamics we explored by conducting numerical simulations using the Weather Research & Forecasting regional model in the convection-permitting scales. Further research is needed to gain a deeper understanding of cloud microphysics and the precise influence of aerosols on cloud droplets.

Towards a new conceptual understanding of the decay of landfalling typhoons

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The most significant impact of typhoons on human lives is felt when they make landfall. Violent winds, heavy rain, and storm surges accompany landfalling typhoons as they decay over land. A textbook understanding of the decay of landfalling typhoons is achieved by the classical spin-down theory, where the decay is conceptualized using a simple framework: an axisymmetric vortex decaying due to friction with the land underneath. The simplicity of the theory allows an analytical expression predicting the decay of the vortex's azimuthal velocity with time.

We critically examine two aspects of the spin-down theory. First, we consider a key parameter that determines the decay rate: the vortex height. For a real landfalling typhoon, there is no clear analog for the vortex height used in the model and its common practice to use it as a free parameter to obtain a best-fit between model and observational data. We examine this practice by comparing the intensity decay predicted by the theory against results obtained from axisymmetric simulations of landfalling typhoon. We show that the vortex height can have a wide range of values that allows the theory to fit almost any kind of simple decay curve, giving a false impression of utility.

In the second part of this work, we look at the core idea of the spin-down theory through the perspective of total angular momentum budget. We show that the theory uses a strong assumption of no net flux of angular momentum across a vertical surface at any radial position, implying that frictional torque acts as the sole source or sink of the typhoon's total angular momentum. We demonstrate using numerical simulations that there is, in fact, a non-negligible contribution of the flux of angular momentum and discuss its implication in terms of the decay of the landfalling typhoon.

Long-term analysis of tropical cyclone intensity using MPI theory based on CMIP6 HighResMIP projections

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In addition to sea level rise, other effects of global warming have already been observed. The intensification of tropical cyclones (TC) is also no exception. This study shows how TCs will change in the future worldwide using MPI (Maximum Potential Intensity) theory, which estimates the maximum development of TCs for given climatological environmental conditions. This study used the CMIP6 HighResMIP (High-Resolution Model Intercomparison Project) experiment, which was evaluated specifically for TCs in IPCC AR6. This data set focuses on the intercomparison of TC intensities under the RCP8.5 scenario, providing high-resolution data and estimating the effect of atmosphere-ocean coupling with AGCM (Atmospheric Global Climate Model) and AOGCM (Atmosphere-Ocean Global Climate Model). The differences in projection between the AGCM and the AOGCM for MPI were analyzed in detail.

The scenario-based projections show significantly intensified TC trends in the monthly mean MPI in WNP (Western North Pacific) and NA (North Atlantic), especially for AOGCM, although each model of HighResMIP has different characteristics. As a most significant linear trend of monthly mean MPI, in NA, it was -0.76 hPa/10 years for AOGCM. As for future changes in MPI, in WNP, most GCMs suggested TC intensity changes are -1~-3 hPa by 2050. You can also easily guess a spatial difference between MPI and the maximum development value of TCs from track data of HighResMIP mainly because TC translation is not considered in MPI theory. Therefore, it is important to reveal the north-south difference when applying MPI to calculating MPS (Maximum Strom Surge height)[1)]. We can accurately predict future changes in maximum storm surge risk by quantifying and filling this difference. The details of the result will be presented at the conference.

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Refined tropical cyclone genesis potential index for enhanced tropical cyclone projection in the western North Pacific region

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The research utilized high-resolution atmospheric general circulation models (AGCM) to simulate tropical cyclones (TCs) and assessed two TC genesis potential indices concerning their ability to depict projected TC changes in the western North Pacific (WNP) under a warming scenario. Both indices effectively captured the seasonal variations in TC genesis frequency (TCGF) and its spatial distribution in historical simulations and observational data.The commonly used TC genesis potential index (χGPI) projected a substantial increase in TCGF in response to a warmer ocean surface. However, this projection contradicted the significant reduction in the model projection due to the predominant influence of sea surface temperature (SST) on χGPI. Higher SST in distant ocean basins often overshadowed the destabilizing effect of locally warmer SST, resulting in more stable atmospheric conditions in the WNP and fewer TC occurrences.In contrast, the revised index (χMqGPI), which takes gross moisture condensation into account, projected a decrease in TCGF that more accurately represented the declining trend of TCGF in the warming simulations by AGCM. Although the reduction was milder than that directly derived from the TC detection scheme, these results suggest the feasibility of using χMqGPI, based on multimodel coarse-resolution CMIP6 climate model outcomes, to forecast future changes in TCGF in the WNP.

The role of cloud-radiation interactions in accelerating tropical cyclone development

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This study uses CERES satellite measurements and WRF model simulations to examine the importance of radiative heating in promoting tropical cyclone (TC) genesis and modulating the prediction skills of TC intensification in an operational hurricane forecasting model. There is a growing recognition that radiative heating plays a critical role in accelerating the development of tropical mesoscale convective systems through cloud-radiation interactions. Therefore, investigating the role of radiative heating that contributes to TC development can advance our understanding of how the large-scale forcing influences TC genesis.

A series of experiments have been conducted using numerical model simulations to address how cloud-radiation interactions modulate the development of TCs. Both satellite measurements and model simulations demonstrate consistent signals of TC genesis that tropical waves (TWs) that develop into the TC category tend to have stronger cloud radiative heating than those that don't, especially within 500 km of the circulation center. While latent heating is known to provide a higher magnitude of energy for TCs, our study finds that radiative heating also contributes substantially to TC genesis. Our numerical simulations reveal that when cloud-radiation interactions are included, the likelihood of TC genesis increases, particularly for storms at the weaker end of the intensity spectrum. The structural differences in cloud radiative heating within and around the TC area created by cloud-radiation interactions are found to be the key driver of this increase in genesis chances. In addition to the importance of radiative heating to TC genesis, the model's ability to capture radiative heating also directly influences the prediction skills of TC intensification in numerical weather forecasting. Our findings suggest that cloud-radiation interactions play a crucial role in triggering the development of TWs and TCs at the early stage of their lifetime.

Sensitivity Analysis of Assimilating Doppler Radar Radial Winds Within the Inner- and Outer-Core Regions of Tropical Cyclones

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The assimilation of Doppler radar radial wind observations is important for improving tropical cyclone (TC) prediction. However, the specific impacts and contributions of these observations over different areas are still unclear. In this study, the impact of assimilating radar radial winds within the innerand outer-cores of TCs is evaluated. For TC Mujigae (2015), analyses suggest that although the outer-core observations better improve the upper-level outflow of the TC, the inner-core observations contribute more to enhancing tangential wind and updraft near the eyewall as well as correcting the TC size, warm core structure, and asymmetrical eyewall convection. The improvements conferred by the assimilating the total observations in the analysis and forecasting of TC tracks and intensities are mainly contributed by the inner-core observations. This is probably because: (a) the model has a higher deficiency in simulating the TC inner-core structure, which leads to a larger background deviation relative to the observations and the assimilation increment contributed by the inner-core observations; (b) as determined by the stronger nonlinearity of the physical processes, the ensemble spread (i.e., model uncertainty) around the inner core is larger, resulting in a more distinct impact of data assimilation. The significant improvements in the inner-core observations are further consolidated by analyses of two other TCs of different sizes and intensities, in which the number of inner-core observations accounts for only 1/3 of the total on average. The TC inner-core area should be a major consideration of future TC observation projects.

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Feng, J., Duan, Y., Sun, W., & Zhou, Y. (2023). Sensitivity Analysis of Assimilating Doppler Radar Radial Winds Within the Inner- and Outer-Core Regions of Tropical Cyclones. *Journal of Geophysical Research: Atmospheres*, *128*(8).

Angular momentum transport and instability in the eye: observational evidence from a 30-second imaging with Himawari-8

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I will be presenting views and results from a recent paper, Horinouchi, T., S. Tsujino, M. Hayashi, U. Shimada, W. Yanase, A. Wada, and H. Yamada, (2023) Stationary and transient asymmetric features in tropical cyclone eye with wavenumber-one instability: Case study for Typhoon Haishen (2020) with atmospheric motion vectors from 30-second imaging. *Mon. Wea. Rev.*, 151(1), 253-273. https://doi.org/10.1175/MWR-D-22-0179.1, whose abstract is as follows:

Dynamics of low-level flows in the eye of Typhoon Haishen (2020) in its late phase of intensification are investigated with a special rapid-scan observation of the Himawari-8 geosynchronous satellite conducted every 30 s. This is accomplished by deriving storm-relative atmospheric motion vectors at an unprecedentedly high spatiotemporal resolution by tracking clouds across five consecutive visible-light reflectivity. The overall low-level circulation center was situated several kilometers away from the storm center defined in terms of the inner edge of the lower part of eyewall clouds. The shift direction is rearward of the storm translation, consistently with a numerical study of the tropical cyclone (TC) boundary layer. Over the analysis period of 10 h, azimuthal-mean tangential wind around this center was increased at each radius within the eye, and the rotational angular velocity was nearly homogenized. The instantaneous low-level circulation center is found to orbit around the overall circulation center at distances around 5 km. Its orbital angular speed was close to the maximum angular speed of azimuthal-mean tangential winds. This rotating transient disturbance is found to transport angular momentum inward, which explains the tangential wind increase and the angular velocity homogenization in the eye. These features are consistent with an algebraically growing wavenumber-1 barotropic instability, whose impact on TC structures has not been explored. This instability enhances wavenumber-1 asymmetry in ring-shaped vorticity, which can be induced by various processes such as translation, environmental shear, and exponential barotropic instability. Therefore, it may appear broadly in TCs to affect wind distribution in their eyes.

Typhoon-generated extreme wave reanalysis by data assimilation with drifting buoy observations

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In recent years, many coastal disasters have been caused by typhoons. Furthermore, typhoon intensity is predicted to increase due to global warming, which is expected to increase the intensity of typhoon waves. Therefore, it is important to improve the accuracy of wave models for extreme high waves around typhoons. Also, in recent years, it has become relatively easy to observe the open ocean using small drifting wave buoys.
This study aims to develop a system to improve the accuracy of wave height prediction for typhoon waves by assimilating observation data from drifting wave buoys into a wave model.

We developed a system to assimilate the drifting buoy observations into the spectral wave model, WAVEWATCH III. We implemented Optimal Interpolation as a data assimilation method. We conducted typhoon wave simulations in the Western North Pacific, targeting the typhoon waves in the summer of 2022. The accuracy of wave simulations was estimated using the Japanese coastal wave observation network. At first, we conducted the initialized experiment in which the initial condition is assimilated with drifting buoy observations, and the model runs for three days without assimilation. As a result, the model improves immediately after data assimilation (initial condition), and the improvement continues for 71 hours. Next, we conducted a sequential data assimilation experiment in which the assimilation process was operated every 1 hour. The sequential data assimilation reduced the wave model error by up to 2.63 m when drifting buoys observed extreme typhoon waves near the center. Even when the assimilation process is operated every 3 hours, the wave model error was reduced by up to 2.36 m. Our results show that the assimilation of drifting buoy observation data can meaningfully improve the wave model for extreme typhoon waves.

Simultaneous observations of atmosphere and ocean directly under typhoons using autonomous surface vehicles

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In recent years, damage to structures and facilities due to extreme weather, such as typhoons, has been increasing. For implementing appropriate, proactive responses to expected damage, it is essential to predict typhoons more quickly and accurately. Therefore, in order to enhance the lead-time for responses, accurate prediction is indispensable while typhoons are forming and moving over the sea before they make landfall. Aircraft observations equipped with a dropsonde have advanced our understanding of the vertical structure of typhoons and confirmed that the accuracy of typhoon intensity prediction is improved by atmosphere-ocean coupled models, suggesting that information on the ocean, which is the energy source of typhoons, is also essential.

This study presents experimental observations to improve typhoon prediction accuracy and to understand interactions between atmosphere and ocean directly under typhoons. Two Wave Gliders (WGs) equipped with interchangeable sensors were sailed toward the path of an approaching Category 5 typhoon "Hinnamnor" in August 2022 in the north-west Pacific Ocean. Sensors on WGs measured atmospheric pressure, wind, atmospheric and seawater temperature, waves, currents, salinity, and chlorophyll-a concentrations in different parts of typhoons. For Hinnamnor, observations were made at 2 locations 11 km and 100 km from the typhoon's center.

These observations made it possible to clarify changes in various phenomena as typhoons approached and to compare differences in storm characteristics measured by the two WGs. Sea surface pressure in the core of a typhoon is useful as an initial predictor of its intensity. Data assimilation into numerical models and other observations are expected to improve prediction accuracy of typhoon phenomena. Furthermore, simultaneous observations of atmosphere and ocean will also be useful for modeling interactions.

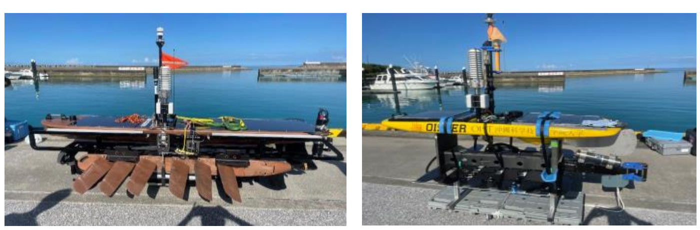

Fig. Observation equipment.
WG/SV3 named "Seiuchi-san" (left) and WG/SV2 named "OISTER" (right).

Impacts of assimilating sea surface observation directly under super typhoon Hinnamnor (2022) in the Northwest Pacific

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It is important to obtain observation over the ocean, to improve typhoon forecast accuracy and to understand typhoon development. Many attempts have been made to observe meteorological conditions near the typhoon centers [1,2], but it is not easy to observe typhoons due to the severe conditions. In 2022, we succeeded in simultaneous observation of the atmosphere and ocean directly under the typhoon Hinnamnor [3].

In this study, we assimilate the observation and forecast with the Weather Research and Forecasting Model's three-dimensional variational data assimilation system (WRFDA for 3DVAR) to see the effect of the observation on improving forecast accuracy.

In the first attempt, we assimilated the observation for the simulation where the typhoon weakened unlike the Japan Meteorological Agency (JMA) analysis, where the typhoon maintained its strength. Then it was found that the resulting pressure drop of 20 hPa approaches the analytical value by assimilating sea level pressure (SLP) and temperature (SLT). However, since in this attempt, the observation is limited at a single point and a single time and the simulation accuracy is low due to the rough resolution, the observation may be overestimated in this assimilation system. The next step is to increase the number of observation points and frequency of data to be assimilated.

Therefore, this time, we would like to assimilate and forecast with both atmospheric and oceanic data at multiple points and multiple times to evaluate the value of our sea surface observation. The results will be compared to the control run and to the JMA Best Track and we discuss the typhoon intensity with the atmospheric pressure obtained by the simulation.

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Atmospheric turbulence observation and simulation in typhoon circulation

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Atmospheric turbulence, characterized by rapid and irregular changes in wind speed and direction, presents significant challenges to aviation, weather forecasting, and simulation. Accurate monitoring and understanding of atmospheric turbulence are crucial for improving flight safety and weather prediction. However, traditional observation methods such as aircraft observations are not suitable for Taiwan, which has complex terrain and terrain compression characteristics. Balloon soundings, on the other hand, cannot provide sufficient spatial and temporal resolution for specific regions. Therefore, we propose the use of unmanned aerial vehicles (UAVs) and research jets as observation platforms to measure the in-situ turbulence in typhoon circulation. UAVs offer flexibility, safety and cheaper solution and maneuverability, allowing them to fly at lower altitudes and in specific regions, collecting real-time in-situ data with high spatial resolution, including aircraft coordinates, inertial navigation data, flight attitudes, and turbulence indicators such as eddy dissipation rate to identify convective regions. The research jets we approach are Gulfstream-100 (ASTRA, AIDC, Taiwan) and Gulfstrea-400 (G-4, DAS, Japan) for tropical storm dropsonde observation. We create a onboard toolkits including a Mateksys FC H743-WLite flight controller unit, and GPS sensor and Mission planner software to record the 50-Hz onboard flight information (latitude, longitude, time, height, pitch/yaw/roll and vertical velocity of aircraft) to estimate the atmospheric turbulence. In addition, we use numerical weather models (WRF) as the environmental base and simulate UAV flights using the X-Plane flight simulator under different weather conditions. Finally, we did an field testing flight experiments 2020 in the Yi-Lan of Taiwan. One UAV combine our toolkits hanged by weather balloon released at 2000m height to played kind of “re-turn” glider recoveried this UAV well. Our toolkits alao took a good testing cases in AIDC-ASTRA jet cabins during Typhoon DOKSURI and any possible typhoon cased in western Pacific Ocean during summer-autumn of 2023. We expect tour toolkit could help us collecting lots of atmospheric turbulence in real typhoon weather condition and to validate the numerical model simulation results.

Optimization of a numerical weather model for the supercomputer Fugaku

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Typhoons and torrential downpours often cause disastrous damage to society. To prevent them, understanding and predicting the mechanisms of these meteorological phenomena is an important social issue at present.

An important method to reveal these mechanisms is the weather simulation. CReSS (Cloud Resolving Storm Simulator) and NICAM (Nonhydrostatic ICosahedral Atmospheric Model) are examples of such simulators. Simulating high-resolution problems is essential for understanding the details of the mechanism and improving prediction accuracy. HPC (High Performance Computing) plays a significant role in executing them. However, there are challenges in computing large-scale weather simulations, such as computational speed, scalability, and data transportation. We are researching technology to enable large-scale weather simulations and use highly efficient computing resources with HPC.

In this study, we conducted performance profiling of CReSS on the supercomputer Fugaku. This mainly includes strong scaling and bottleneck analyses. In terms of strong scale analyses, we confirmed that CReSS has scalability, i.e., increasing the number of computation nodes led to a decrease in computation time. However, the scalability was slower when using more than 16 computation nodes. In terms of the bottleneck analyses, the process of “saturation adjustment” accounted for about 20% and had the maximum computation time among all processes when using intra-node computation. Furthermore, in MPI (Message Passing Interface) communication, the process of “AllReduce” including error information collection accounted for about 80% when using inter-node computation.

As the next step in our research, we will analyze the performance of SCALE (Scalable Computing for Advanced Library and Environment), which adopts similar models to CReSS, and compare them. Additionally, we will identify points for optimizing CReSS and develop novel technology to effectively execute CReSS on Fugaku.

Near landfall intensification of tropical cyclones in the South China Sea: Coastal shallow water responses

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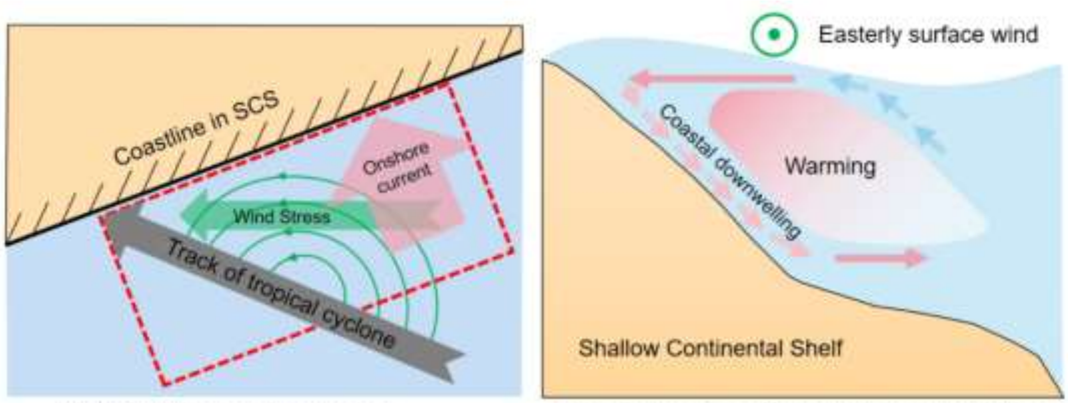
Over a quarter of TCs experienced rapid intensification in the South China Sea (SCS), which is comparatively higher than those in western north Pacific. As most of those intensification occurred over the shallow continental shelf in the northern SCS, it is important to find out the possible favorable oceanic responds during the passage of Near-landfall Intensification (NLI) TCs. The coastal shallow water dynamic and thermal process during the passage of three NLI TCs and other non-NLI ones is studied.

The cooling effect of Sea Surface Temperature (SST) happens after the passage of TCs, while the SST in the forward direction of NLI TCs track is maintaining or even increasing when approaching land. The coastal mixed layer warming along the coastline can be explained by Ekman transport under sustained wind stress under easterly surface winds forcing on the right side of TC tracks. The magnitude of easterly wind stress during the passage of NLI TCs is 3 times more than those without intensification. Successive deepening of coastal boundary layer and increasing warming up of density mixed layer, where the vertical integrated temperature increase up to 0.3℃ on average, could maintain oceanic heating before landfall.

Coastal Ekman transport could favor coastal downwelling to compensate the loss of warm water, indicating the critical importance of coastal ocean dynamics and air-sea interactions.



(a) Horizontal conceptual diagram (b) Vertical cross-coastline section conceptual diagram

Figure. Conceptual diagram of (a) Horizontal and (b) vertical cross-coastline section of shallow water responds during the passage of NLI TCs.The red dashed box is defined as shallow continental shelf area in SCS. The gray thick arrow indicates the prevailing track in the SCS. The green vectors represent the surface wind by TC forcing; Pink vectors and shading areas denotes coastal downwelling and corresponding warming averaged in red dashed box.

The impact of varying SSTs on the track and intensity of Tropical Storm WASHI (2011)

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High sea surface temperatures (SSTs) supply thermodynamic energy to tropical cyclones (TCs). As global SSTs increase, it is essential to understand how SST affects TC track and intensity. This study investigates the effects of changing the SST magnitude over the Philippine Sea (125°E to 150°E and 5°N to 15°N) on the track and intensity of TC WASHI (2011), a catastrophic TC that hit Mindanao Island, southern Philippines, using the Weather Research and Forecasting (WRF) model. This TC exhibited an almost linear and westerly track that passed through warmer than normal waters. Simulations were conducted wherein the SST over the Philippine Sea was adjusted uniformly with the following magnitudes: ±0.5K, ±1.0K, and ±2.0K. The results show that as the SST magnitude increases (decreases), the TC intensity strengthens (weakens), the translational speed increases (decreases), and the track deflects northwards (southwards) when the TC is still on open waters and without topographic interaction. This is attributed to the fact that higher (lower) SST facilitates (impedes) evaporation, which leads to enhanced (reduced) latent heat transfer, condensation, and adiabatic heating. This results in greater (lesser) surface wind circulation, increased (decreased) translational speed, and a stronger (weaker) maximum sustained wind speed of the TC. The impact of SST on the track was further analyzed in terms of potential vorticity (PV) and its tendency (PVT), which was decomposed into its horizontal advection, vertical advection, and diabatic heating components. The results show a larger contribution of the horizontal advection component than the vertical advection and diabatic heating components to the TC track, such that a northward (southward) deflection occurs when SST magnitude increases (decreases). Specifically, the TC tends to move to an area with higher values of the horizontal advection component of the PVT. These findings provide additional insights into the effects of SST variability and future changes on TCs within the Philippine Sea.

Keywords: WRF, Tropical Cyclone, TS WASHI, sea surface temperature, carnot engine, Mindanao Island

Changes in intensity and tracks of tropical cyclones crossing the central and southern Philippines from 1979 to 2020: an observational study

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Observational studies on the characteristics of tropical cyclones (TCs) crossing Mindanao and Visayas Islands, in the southern and central Philippines, respectively, remain limited. To address this research gap, this study investigates the changes in the translational speeds, the direction of motion, and intensities of 8 and 39 landfalling TCs crossing Mindanao and Visayas Islands, respectively, from 1979 to 2020. The intensities, translational speeds, and direction of motions of the TCs were characterized by their position before (approaching point; AP), during (landing point; LP), and after (departing point; DP) traversing through Mindanao and Visayas Islands. The results show a significant linear relationship in the intensity change between AP and DP, indicating a general weakening of TCs as they traverse both island groups. About 5 (29) TCs showed a decrease in intensity based on the maximum sustained wind speed (MSW) after crossing Mindanao (Visayas). The intensity of TCs with at least Typhoon category upon landfall, decreased on average (percentage) by about 23.33 kts (− 25.4%) and 24.29 kts (− 45.5%) after crossing Mindanao and Visayas, respectively. The MSW of weaker TCs decreased on average by about 6.67 kts (− 25.0%) and 8.13 kts (− 20.5%) after traversing Mindanao and Visayas, respectively. Cases with increased (1 TC for Mindanao and 6 TCs for Visayas) and no change in intensities (2 TCs for Mindanao and 4 TCs for Visayas) after crossing the island were also found. Landfalling TCs over Mindanao exhibited a characteristic where those defected rightward (leftward) at AP tend to be defected rightward (leftward) at DP, while no pattern was found for the TCs traversing Visayas. Furthermore, TCs moving across Mindanao and Visayas tend to decelerate as they approach and move away from the island. The findings of this study are essential for disaster mitigation and a greater understanding of the TCs behavior in terms of intensity, translational speed, and defection.

Numerical simulation of topographic influence on the heavy rainfall of Typhoon Rammasun

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The heavy rainfall caused by Super Typhoon Rammasun (2014), the strongest typhoon that has landed in China since meteorological records began, has caused huge economic and social losses to China. Preliminary analysis showed that the intensity and area of the rainfall were closely related to Wuzhi Mountain, China. However, the physical mechanisms need to be analyzed in depth. Using the WRF V3.9 model, a high-resolution numerical simulation of topographic influence on the heavy rainfall of Typhoon Rammasun was carried out. The results show that the topographic rise significantly weakened the rainfall intensity and changed the location of the heavy rainfall center of Typhoon Rammasun. If the topography of Hainan Island increased to twice the original altitude, the maximum daily rainfall caused by Rammasun decreased by 35.2%, and the heavy rainfall center shifted from western Hainan Island (WHI) to southwestern Hainan Island (Fig. 1).

On one hand, the topographic rise increased the friction of the topography and weakened the intensity of Rammasun, resulting in a weaker rainfall in WHI (the observed heavy rainfall center). On the other hand, the topographic rise changed the structure of Rammasun. The control experiment showed that the heavy rainfall in WHI was mainly caused by meso-micro scale systems on an outer spiral cloud belt of Rammasun. If the altitude rose, the low-level convergence and the mid-low level ascending movement in WHI were weakened, making it difficult to form long-lasting, quasi-stationary meso-micro scale systems, eventually leading to the rainfall center transferring to southwestern Hainan Island.

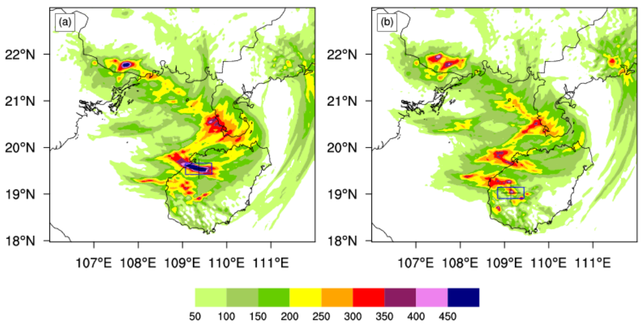

Fig. 1 The simulated daily rainfall of Typhoon Rammasun on 19 July 2014 in domain 1 (unit: mm, The black crosses in (a) and (b) represent the heaviest rainfall position of CTRL (P1) and that of SEN2 (P2), respectively. The rectangular boxes in (a) and (b) represent the heaviest rainfall area of CTRL (A1) with P1 as the center and that of SEN2 (A2) with P2 as the center, respectively.)
(a) CTRL experiment; (b) SEN2 experiment

Tropical cyclone wind field reconstruction for hazard estimation via Bayesian hierarchical modeling

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Tropical cyclones (TCs) are one of the biggest threats to life and property around the world. Usually, TC wind hazard is quantified in terms of return periods/levels of wind fields. Accurate estimation of TC wind hazard, especially for extreme TC wind, requires estimation of catastrophic TCs having a very low occurrence probability, or equivalently a very long return period spanning up to thousands of years. Since reliable TC data are available only for recently decades, stochastic modeling and simulation turned out to be an effective approach to achieve more stable hazard estimates, particularly for regions where little or no historical TC records exist.

The common practice consists of two stages. The first stage is to fit a basin-wide TC full-track model to TC track data, to generate hundreds of thousands of synthetic TCs that can make up for the sparseness of TC observations while still complying with the statistical characteristics of the observed TCs. The second stage is to couple these synthetic TCs with TC wind field models, either to simulate landfall TC wind fields for wind hazard estimation, or to further drive storm surge models for coastal flood hazard estimation. The performance of the synthetic TCs is crucial to the subsequent hazard estimation. The authors have developed a novel approach to the full-track TC modeling and simulation via multivariate functional principal component analysis (Yang et al. 2021), which shows high performance and high efficiency for the first-stage task.

Here, we present a Bayesian hierarchical modeling approach to TC wind field reconstruction to fulfil the second-stage task, based on synthetic TCs generated from the first stage. The reconstructed TC wind fields are ready for hazard estimation. Through this and our previous works, we have completed a systematic approach to TC wind hazard estimation. As an illustration, we applied our approach to western North Pacific basin yielding a 10,000-year TC wind field series, and estimated TC wind hazards for China coastal cities and offshore waters. Our proposed approach has the following advantages:

- From full-track simulation to wind field reconstruction, only minimal dataset, i.e. the TC best-track data, is used throughout our approach, whose sources are usually stable and consistent.
- Only one single model is used for each stage task, so that aspects of a synthetic TC and its wind field are consistent with each other, and correlations between them are considered.
- Our approach is computationally efficient and can run on a modern desktop PC, therefore the turnaround time can be greatly reduced, especially when newly available TC data are incorporated periodically into the model, so that it can be used for various purposes relating to TC wind hazard estimation.

Yang C, Xu J, Yin J. (2021). Stochastic Simulation of Tropical Cyclones for Risk Assessment at One Go: A Multivariate Functional PCA Approach. *Earth and Space Science*, 8(8). https://doi.org/10.1029/2021EA001748.

Impacts of Typhoons, Western Pacific Subtropical Highs, and Upper-Level Jets on a predecessor rain event in Central China

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Based on high-resolution WRF simulation results, this study mainly utilizes the Piecewise Potential Vorticity Inversion (PPVI) method to quantitatively analyze the influence of Typhoon "In-Fa" (2021), the Western Pacific Subtropical High (WPSH), and the Upper-Level Jet Stream (ULJ) on a predecessor rain event (PRE) in Central China. The patterns of the WPSH, Typhoon "In-Fa", ULJ and precipitation are well reproduced in the control experiment (CTL). The magnitude of potential vorticity anomaly associated with the WPSH (Typhoon "In-Fa") is increased and decreased by 50% in the initial condition based on the PPVI method, namely SH150 and SH050 (TC150 and TC050), respectively. The analysis shows that the 54-h rainfall accumulations in TC150 and TC050 are reduced by 39.5% and 31.8% compared to CTL, respectively, more than 28.8% in SH150 and 20.1% in SH050, indicating that Typhoon "In-Fa" plays a more critical role in the rainfall amplification than the WPSH. This result also confirms that this PRE occurs within the quite favorable configuration of WPSH and Typhoon "In-Fa" circulations. The WPSH and Typhoon "In-Fa" majorly control the meridional and zonal moisture transports, respectively. The diagnosis of moist ageostrophic ω turns out that diabatic heating is closely related to the vertical motion during this PRE. Besides, the heavy rainfall region is also closely attributed to the distributions of equivalent potential temperature and divergence.

Additionally, we also discussed the implications of ULJ for this PRE. In the sensitivity experiment (NOULJ), the ULJ is largely suppressed by mitigating the adjacent upper-level troughs and ridges according to the PPVI method. As a result, the upper-level divergence, secondary circulation, lower-level jet (LLJ), and precipitation in NOULJ are weaker than those in CTL. A forward trajectory analysis further indicates that the secondary circulation is suppressed in NOULJ, mainly due to the weakening of upper-level pumping effect. The 54-h accumulated rainfall in NOULJ is 31% lower than that in CTL, which can be attributed to three facets: 1) the moisture accumulation is majorly controlled by wind convergence, which is closely related to the ULJ and LLJ; 2) the upward motion is primarily organized by the thermally direct secondary circulation on the right-entrance region of ULJ, with a minor contribution from the baroclinic trough; 3) the atmosphere instability and slantwise vorticity development are weakened in NOULJ.

Tropical cyclone induced remote precipitation over Yangtze River Basin during the last stage of Meiyu Period

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1. Introduction

The precipitation associated with a tropical cyclone can be broadly classified into two primary categories: precipitation induced by the TC's circulation, and Tropical Cyclone Remote Precipitation (TRP). Under favorable atmospheric conditions, it has been discovered that the interaction between TC with mid-latitude weather systems tends to result in substantially higher levels of precipitation than those produced solely by the TC body circulation, which has become one of the most important forms of summer rainstorm in mid-latitude regions. This study will focus on a significant rainstorm event took place towards the end of the Meiyu season in 2016 over the Yangtze river basin (YRB) in China, which potentially influenced by Typhoon Nepartak and recognized as a TRP event.

2. Data & Method

The NCEP FNL data were prepared operationally produced every six hours and consist of 1°x1° grids. The numerical simulation was conducted using WRF-ARW v4.4. Typhoon best track data are provided by JMA and JWTC. The CMORPH data was utilized for the systematic evaluation and validation of simulated precipitation results. China Ground station dataset were employed to observe the intensity of precipitation over YRB. We applied the TC isolation and removal algorithm on the WRF run to further investigate the remote effect of TC. The anomalous features were removed using the following 9-point smoothing operator.

3. Results

Around July 6th, extreme precipitation occurred over Wuhan and part of Anhui Province over YRB in China. To further investigate characteristics of TRP process, we utilized the WRF model for numerical simulation experiment. The following analysis are based on the simulation results.

The moisture over rainfall area supplied by two moisture channels from the south China sea and the Pacific to the rainfall area, which is primarily driven by TC Nepartak and West Pacific Subtropical High circulation. Over the rainfall area, a distinct correlation can be discerned with positive Moisture Flux Convergence (MFC) region.

Following the removal of the TC, a marked reduction in precipitation was observed within the rainfall region (Fig.1 (a)). While the effects of the TC were not entirely eliminated, the precipitation over YRB still significantly decreased by approximately 25%. Accompanied by this, though the moisture channel hasn't change, the MFC was substantially reduced over YRB and two moisture channels (Fig.1 (b)). The removal of the TC led to an increase in geopotential height on the southwest and south flank of the WSPH, resulting in a corresponding weakening of the wind fields. Such change significantly reduced the transport of moisture towards the YRB direction resulting in the decreasing of precipitation.

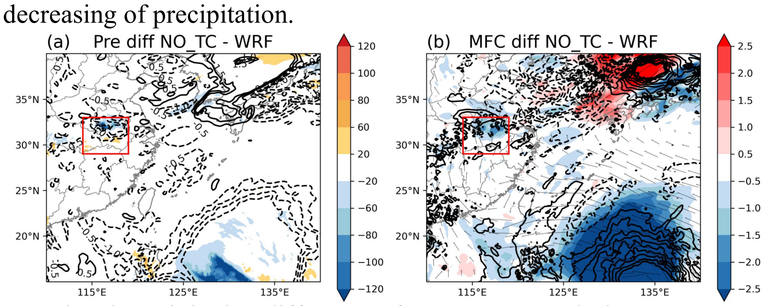

Fig.1 Accumulated precipitation difference of NO_TC – F06 during TRP **Contour**: MFC difference (b) Vertical integrated MFC difference of NO_TC – F06 at peak time of rainfall **Arrow**: Moisture flux in NO_TC run **Contour**: Geopotential height difference

The association of West Pacific subtropical high with Typhoons over the western North Pacific Ocean and its impact on Indian summer monsoon rainfall

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The present study examined the interrelationship between the Indian summer monsoon (ISM) rainfall, west Pacific subtropical high (WPSH) and Tropical cyclone (TC) activity over the western north Pacific (WNP) Ocean during the peak summer monsoon season in 1951-2019. When WNP TCs are inactive (active), there is a noticeable 10° westward (eastward) shift observed in intense (weakened) WPSH. The WPSH and WNP TC activities divided into four categories: Eastward shift of WPSH with active TCs (EA) and inactive TC (EI), westward shift of WPSH with active TCs (WA) and inactive TCs (WI) in order to investigate the combined influence of WPSH and WNP TCs on ISMR during NonENSO. In EA, surplus (deficit) rainfall noticed over the central (southern peninsular) India as result of moderate cold PDO pattern and moisture convergence (low CAPE, abnormal moisture divergence and downdraft). The eastward shift of WPSH and inactive WNP TCs during NonENSO helps to increase (decrease) the regional convective activity over east central India and parts of north India (southern peninsular India) through regional changes in atmospheric circulations and mid-tropospheric vertical velocity. In contrast, westward shift of WPSH along with inactive (active) TCs, the majority of India (southern peninsular and northeast India) experiences excessive precipitation while east central India (east and west central India) undergoes deficit rainfall in WI (WA) cases. These rainfall patterns are consistent with spatial distribution of moisture flux convergence, CAPE and mid-tropospheric vertical velocity over the region. In the cases of NonENSO, the westward shift of WPSH associated with inactive TCs is a more favourable condition for ISMR than active TCs.

Quantification and attribution of ocean cooling induced by the passages of Typhoons Faxai (2019) and Hagibis (2019) over the same region using a high-resolution ocean model and cooling parameters

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A typhoon develops by receiving thermal energy from the ocean. It is also known that the sea surface temperature (SST) decreases with the passage of typhoons, which is important to predict typhoon intensity. In this study, we quantitatively evaluated the typhoon-induced SST cooling caused by typhoons Faxai (2019) and Hagibis (2019) using a high-resolution ocean model (Tanaka et al., 2018) and the cooling parameter (Co) proposed by Miyamoto et al. (2017).

Co is a non-dimensional number that theoretically indicates the magnitude of SST cooling during the passage of a typhoon. The model is based on the ocean general circulation model MRI.COM Ver. 4.7 (Tsujino et al., 2017). The horizontal resolution is $1/60^{\circ}$ and the vertical is 35 layers.

Faxai and Hagibis both passed over the same ocean region south of Japan with similar tracks, but the associated average SST cooling differed. Mean SST cooling by Faxai was less than 2 degrees, while Hagibis was more than 2 degrees. The average Co value was 1.6 for Faxai and 3.6 for Hagibis, indicating that SST was more easily cooled by Hagibis than by Faxai. This is consistent with the observations. In the impact of ocean conditions in Co, Hagibis was 2.6 times larger than Faxai. It indicates that the ocean before Hagibis passes is less hard to cool ocean than Faxai. In short, it is important for ocean cooling not only ocean conditions but also typhoon characteristics because in fact, Hagibis cooled the ocean more than Faxai. In addition, the impact of typhoon characteristics in Hagibis was 4.8 times larger than in Faxai. Thus, SST was more likely to cool by typhoon characteristics in the case of Hagibis. Especially, typhoon size in the horizontal direction had the most efficient effect on SST cooling.

Therefore, Co can estimate the effects of typhoon characteristics and ocean conditions separately. This study quantitatively shows differences in the attribution of typhoon-induced SST cooling caused by Faxai and Hagibis. We propose that Co is a practical indicator for estimating SST cooling caused by a typhoon and comparing factors of typhoon-induced SST cooling in multiple cases although Co does not consider the effects of upwelling and advection.

Rainfall strength and area from landfalling tropical cyclones over the North Indian and western North Pacific oceans under increased CO2 conditions

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To understand the characteristics and changes in rainfall associated with landfalling tropical cyclones (TCs) from various perspectives, several studies have been conducted: 1) examining the characteristics and future projections of TC-induced rainfall in the North Indian Ocean (NIO) and western North Pacific (WNP), 2) investigating the influence of environmental factors on TC-induced rainfall and its future changes in the NIO, and 3) exploring the impact of environmental factors on TC-induced rainfall and its future changes in the WNP.

Firstly, the rainfall characteristics of TCs were divided into rainfall strength (RS) and rainfall area (RA). Currently, the WNP exhibits higher intensity and larger area of TC-induced rainfall compared to the NIO. Moreover, the changes in rainfall characteristics under different scenarios of increasing carbon dioxide (CO_2) varied across different regions. Particularly, in the NIO, there was a greater increase in RS, while in the WNP, the RA showed a larger increase. This indicates that TC-induced rainfall and the associated environmental conditions differ between regions.

Secondly, the temporal and spatial relationships between TC-induced rainfall and environmental variables were examined in the NIO, focusing on the pre- and post-monsoon periods and dividing the region into the Arabian Sea and the Bay of Bengal. Regardless of the region, there was a close relationship between TC intensity and RS. It was observed that the frequency of TCs in the Arabian Sea. These findings suggest an increased risk due to the higher frequency and intense RS associated with TCs in the Arabian Sea, highlighting the need for appropriate measures.

Lastly, in the WNP, the temporal analysis revealed that TC-induced rainfall predominantly occurs from July to October, while the spatial analysis divided the region into the South China Sea and East Asia. In terms of RA, all environmental variables showed significant relationships in the South China Sea, while in East Asia, mid-level relative humidity was not a significant factor and vertical shear played a particularly important role. This highlights the importance of understanding the regional variations and mechanisms that regulate TC-induced rainfall in the WNP.

In conclusion, the studies provide insights into the characteristics and changes in precipitation associated with landfalling TCs in the NIO and WNP from different perspectives. The findings emphasize the need to improve our understanding of the regional factors that modulate TC-induced rainfall. Furthermore, considering the potential risks associated with increased TC frequency and intense rainfall, appropriate measures and policies should be developed for effective management and response within the affected regions.

Risk assessment for sediment disaster using Typhoon Path Ensemble Simulation

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With the increasing risk of disasters due to climate change, there is an urgent need for local governments and companies in Japan to establish measures to mitigate disaster risks. However, the experience of local governments in disaster prevention largely depends on past disaster experiences, and there is a need to support disaster reduction awareness in municipalities that have not experienced major disasters in the past through unconventional approaches. The purpose of this study is to create a time-series data of alert and warning information related to virtual sediment-related disasters based on the Typhoon Path Ensemble Simulation (TPES, Yamasaki et al., 2017), which is an ensemble dataset that simulates the shift of typhoon paths from east to west for 30 real typhoon cases.

The TPES precipitation data, with a horizontal grid size of 5 km and a time interval of 30 minutes, are converted to a 1 km grid size with a time interval of 10 minutes, similar to the analyzed rainfall. In addition, a frequency bias correction is applied to adjust the occurrence frequency of extreme precipitation values. A newly implemented serial three-tank model, similar to the one used by the Japan Meteorological Agency developed by Ishihara and Kobatake (1979), is used to calculate the soil-water index values from precipitation data. The soil-water indexes are converted to (virtual) Landslide Risk Map.

There are differences in the occurrence frequency of extreme precipitation between the rainfall data calculated using the numerical weather model WRF in Typhoon Path Ensemble Simulation and the Radar-AMeDAS rainfall. To minimize the impact of these differences, the frequency bias correction method (e.g., Matsushita, 2012) is applied based on the historical data of the Japan Meteorological Agency's MSM rainfall from October to March between 2011 and 2020, which has a comparable resolution to TPES despite being a different model. The Radar-AMeDAS rainfall was converted to a 5 km mesh following Urita et al. (2011). The cumulative frequency for thresholds of precipitation was calculated for both the Radar-AMeDAS rainfall and MSM. The precipitation in MSM and TPES is corrected following the corresponding cumulative frequency of the Radar-AMeDAS precipitation

We compared the maximum soil-water index during Typhoon Hagibis event in 2019 between the analysis, the simulation of TPES with and without the frequency bias correction. It seems that TPES underestimates the soil-water indexes compared to the analysis, while the bias-corrected TPES appears to be closer to the analysis. We also found the frequency bias correction works well in other Typhoon cases.

In the future, we plan to apply Typhoon Path Ensemble Simulation to various fields related to risk management, such as the formulation of business continuity plans (BCPs) for private companies and/or local governments. It is also possible to create the multi-hazard index data, including virtual flood and inundation hazards based on the Typhoon Path Ensemble Simulation, which will be a future work.