AAS01-01 Room:101A Time:May 23 09:00-09:25

# An Ocean Cooling Potential Intensity Index for Tropical Cyclones

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Timely and accurate forecasts of tropical cyclones (TCs, i.e. hurricanes and typhoons) are of great importance for risk mitigation. Though in the past two decades there has been steady improvement in track prediction, improvement on intensity prediction is still highly challenging. Cooling of the upper ocean by TC-induced mixing is an important process that impacts TC intensity. Based on detail *in situ* air-deployed ocean and atmospheric measurement pairs collected during the Impact of Typhoons on the Pacific (ITOP) field campaign, we modify the widely used Sea Surface Temperature Potential Intensity (SST_PI) index by including information from the subsurface ocean temperature profile to form a new Ocean Cooling Potential Intensity (OC_PI) index. Applied to a 14-year (1998-2011) western North Pacific TC archive, OC_PI reduces SST_PI-based overestimation of archived maximum intensity by more than 50% and increases the correlation of maximum intensity estimation from $r^2$=0.08 to 0.31. For slow-moving TCs that cause the greatest cooling, $r^2$ increases to 0.56 and the root-mean square error in maximum intensity is 11 $ms^{-1}$. As OC_PI can more realistically characterize the ocean contribution to TC intensity, it thus serves as an effective new index to improve estimation and prediction of TC maximum intensity.

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# Maximum potential storm surge under the present and future climates estimated by a coupled TC-ocean model

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Recently, there is growing concern that the average intensity of global tropical cyclones (TCs) is likely to be enhanced by the warmed sea surface in the future climate. According to the IPCC AR4 report, future-climate TCs possibly cause more serious disasters such as high wind, high wave and storm surge. To evaluate the TC-induced disasters with high-resolution grids, 2-dimensional TC models, which are typically based on empirical, statistical and parametric approaches, are used traditionally. However the 2-dimensional TC model is not capable of being applied to the future climate scenarios, because such an empirical approach is not necessarily consistent with TCs under the future climate scenarios. Therefore it is necessary to substantially revise the traditional methods and to improve our understandings of the maximum potential storm surge spawned by future-climate TCs.

In this study, we develop a fully dynamic algorithm for estimating the potential maximum storm surge under the present and future climates. The algorithm mainly consists of two essential components: 1) dynamic TC initialization and 2) dynamic storm surge estimation. The first component is aimed at initializing atmospheric conditions dynamically for an atmospheric model using the TCPV bogussing scheme, which is based on the combination of an axisymmetric TC model and an Ertel's potential vorticity inversion technique. The axisymmetric TC model, developed by Emanuel (1985), is intended to dynamically estimate the axisymmetric potential vorticity structure inside of a well-developed TC reaching to the maximum potential intensity under the present and future climate conditions. The Ertel's potential vorticity inversion, developed by Davis and Emanuel (1991), is used to inversely convert from the obtained potential vorticity fields to the initial atmospheric fields (wind vector, temperature, and geopotential height), which can be estimated to satisfy both of the dynamic and thermodynamic equilibriums. The TCPV bogussing scheme can arbitrarily control initial positions of TCs, resulting in controlling TC tracks in the atmospheric model, and is able to be adapted to a variety of situations in any region and in any climate by reasonably modifying the mean and/or anomalous potential vorticity fields in TC environment. The second component is aimed at dynamically simulating the storm surge height using a coupled TC-ocean model, which is based on MM5 (Dudhia, 1993) and CCM (Murakami et al., 2004). Initializing many TCs with many slightly different positions, the coupled model enables us to evaluate the maximum potential storm surge induced by a well-developed and worst-hit TC striking the target area.

A number of numerical experiments are conducted at 9km resolution, in which Typhoon Vera (1959) reaching a maximum potential intensity of about 910hPa (SST= 29.0 degree C) is initialized with many slightly different positions. Results indicate that the maximum potential storm surge at the port of Nagoya proves to be +4.5m MSL which exceeds the historical record (+3.5m MSL) brought by Typhoon Vera. On the other hand, to evaluate the climate change impact on storm surge, the Typhoon Vera's environment is modified based on the CMIP3 multi-model ensemble of the SRES A1B emission scenario. The TCPV bogussing scheme shows a maximum potential intensity of about 880hPa (SST=30.2 degree C) under the future-climate environment. The projected maximum storm surge at the port of Nagoya is expected to increase to +6.5m MSL in the late 21st century as a result of the global warming, indicating that the existing coastal facilities are insufficient to meet future needs for disaster prevention (see Figure).

Keywords: tropical cyclone, storm surge, climate change, TCPV bogussing scheme, TC-ocean coupled model

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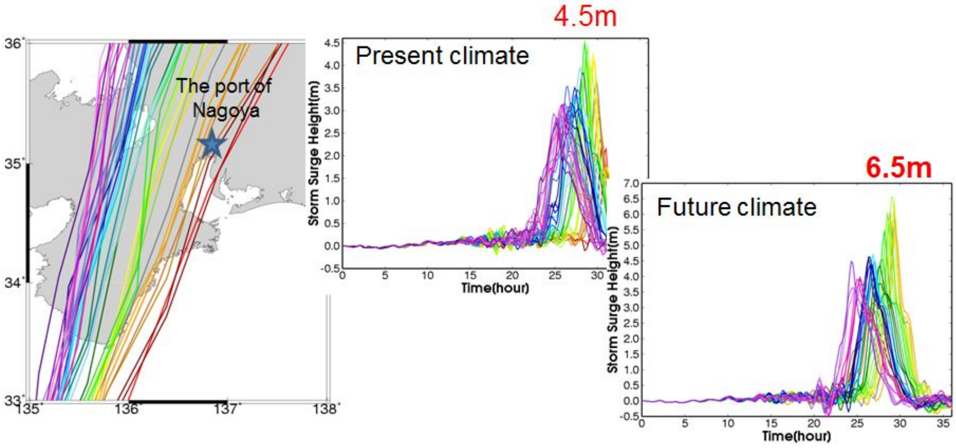

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AAS01-03 Room:101A Time:May 23 09:45-10:00

# A transition mechanism for the spontaneous axisymmetric intensification of tropical cyclones

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A mechanism for the transition of tropical cyclones (TCs) to the spontaneous rapid intensification (RI) phase is examined using a three?dimensional full?physics model. The rapid intensification phase of the simulated TC is divided into three sub?phases according to the rate of intensifition: I) a slowly intensifying phase, II) a RI phase, and III) an adjustment phase toward the steady state. The evolution of a TC vortex is diagnosed by the energy budget analysis and using a parameter representing the degree of axisymmetric structure of the TC vortex, and the simulated TC is determined to be axisymmetrized 12 h before the onset of RI. It is found that equivalent potential temperature in the lowest layer suddenly increases inside the radius of maximum wind (RMW) after the TC becomes axisymmetric. The forward trajectory analysis revealed that the enhanced convective instability in the TC core region where the eyewall subsequently forms results from the increased inertial stability. Since fluid parcels remain longer inside the RMW owing to the increased inertial stability of the TC core, the parcels obtain more enthalpy from the underlying ocean. As a result, low?level equivalent potential temperature and hence convective available potential energy (CAPE) increase. Under a suitable condition (i.e., large CAPE) for the formation of eyewall, the convergence of the low?level inflow becomes larger owing to the enhanced secondary circulation; this process is considered to be the trigger of RI in agreement with the previous study. As the inertial stability becomes large, the condensation around the TC core effectively enhances the primary circulation as well as CAPE inside the RMW. Thus, the positive feedback works until the TC goes into the RI phase.

Keywords: tropical cyclone

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# Analysis of tropical cyclone warm core structure by using the Advanced Microwave Sounding Unit (AMSU) data

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A warm core, defined as the central area of a tropical cyclone (TC) warmer than the surrounding area, is a characteristic feature for TC identification and is physically related to the minimum sea level pressure (MSLP). Intensification of the warm core is related to the decrease of MSLP due to the latent heat release caused by convections in the TC. In addition, adiabatic heating by air subsidence inside the eye contributes to the intensification of the warm core. To capture the characteristics of TC warm core, this study uses the 55-GHz band brightness temperature (TB) data of the Advanced Microwave Sounding Unit-A (AMSU-A) for TCs in the Western North Pacific basin.

Investigations on the warm core intensity defined as the maximum TB anomaly showed that the correlation coefficient between the warm core intensity and the best track MSLP of the Japan Meteorological Agency was +0.91 for TCs in 2008. Further, MSLPs were estimated from the warm core intensity for TCs in 2009 - 2011 by the estimation equation derived from AMSU-A data and the best track MSLP for TCs in 2008. The validation of the MSLP estimates showed that the accuracy to the best track MSLP is 8.55 - 11.66 hPa in root mean square error and -0.48 - +2.67 hPa in bias.

We also focused on the evolution of a warm core height and intensity using temperature profiles analyzed from AMSU-A TB data and the Cooperative Institute for Research in the Atmosphere (CIRA) algorithm (Demuth et al. 2004). In addition to the intensification of warm core with the decrease of MSLP, this study revealed that the warm core height depended on the TC life stage. For example, the height of warm core for Typhoon Talas (2011) shifted upward from the developing stage to the mature stage, and downward from the mature stage to the decay stage. We will discuss the influences of environment (sea surface temperature, vertical wind shear, and so forth) on this warm core structure change.

Reference:

Demuth, J. L., M. DeMaria, J. A. Knaff, and T. H. Vonder Haar, 2004: Evaluation of Advanced Microwave Sounding Unit tropical-cyclone intensity and size estimation algorithms. J. Appl. Meteor., 43, 282-296.

Keywords: tropical cyclone, warm core, satellite observation

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# Including uncertainties of sea surface temperature in an ensemble Kalman filter

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Sea-surface temperature (SST) plays an important role in tropical cyclone (TC) lifecycle evolution, but often the uncertainties in SST estimates are not considered in the ensemble Kalman filter (EnKF). The lack of uncertainties in SST generally results in the lack of ensemble spread in the atmospheric states near the sea surface, particularly for temperature and moisture. In this study, the uncertainties of SST are included by adding ensemble perturbations to the SST field, and the impact of the SST perturbations is investigated using the local ensemble transform Kalman filter (LETKF) with the Weather Research and Forecasting (WRF) model in the case of Typhoon Sinlaku (2008).

Keywords: data assimilation, ensemble Kalman filter, sea surface temperature

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# Intensity of typhoons in the western North Pacific: numerical experiments with atmosphere-ocean coupled models

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Intensity of tropical cyclones (TCs) greatly depends on the sea surface temperature (SST) distribution. Cold SST distribution is observed locally around the track of a TC passing, which is produced by mixing/upwelling in the upper layer in the ocean. In numerical experiments utilizing with atmosphere-ocean coupled models, local decrease of the SST after TCs passing is simulated with representing mixing/upwelling in the ocean, resulting in suppression of the minimum central pressure of TCs, one of the indexes of the intensity of TCs. Suppression of the intensity is apparent in the TCs of slow moving. On the other hand, the ocean itself has currents. The SST decreasing in a TC passing is recovered and canceled by strong warm horizontal ocean currents, which leads to less suppression of the intensity of the TC.

In this study, the intensity change of TCs with air-sea interaction was investigated in the western North Pacific, where local warm SST distributes around Kuroshio currents. Numerical experiments were performed utilizing with atmosphere-ocean regional coupled/non-coupled model; slab ocean model was for one-dimensional ocean coupled experiments and CReSS-NHOES was for three-dimensional ocean coupled experiments. In the comparison of the results, remarkable differences of intensities resulting from air-sea interaction were represented, with successfully simulating typical structures of typhoons. The magnitude of the central pressure deepening in the mature stage was not always more suppressed in the three-dimensional ocean coupled experiment including upwelling, compared to that in a slab ocean experiment of one-dimensional vertical mixing heat transfer in the ocean upper layer around the strong Kuroshio currents, which suggested heat supply by the warm horizontal currents.

We will discuss intensity change of TCs (typhoons) in the western North Pacific in focusing three-dimensional air-sea interactions around the Kuroshio currents.

Keywords: Typhoon, Tropical cyclone, Air-sea interaction, Atmosphere-ocean coupled model, Cloud resolving mesoscale regional model, Numerical experiment

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# Kuroshio variations in the northeast of Taiwan associated with typhoon revealed by ocean radar and numerical model

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The Kuroshio flows northward east of Taiwan, and then turns to northeastward along shelf edge in the northeast of Taiwan. The Kuroshio in the northeast of Taiwan fluctuates with various time-scales. Seasonally, the Kuroshio flows along the shelf edge in summer and moves shoreward in winter. Shoreward movement of the Kuroshio in winter is considered to be related with northeast monsoon or winter cooling. Previous studies reported that the Kuroshio northeast of Taiwan varies with a time-scale of several tens of days. The Kuroshio axis movement around Taiwan associated with typhoon passage also reported by some studies. The mechanism of the Kuroshio axis movement due to typhoon passage has been continued to be a matter of discussion. In the present study, we investigated the Kuroshio axis variation associated with typhoon passages using the Long Range Ocean Radar data from 2001 to 2008. In addition, we conducted numerical experiment for the case of two typhoons by mean of an ocean-atmosphere coupled model.

We made daily Kuroshio axis data from sea surface current vectors observed by the Long Range Ocean Radar data. We examined relationship between typhoon passage and the Kuroshio axis variation for 23 typhoons during observed period. At 7 typhoons, the Kuroshio axis moved shoreward after typhoon passages. Comparing wind variation with the Kuroshio axis variation for the cases of the Kuroshio axis moved or not, we could not see characteristics in common. However, it was found that typhoon moved from east to west around Taiwan when the Kuroshio axis moved shoreward.

We coupled both CReSS (Cloud Resolving Storm Simulator) and NHOES (Nonhydrostatical Ocean Model for Earth Simulator) to reproduce the Kuroshio axis movement associated with typhoons Hai-Tang in 2005 and Morakot in 2009. The paths of the typhoons calculated were consistent well with those observed. Model wind at Yonaguni Island was a little stronger than observation, but tendency of variation was almost the same each other. The Kuroshio flowed north-eastward along shelf edge in the model before typhoon approach, and then the Kuroshio axis changed the direction to the north. Our model well reproduced phenomena around northeast of Taiwan during typhoon Hai-Tang. It was suggested from the numerical model result that the Kuroshio axis movement to the north associated with typhoon passage is caused by a negative vorticity supplied to the shelf due to Ekman transport and water mass with low water temperature transport from subsurface in the Kuroshio region to the shelf by coastal upwelling.

Keywords: Kuroshio, Typhoon, Ocearn Radar, Numerical Model

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# Structural Changes of a Tropical Cyclone Moving across the Oceanic Frontal Zone in the Southern East China Sea

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Many of the tropical cyclones (TCs) that reach in midlatitude baroclinic zones change their structure into that characteristic of extratropical cyclones. This process, called extratropical transition (ET), has been discussed in many studies with particular focus on structure changes of TCs that occur in deep baroclinic zones associated with midlatitude westerly jets. Possible influence on ET that can be exerted by strong SST gradient associated with a midlatitude oceanic frontal zone has been overlooked, despite the importance of a near-surface baroclinic zone anchored by an oceanic front for the development of extratropical cyclones, as pointed out recently. However, an oceanic frontal zone and a westerly jet are often collocated, which makes it difficult to distinguish their individual effects on structure changes of TCs. To overcome this difficulty, this study investigates a particular TC, typhoon Songda (T1102), that approached an early-summer oceanic frontal zone in the southern East China Sea far south of a westerly jet, with particular focus on the influence of its frontal SST gradient on the thermal structure of the TC within the planetary boundary layer (PBL). The investigation is based on the JMA meso-scale analysis (MANAL), in addition to, a control and two sensitivity experiments with modified SST gradient performed with a cloud-resolving model (CReSS). One of the sensitivity experiments was conducted with a particular SST distribution that had been obtained by applying meridional running mean with 10 degree width to the high-resolution SST distribution used for the control experiment, while the other uses another SST distribution that had been obtained by applying zonal averaging further to the smoothed distribution used for the former sensitivity experiment.

MANAL reveals that zonal asymmetry in thermal structure emerges first in PBL mainly within the western outer region of the TC in the vicinity of the oceanic frontal zone, which precedes the emergence of deeper asymmetric structure within the deep baroclinic zone associated with the westerly jet. The near-surface asymmetric structure is caused by cold advection with TC-associated northerlies acting on persistent air temperature gradient that is maintained through sensible heat exchanges with the underlying ocean. In the upper portion of PBL, the corresponding cold advection is contributed to also by air temperature gradient kept intensifying nonlinearly with the cold advection.

Although all the CReSS experiments well represent the TC approaching the oceanic frontal zone, the degree of the zonal asymmetry in thermal structure of the TC within PBL is found sensitive to the strength of the SST gradient prescribed at the model boundary. Specifically, the enhancement of near-surface air temperature gradient by stronger SST gradient in the control run yields stronger cold advection and thereby stronger cold anomaly in the western outer region of the TC than in the sensitivity experiments. The results of the present study indicate particular importance of SST distribution assigned to a numerical model in reproducing a TC.

Keywords: Extratropical transition, Oceanic frontal zone, East China Sea, Planetary boundary layer, Data analysis, Numerical experiment

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# Typhoon-driven variations of phytoplankton and bacterial production in the coastal waters of Sagami Bay, Japan

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Variations of physical and chemical environments, and responses of phytoplankton and bacterial communities after the passage of typhoon Malou (T1009) in the coastal water of Sagami Bay, Japan, were investigated in order to clarify the effect of a typhoon passage on the temperate coastal ecosystem. Water temperature, salinity, nutrients (dissolved inorganic nitrogen; DIN, phosphate and silicate), dissolved organic carbon (DOC), chlorophyll *a* (Chl *a*), primary production (PP), bacterial abundance (BA) and bacterial production (BP) were measured. Malou approached the study site in Sagami Bay on 8 September 2010 and induced large-scale terrestrial runoff, which led to decrease in salinity to 22.1. Simultaneously with decrease in salinity, concentrations of inorganic nutrients and DOC increased (DIN = 22.4 uM, phosphate = 1.05 uM, silicate = 61.6 uM and DOC = 3.1 mg C $L^{-1}$), which were more than 3 times higher than the average concentrations of the study site in summer. BP and BP/BA showed relatively fast responses to the passage of Malou reaching maximums of 132 mg C $m^{-3}$ $d^{-1}$ and $13.3*10^{-8}$ ug C $cell^{-1}$ $d^{-1}$ two days after the passage of Malou, respectively. BA increased gradually reaching a maximum of $2.84*10^{9}$ cell $L^{-1}$ six days after Malou passage. PP/Chl *a* was relatively low just after passage of Malou, and reached a maximum of 184 mg C [mg Chl $a]^{-1}$ $d^{-1}$ three days after typhoon passage. PP showed the highest value of 554 mg C $m^{-3}$ $d^{-1}$ five days after Malou passage, and Chl *a* reached a maximum of 7.65 mg $m^{-3}$ six days after typhoon passage. BP and PP showed no correlation and the maximum value of BP/BA was 6.8 times higher than the average value of the study site in summer, which implied that the allochthonous substrate loaded by typhoon passage enhanced bacterial activity just after the passage. BP/PP was highest at 1.5 one day after the passage of Malou, and decreased to 0.1 on the fifth day after typhoon passage suggesting dominant carbon flux changed dynamically from BP to PP in a short time after typhoon passage. Moreover, the integrated PP for 7 days after the passage of Malou accounted for 9% of the annual PP in the upper water of Sagami Bay. Meteorological disturbances such as typhoons, which will likely intensify as global climate change progresses, should be considered in annual production models.

Keywords: typhoon, primary production, bacterial production, temperate coastal region

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# Meso 4D-VAR data assimilation system using a coupled atmosphere-ocean model

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Mesoscale data assimilation schemes have recently been developed as important components in operational forecasting, particularly for high-impact weather events. This development is driven by the significant advances in computing resources. For example, the Japan Meteorological Agency (JMA) has incorporated an adjoint-based four-dimensional variational (4D-Var) method in their regional forecast system that is based on the JMA nonhydrostatic model (JMA-NHM). This JMA Nonhydrostatic model based Variational data Assimilation system (hereafter, JNoVA) has been used operationally by JMA to construct a mesoscale objective analysis dataset and for regional forecasts since April 2009.

The JNoVA optimizes the fitting of time trajectories to observational records by controlling the initial conditions of an assimilation window. It has substantially improved the forecast skill. However, further improvements are likely around a tropical cyclone since the impact of ocean mixing along with the typhoon passage has not been considered so far.

The aim of this study is to enhance the skill of JNoVA by developing a coupled atmosphere- ocean model. As a first step toward constructing the sophisticated coupled model, a simple one-dimensional mixed layer model proposed by Price et al. (1986) is used. The initial condition of sea surface temperature at the first data assimilation cycle is set to the same as used in the JNoVA. Ocean temperature (except the sea surface temperature) and salinity is taken from World Ocean Atlas 2009. The experiment is initiated at the state of rest, for simplicity. At this moment, the sea surface temperature is restored toward that originally used in JNoVA in a time-scale of one day since the ocean model is too simple to represent the long-term features.

The data assimilation experiment was conducted for the case of Typhoon Talas (2011) (from August 31 to Sep 2, 16 data assimilation cycles). The result exhibits the sea surface temperature decrease around the tropical cyclone. The temperature decrease is maximized in the right of the tropical cyclone pathway with the values of 1-2 K, which is consistent with the observation. The total cost function, which quantifies the misfit in a whole domain between the model results and observations and between the first-guess and the updated initial state, is decreased by 1-3% after coupling the ocean mixed layer model. It is an encouraging evidence to illustrate that the skill of sophisticated data assimilation system can be further enhanced thanks to the coupling to the ocean model.

The typhoon intensity during the data assimilation period in the original JNoVA is improved by the ocean coupling but it is only a slight amount. This is because the use of typhoon bogus results in the reasonable estimate of tropical cyclone intensity in the both data assimilation experiments. In contrast, the forecast skill of typhoon intensity is improved very much according to the coupling to the mixed layer model. The typhoon intensity is overestimated in the original experiment, while the sea surface cooling in a coupled model brings about the closer estimate of typhoon intensity.

Keywords: data assimilation, typhoon, coupled atmosphere-ocean model

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# Numerical study on TC-induced oceanic carbon system changes

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Recent observations have indicated that strong surface winds during the passage of tropical cyclones (TC) lead to rapid TC-induced carbon dioxide outgassing. Understanding the local carbon system is important for estimating the climatological impact of the TC on the annual global carbon dioxide effluxes. In order to understand TC-induced local carbon system and to estimate their impact on the annual global carbon dioxide effluxes, the comprehensive interdisciplinary approach is needed. Among various approaches, numerical modeling studies help understand interdisciplinary processes in both the atmosphere and the ocean.

This study presents the development of the Meteorological Research Institute Community Ocean Model coupled with a carbon equilibrium model to investigate rapid TC-induced carbon dioxide outgassing observed at a moored buoy in the East China Sea during the passages of T9711 (Tina) and T9713 (Winnie). The carbon equilibrium model was also incorporated into an atmosphere-wave-ocean coupled model to examine variation in the partial pressure of surface ocean carbon dioxide by passage of T0914 (Choi-wan) observed at the Kuroshio Extension Observatory moored buoy. These numerical results indicated that variations in the partial pressure of surface ocean carbon dioxide are affected by variations in not only water temperature but also salinity and dissolved inorganic carbon caused by TC-induced advection and vertical turbulent mixing.

Keywords: Typhoon, Carbon dioxide efflux, Moored buoy