Transport of suspended sea spray droplets intensifying tropical cyclones

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A conventional bulk model for the surface layer assumes that the evaporation, in which liquid water turn into water vapor, depends on the local surface humidity and wind speed. In reality, sea spray droplets can stay for a few minutes to evaporate under the violent wind condition beneath tropical cyclones (TCs), and travel several kilometers toward the center of a TC. Although this transport has been neglected so far in numerical models, it can be one of the missing processes that intensify the vortex because the intensity of the TC relies on the inward accumulation of water vapor primarily. Here, a set of ensemble simulations with a simple atmosphere-ocean coupled model for intense TCs are conducted to verify this hypothesis with (i) no sea spray (NoSS), (ii) sea spray evaporating locally (SS_NoTrans), and (iii) sea spray having the duration of flight (SS_Trans). On average, steady-state TCs in SS_Trans are more intense than those in NoSS and SS_NoTrans. The difference between SS_NoTrans and SS_Trans is 25 hPa and 12 m/s and statistically significant. As expected, this intensification is consistent with the inward accumulation of water vapor that brings the inward transport of absolute angular momentum.

Keywords: Tropical cyclone, Sea spray droplets

Atmosphere-Ocean Coupling Effect on Typhoon Megi (2010)

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Typhoon Megi (2010) was one of the most intense tropical cyclones and the only typhoon that attained the minimum central pressure below 890 hPa in the decades after 1984. To investigate the ocean response to Typhoon Megi and the impact of sea surface temperature (SST) on Typhoon Megi, we used a high-resolution coupled atmosphere–ocean regional model, in which the atmospheric model is CReSS (Cloud Resolving Storm Simulator; Tsuboki and Sakakibara 2002) and the ocean model is NHOES (Non-Hydrostatic Ocean model for the Earth Simulator; Aiki et al. 2006, 2011), and the coupled model is referred to as CReSS–NHOES (Aiki et al. 2015). Three sensitivity experiments were conducted: two experiments using CReSS (hereafter FO and 1dO) and one experiment using CReSS-NHOES (hereafter 3dO). A time-fixed SST was used in the FO experiment. A simple vertical diffusion model for the ocean upper layer temperature (the so-called 1D-slab ocean model) was used in the 1dO experiment. The full three-dimensional structure of ocean was simulated in the 3dO experiment. The computational domain is 5°N –25.5°N and 109°E –150°E (Figure 1). The domain consists of 2048x1024 grid points, and the horizontal grid size of all models is 0.02° longitude by 0.02° latitude. All experiments started at 0000 UTC 14 October 2010. The integration time was 9 days.

Typhoon Megi was formed in 14 October and traveled westward in relatively large translation speed faster than 5 m s^{-1} as intensifying gradually (Figure 1a). Around 0000 UTC 17 October 2010, the storm started to intensify rapidly (hereafter, RI) and attained the minimum central pressure of 885 hPa at 1800 UTC 17 October 2010. Although all experiments represent the relatively accurate tracks over the Philippine Sea, the intensity of simulated storm differs significantly among the experiments; the minimum central pressure of the storms are 839, 901, and 892 hPa in the FO, 1dO and 3dO experiments, respectively (Figure 1b). Only the 3dO experiment represents reasonably the evolution and maximum intensity of Typhoon Megi. The simulated results reveal clear differences in the SST-cooling patterns in the vicinity of Typhoon Megi between the 1dO and 3dO experiments. In addition, the impacts of ocean responses to the storm are the most evident during the RI phase. Detailed analysis of the storm inner-core, defined by the region within a radius of 100 km, indicates that the convective activity around the storm center and onset of the RI phase could be modulated by the radial profiles of SST beneath the storm center.

Figure caption.

Figure 1. Six-hourly tracks (a) and central pressure (b) of Typhoon Megi from RSMC best-track dataset (black) and in the FO (green), 1dO (blue) and 3dO (red) simulations between 0000 UTC 14 October 2010 to 0000 UTC 23 October 2010. Large circles in (a) indicate the locations at 0000 UTC.

Keywords: Typhoon, Atmosphere-Ocean Coupling Model

a)

RSMC
FO
1dO
3dO

23OCT
22OCT
21OCT
20OCT
19OCT
18OCT
17OCT
16OCT
15OCT
0000UTC14OCT2010

b)
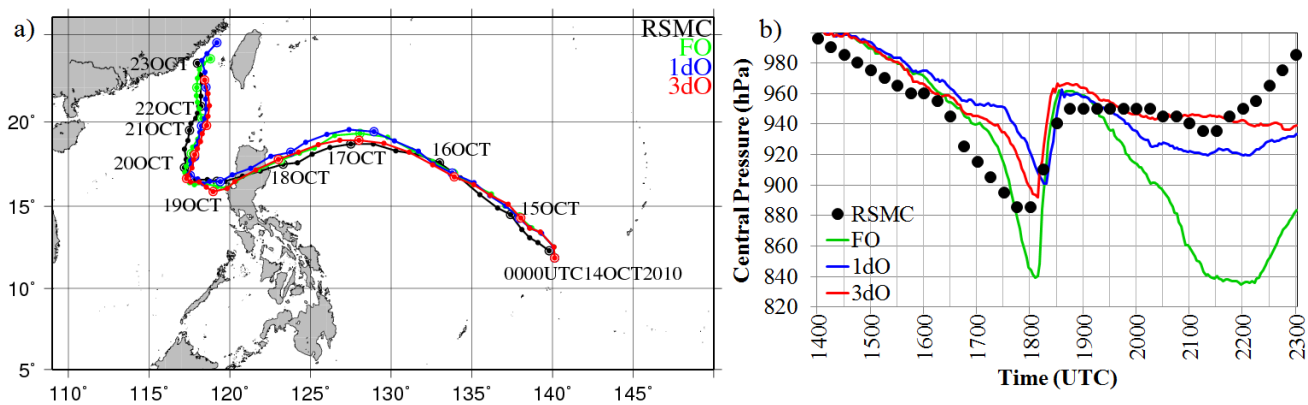
The Development of the Ensemble Based Typhoon Track Forecast Technique

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The purpose of this study is effective in improving the ensemble technique for typhoon track forecasts using multi-model ensembles. The models from global (ECMWF, NCEP) and regional ensembles (CWB EPS, TTFRI EPS) were applied to develop the ensemble based technique. A selective ensemble technique is based on the 12-h typhoon track distance from the CWB (Taiwan's Central Weather Bureau) best-track for 2014-2015. The results show that the superior performance of ensemble based technique to all ensemble means by reducing 12.1%, 6%, 4.1% track errors of 24-, 48- and 72-h forecast, respectively. We also applied this technique for tropical cyclones forecast over the Western North Pacific Ocean in 2016 . The detailed analyses on ensemble technique and individual ensemble models will be presented in the conference.

How much rainfall extremes associated with tropical cyclones can be attributable to anthropogenic influences?

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The rainfall extremes and strong winds associated with tropical cyclones lead to significant damages and lost to where they make landfalling. Upward trend in term of financial lost was indicated for the past few decades from the report of major reinsurance firms. Whether the past anthropogenic warming played a significant role in such extreme event and their changes remained very controversial. On one hand, people argue it's nearly impossible to attribute an individual extreme event to global warming. On the other hand, the increase of heavy rainfall is consistent with the expected effects of climate change on tropical cyclone. To diagnose possible anthropogenic contributions to the odds of heavy rainfall associated with tropical cyclone, we adapt an existing event attribution framework of modeling a 'world that was' and comparing it to a modeled 'world that might have been' for that same time but for the absence of historical anthropogenic drivers of climate. The analysis was applied to Typhoon Morakot (2009) as an example. There was more than 2000 mm rainfall occurred over southern Taiwan when a category 1 Typhoon Morakot pass through Taiwan in early August 2009. Entire village and hundred of people were buried by massive mudslides induced by record-breaking precipitation. One limitation for applying such approach to high-impact weather system is that it will require models capable of capturing the essential processes lead to the studied extremes. Using a cloud system resolving model that can properly simulate the complicated interactions between tropical cyclone, large-scale background, topography, we first perform the ensemble 'world that was' simulations forced by the high resolution ECMWF YOTC analysis. We then re-simulate, having adjusted the analysis to 'world that might have been conditions' by removing the regional atmospheric and oceanic forcing due to human influences estimated from the CMIP5 model ensemble mean conditions between all forcing and natural forcing only historical runs. Thus our findings are highly conditional on the driving analysis and adjustments therein, but the setup allows us to elucidate possible contribution of anthropogenic forcing to changes in the likelihood of heavy rainfall associated tropical cyclone.

Keywords: Extreme Event Attribution, Climate Change

ENSO control on Arabian Sea tropical cyclones in a changing climate

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Tropical cyclones rarely occur in the Arabian Sea during the pre-monsoon month of May.
However, our analysis reveals that there has been a significant increase in the number of cyclones
in this region during the recent years. While the first half of the satellite era (1979-1996) saw a
single cyclone, the second half (1997-2014) witnessed an increase of up to six cyclones. We
investigate the mechanism and largescale conditions regulating the changes in cyclonic activity,
and explore if this increase in the frequency of cyclones will continue into the future. Our analysis
using observations and CMIP5 model simulations suggest an ENSO control on the pre-monsoon
tropical cyclones in the Arabian Sea. We find that La Niña-like conditions during the recent years
have resulted in an anomalous cyclonic circulation and reduced vertical wind shear in the Arabian
Sea via a modification of the Walker circulation, thereby providing favorable conditions for
cyclone genesis and development. This anomalous cyclonic circulation associated with the La
Niña conditions are observed throughout the middle troposphere (700-400 hPa). Nevertheless,
CMIP5 model projections suggest a 50% reduction in the number of tropical cyclones in the future
(2051-2100), as compared to the recent decades (1951-2000). Our analysis shows that this decrease
in cyclones is a response to the positive skewness towards El Niño like conditions in the future,
which results in an anomalous anticyclonic circulation in the Arabian Sea along with increase in
wind shear and decrease in relative humidity inhibiting the formation of cyclones in the region.

Keywords: Pre-monsoon cyclones, ENSO, climate change

Impacts of Boreal Summer Intraseasonal Oscillation on the Western North Pacific Typhoons and Rainfall in Taiwan

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This study discusses the boreal summer intraseasonal oscillation (BSISO) impact on the western North Pacific (WNP) typhoons and the summer rainfall in Taiwan. The real time BSISO1 and BISISO2 indices are created using the first two and the third and fourth principal components of the multivariate empirical orthogonal function analysis, based on outgoing long-wave radiation and zonal wind at 850 hPa from Lee et al. (2013). The results show that heavy rainfall in Taiwan and the associated WNP typhoon frequency patterns are closely related to the 10 - 30 days BSISO2 phases during the typhoon season (July - October). Taiwan has larger rainfall during BSISO2 phases 3, 4, and 5 when the major BSISO2 convection moves northwestward from the Philippine Sea to the Taiwan area. During phases 3 and 4 the anomalous low-level cyclonic flow and the increased typhoon frequency directly result in larger rainfall in Taiwan. For the phase 5, enhanced low-level southwesterly flow which transports the moisture to Taiwan is responsible for more summer rainfall in Taiwan.

Keywords: Typhoon, BSISO, Taiwan

A Numerical Study of Outer Rainband Formation in a Sheared Tropical Cyclone

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The dynamical process of outer rainband formation in a sheared tropical cyclone (TC) is examined in this study using the fully-compressible, nonhydrostatic TC model. After the easterly vertical wind shear of 10 m s^{-1} was imposed upon an intensifying strong TC, an outer rainband characterized by a wavenumber-1 structure formed as a typical principal rainband downshear. Further analysis indicates that the outer rainband formation was closely connected to the activity of the inner rainband previously formed downshear. Moving radially outward, the inner rainband tended to be filamented due to the strong radial gradient of angular velocity. As the inner rainband approached the outer boundary of the inner core, convection in its middle and upwind segments reinvigorated and nascent convective cells formed upwind of the rainband, caused mainly by the decreased filamentation and stabilization. Subsequently, the rainband reorganized into a typical outer rainband. Three different scenarios are found to be responsible for the outer rainband formation from downshear inner rainbands. The first is the outer rainband forming from an inner rainband downshear as a sheared vortex Rossby wave. The second is the outer rainband forming directly from a single deformation-induced inner rainband. The third is the outer rainband developing from an inner rainband downshear organized from a blend and merger of inner rainbands that were initiated from locally deformed convection upshear right.

Keywords: Tropical cyclone, Outer rainband, Vertical wind shear

High-Resolution Simulation of Super Typhoon Nepartak (2016)

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Typhoon Nepartak was the first category 5 tropical cyclone of 2016 and had significant social impacts. It formed as a tropical depression on July 2 near Guam in the western Pacific Ocean and strengthened to tropical storm the following day. It had a rapid intensification (RI) with the decrease in minimum sea-level pressure (MSLP) from 970 hPa at 00Z 5 July to 910 hPa at 06Z July 6, followed by a secondary eyewall formation (SEF), as shown from satellite observation before making landfall in Taiwan on July 8. The storm hammered Taiwan with 135 knots and a huge torrential rain, causing three deaths and 142 injuries as reported. It made second landfall in Fujian, China, on July 9 with a 65 knots wind speed, causing more than 188 deaths or missing and the most devastating flooding since 1998. The super typhoon Nepartak is a very interesting, while challenge case to study.

The high resolution simulations are conducted using the Coupled Ocean/Atmosphere Mesoscale Prediction System –Tropical Cyclone (COAMPS-TC) to understand the RI, SEF, eyewall replacement cycle (ERC) processes, and the associated heavy rainfall. The detailed diagnostics of the inner-core eyewall structures and the associated strong convection during RI and ERC will be performed to examine and understand the dynamics and physics. Detailed results will be presented at the conference.

Keywords: Tropical Cyclone, Typhoon, Rapid intensification

Global cloud-permitting simulations of Typhoon Fengshen (2008)

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Large-scale fields and inner-core processes relevant to the formation and intensification of Typhoon Fengshen (2008) were examined by simulations using Nonhydrostatic Icosahedral Atmospheric Model (NICAM; Satoh et al. 2014) with a cloud-permitting (3.5-km mesh) resolution (Nasuno et al. 2016). Fengshen was formed in mid-June during the onset of the WNP monsoon and the active phase of a boreal summer intraseasonal oscillation (BSISO) event. The TC genesis was preceded by the formation of a lower tropospheric large-scale gyre associated with enhanced equatorial westerlies and a middle tropospheric wave trough intruding above the gyre.

To understand the impact of atmospheric conditions and the convective effects on the TC environment and precursor disturbance, five simulations were performed by varying the initial data (interpolated using ECMWF YOTC or NCEP FNL analysis) and cloud microphysics settings.

In three simulations initialized using the ECMWF YOTC, a middle tropospheric trough developed within a few days following a large-scale latent heat release, which enabled the successive occurrence of deep convective events within the 50-km radius of the incipient disturbance and subsequent TC formation. In the run with weaker latent heating in the lower troposphere, the trough was weak and TC formation was significantly delayed.

In the run initialized using the NCEP FNL, where the latent heat release averaged over the entre simulation was the same as its ECMWF YOTC counterpart, neither the trough nor a TC developed, lacking the collocation between the latent heat release and large-scale gyre in the early period. Under the vertical wind shear increasing poleward, it was critical for the incipient vortex to experience upward penetration before it moved farther northward.

These results indicate that the superposition of large-scale disturbances in the lower and middle troposphere and their linkage through convective enhancement played an important role in the genesis of Fengshen by preconditioning the establishment of a deep upright inner core. Another implication is that the modeled TC genesis is sensitive to difference in initial environment under a strong vertical shear like in this case.

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Satoh, M., and others, 2014: The Non-hydrostatic Icosahedral Atmospheric Model: Description and Development. Progress in Earth and Planetary Science, 1, 18. doi:10.1186/s40645-014-0018-1.

Keywords: Tropical cyclogenesis, global nonhydrostatic model, cloud-permitting simulation

Inner Core Structure of Hurricane Patricia Observed During TCI-2015

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Hurricane Patricia (2015) rapidly intensified from a tropical storm to an estimated 185 kt intensity in 36 hours, making it the strongest tropical cyclone in the Western Hemisphere on record. Four high-altitude research flights with the NASA WB-57 aircraft were conducted into Patricia as part of the Office of Naval Research (ONR) sponsored Tropical Cyclone Intensity (TCI) field experiment from 20 to 23 October. The WB-57 was equipped with a new high-density sounding system (HDSS), enabling full-tropospheric profiling of temperature, humidity, and winds throughout Patricia's inner and outer core. A total of 257 dropsondes were released from the HDSS over the four day intensive observing period, spanning the development from a tropical depression to category 5 intensity. Doppler radar and dropsonde observations were obtained by the NOAA WP-3D aircraft reconnaissance from 21 to 23 October, allowing for complementary observations of the precipitation and kinematic structure during the rapid intensification period. Integrated kinematic and thermodynamic analyses of the full-tropospheric structure derived from dropsonde, radar, in situ, and satellite observations using a variational spline-based mesoscale analysis technique will be presented. The high-resolution observational analyses allow for calculation of axisymmetric potential vorticity (PV) during the extreme rapid intensification period. These new calculations reveal a compact inner core with an intensifying PV tower that breaks down just prior to landfall. The dynamics of Patricia's rapid intensification and weakening inferred from the observations will be discussed.

Keywords: Tropical Cyclone, Hurricane Patricia, Field Observations, TCI-15

Three-dimensional structure of Typhoon Mindulle (2016) observed by phased array radar

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Since 2015, Meteorological Research Institute has been operating a phased array radar (PAR, hereafter) which is a modern technology that performs high-speed volumetric scan in 10–30 seconds. On 22 August 2016, Typhoon Mindulle made landfall near Tateyama, Chiba and moved north across the Kanto Plain. We therefore succeeded in observing a fine-scale three-dimensional structure of Mindulle as it passed close to the PAR observation site in Tsukuba, Ibaraki. The obtained data show that the inner region of Mindulle consisted of several spiral rainbands located around the center of circulating winds, in which many convection cells with 20-dBZ echo top altitudes of 5–8 km were embedded. We derived wind fields by carrying out a synthesis analysis of the Doppler velocity data obtained by PAR and a nearby operational radar. The low-level synthesis data show a strongly circulating wind region with a velocity of >25 ms^{-1} which originally existed at several tens of kilometers from the center. The radius of the strong winds then monotonically decreased to <10 km in 20–30 minutes, implying a contraction of circulating winds presumably caused by a surface frictional force. Meanwhile, the PAR reflectivity data exhibited rapidly developing convection cells in the innermost rainband, with 20-dBZ echo top altitude increasing from ˜8 km to 14–16 km. This convection intensification was also detected by a meteorological satellite (Himawari-8) as a signature of brightness temperature lowering from 205 K to 199 K around the region in question. These results suggest a frictionally forced updraft occurring in the inner region of Mindulle during its decaying stage. It is apparent that PAR finely resolves three-dimensional structure of typhoon and detects signatures of underlying physical processes.

Keywords: typhoon, three-dimensional structure, phased array radar

Doppler radar analysis of intensity and inner-core structure of Typhoon Haiyan (2013) near landfall

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Intensity and inner-core structure of the second most intense tropical cyclone in the world since 1979, Typhoon Haiyan (2013), were examined using ground-based Doppler radar data observed by the Guiuan radar over about 2.5 h immediately before landfall on Leyte Island in the Philippines. The wind fields of Haiyan from 2- to 6-km altitude were retrieved by the ground-based velocity track display (GBVTD) technique from the Doppler velocity data. The GBVTD-retrieved maximum wind speed reached up to 101 m s^{-1} at 4-km altitude on the right side of the track. A relatively fast moving speed of Haiyan, about 11 m s^{-1}, largely contributed to the increase in the maximum wind speed. Azimuthal mean tangential wind increased with height from 2- to 5-km and a local maximum lay at 5-km altitude with a value of 86 m s^{-1}. The central pressure was estimated at 908 hPa with uncertainty of ±5 hPa by using the GBVTD-retrieved tangential wind and by assuming the gradient wind balance. The radius of maximum radar reflectivity was located at about 23-km radius from the center, a few kilometers inside the radius of maximum wind. The reflectivity structure was highly asymmetric at 3-km altitude and above, and was almost axisymmetric below 3-km altitude in the presence of relatively weak vertical shear (~4 m s^{-1}). The axis of the eyewall ring tilted to the downshear direction. In addition, vortex precession with a period of about 75 min was analyzed.

Keywords: tropical cyclone, Doppler radar

Modeling of the Influence of Saharan Dust and Other Aerosols on Hurricane Nadine (2012) During the NASA Hurricane and Severe Storm Sentinel (HS3) Investigation

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The Hurricane and Severe Storm Sentinel (HS3) was a multiyear field campaign (2012-14) with the goal of improving understanding of hurricane formation and intensity change and determining the extent to which the Saharan air layer (SAL) impacts storm intensification. This talk will focus on simulations of the early stages of Hurricane Nadine (2012), which interacted with the SAL and never intensified beyond a minimal hurricane. Given the complexity of aerosol effects on cloud microphysics and radiation and their subsequent effects on deep convective clouds, there is a need to assess the combined aerosol effects of microphysics and radiation. We use the Goddard Space Flight Center version of the Weather Research and Forecasting model with interactive aerosol-cloud-radiation physics to study the influence of the SAL and other aerosols (sea salt and black/organic carbon) on Nadine via a series of model sensitivity runs. We also use three 30-member ensemble simulations of Nadine, one ensemble with aerosols of all types (dust, pollution, biomass burning, sea salt), one with dust only, and one without aerosol interactions. The role of the SAL is partly assessed through a correlation analysis relating relevant fields (temperature, humidity, winds) to the intensity of the simulated storms averaged over the final three days of simulation. The impacts of Saharan dust and other aerosols are evaluated by looking at the differences between the control (no aerosol) and either the all-aerosol or dust-only ensemble members.

Keywords: tropical cyclone, aerosol-cloud-radaition interaction, numerical modeling

Is the State of the Air-sea Interface a Factor in Rapid Intensification and Rapid Decline of Tropical Cyclones?

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Some of tropical storms undergo spectacular rapid intensification and rapid decline. These processes have not yet been completely understood and still are a serious challenge in the tropical storm intensity prediction. Important physics of atmospheric, oceanic, and interfacial components are not yet well understood and implemented in tropical cyclone forecast models. Specific ambient environmental conditions including the ocean thermal and salinity structure and internal vortex dynamics (e.g., eyewall replacement cycle) have been considered by hurricane researchers among the factors favorable for rapid storm intensification. Here, we pursue the hypothesis that the state of the sea surface is another factor in rapid storm intensification and the rapid storm decline. In a laboratory experiment and coordinated numerical simulation, we have found that the air-water interface under hurricane force wind may develop Kelvin-Helmholtz shear instability. The resulting two-phase environment suppresses short waves and alters the aerodynamic properties of the sea surface (Soloviev et al. 2014). The unified wave-form and two-phase drag parameterization model shows the well-known increase of the drag coefficient (C_d) with wind speed, up to ~30 m/s. The negative slope of the Cd wind-speed dependence from approximately 40 m/s to 60 m/s favors rapid storm intensification.Around 60 m/s, one version of the new parameterization shows a local minimum ("sweet spot") of C_d. However, the positive slope of the C_d wind-speed dependence above approximately 60 m/s favors rapid storm decline. The storms that go above category 3 may have tendency to rapidly decline, when they enter areas of lower ocean heat content or less favorable atmospheric conditions.

Soloviev, A., R. Lukas, M. Donelan, B. Haus, and I. Ginis. The air-sea interface and surface stress under tropical cyclones. *Nature Scientific Reports* 4, 5306 (2014).

Keywords: Air-sea Interface, Tropical Cyclone, Rapid Intensification, Rapid Decline
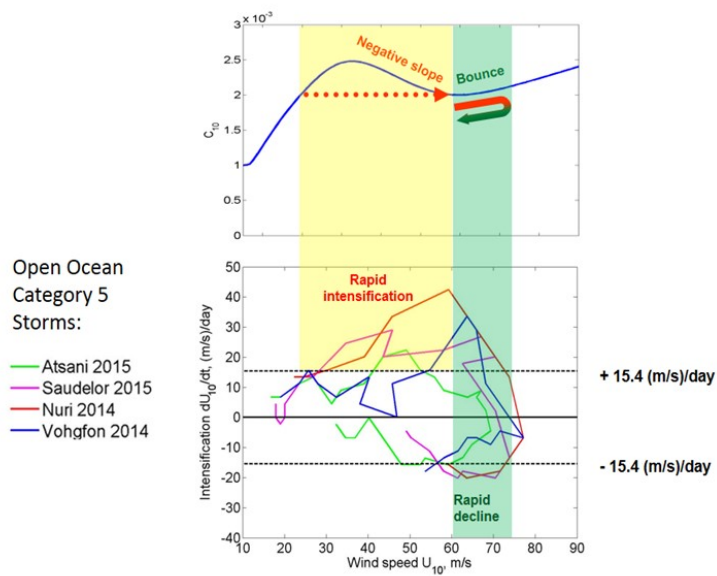
Figure. Rapid intensification and rapid decline of some 2014-2015 Category 5 Tropical Cyclones. Top: The air-sea drag coefficient as a function of wind speed; (bottom) the rate of wind speed change DU_{10}/Dt in (m/s)/day as a function of wind speed U_{10} in m/s. Rapid intensification is defined as a tropical cyclone intensity increase of at least 15.4 m/s in 24 hours; this level is shown by a dashed line U_{10} = 15.4 m/s. Rapid decay is defined as a tropical cyclone intensity decrease of at least 15.4 m/s in 24 hours; this level is shown by a dashed line U_{10} = -15.4 m/s.

Drag coefficient comparisons between observed and model simulated directional wave spectra under hurricane conditions

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In this study, Donelan et al. (2006) source function is used to calculate drag coefficients from both the scanning radar altimeter (SRA) measured two dimensional wave spectra obtained during hurricane Ivan in 2004 and the WAVEWATCH III simulated wave spectra. The drag coefficients disagree between the SRA and model spectra mainly in the right/left rear quadrant of the hurricane where the observed spectra appear to be bimodal while the model spectra are single peaked with more energy in the swell frequencies and less energy in the wind sea frequencies. These results suggest that WAVEWATCH III is currently not capable of providing sensible stress calculations in the rear quadrants of the hurricane.

Keywords: air-sea interaction, hurricane prediction, surface gravity waves

Tropical Cyclone-Ocean Interaction and Global Warming

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Tropical cyclones (TCs, i.e., hurricanes and typhoons) are among the most damaging natural disasters on earth. Its possible change under future global warming condition in the coming century is undoubtedly of critical importance to the humankind. There is much concern that global warming can lead to increase in TC intensity and thus its destructiveness, and this topic is one of the most active current research topics in the international community. In 2015, Huang, Lin et al. (Nature Commu.) discovered that if consider the contribution from subsurface ocean, there is a suppression effect to slow down the rapid TC intensity increase. Under global warming, though both ocean surface temperature (SST) and subsurface ocean warms, subsurface ocean warms slower than SST and increases upper ocean thermal gradient. As a result, the TC-ocean coupling effect is stronger under global warming and can contribute to suppression of TC intensity. This idea was soon confirmed by Emanuel (J. Climate 2015) and he reported that this sharpening can contribute to ˜ 15% drop in category 4 and 5 TC occurrences and 13% drop in TC destructive potential (the power dissipation index, PDI), as compared to the projection without considering the ocean subsurface effect. This presentation will present latest development in this new field, including differences in this subsurface suppressive effect to future TC intensification over different regions.

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Intensification of landfalling typhoons over the northwest Pacific since the late 1970s

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Intensity changes in landfalling typhoons are of great concern to East and Southeast Asian countries. Regional changes in typhoon intensity, however, are poorly known owing to inconsistencies among different data sets. Here, we apply cluster analysis to bias-corrected data and show that, over the past 37 years, typhoons that strike East and Southeast Asia have intensified by 12–15%, with the proportion of storms of categories 4 and 5 having doubled or even tripled. In contrast, typhoons that stay over the open ocean have experienced only modest changes. These regional changes are consistent between operational data sets. To identify the physical mechanisms, we decompose intensity changes into contributions from intensification rate and intensification duration. We find that the increased intensity of landfalling typhoons is due to strengthened intensification rates, which in turn are tied to locally enhanced ocean surface warming on the rim of East and Southeast Asia. The projected ocean surface warming pattern under increasing greenhouse gas forcing suggests that typhoons striking eastern mainland China, Taiwan, Korea and Japan will intensify further. Given disproportionate damages by intense typhoons, this represents a heightened threat to people and properties in the region.

Keywords: Typhoons, Intensity change, Climate variability and change

Recovery of tropical cyclone activity in the western north Pacific in 1950

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Tropical cyclone (TC) activity is influenced by the background atmosphere and ocean conditions; El Niño Southern Oscillation (ENSO), Madden-Julian Oscillation (MJO), Pacific-Japan pattern etc. Those have impacts to modulate the genesis numbers and locations, tracks and intensities of the TCs. In 2016, monsoon gyre was formed in the south of Japan in August. Seven TCs were generated in and around the monsoon gyre and four of them were landed mainland Japan.

Historical TC track data have been collected from various bulletins stored in US, Japan, Philippines, China and other countries back to late 19th century through the "data rescue" activity. The TC landfall numbers in mainland Japan were analyzed using historical TC track data and station data from 1900. TC is defined when it was generated south of Japan and measured less than 1000hPa near the cyclone. Landfall is defined when the minimum sea level pressure measured less than 1000 hPa near the landfall point and the right/left side station measured clockwise/anticlockwise wind direction change during the passage in Japan.

In 1950, ten TCs were landed Japan which was the maximum annual landfall numbers from 1900. Among ten, six of the TCs were landed in August. In this study, the background atmospheric condition and TC activities in August 1950 are recovered and discussed using the historical documents and data. Monsoon gyre was formed in the south of Japan in August 1950. Numbers of small TCs were formed in and around the monsoon gyre. On the other hand, the predecessor of Joint Typhoon Warning Center detected two TCs in August.

Keywords: tropical cyclone, data rescue, monsoon gyre

Tropical cyclone-ocean interactions on Typhoon Haiyan (2013) simulated by a coupled atmosphere-wave-ocean model

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Typhoon Haiyan, the deadliest tropical cyclone (TC) ever recorded in the Philippines, made landfall in the central Philippines on 8 November 2013. To understand roles of TC-ocean interactions on Haiyan, numerical simulations of Haiyan and analogous Typhoon Mike (1990) were performed using a 2-km-mesh nonhydrostatic atmosphere model (NHM) and its atmosphere-wave-ocean coupled model (CPL). Comparison between Haiyan and Mike revealed that relatively rapid translation and small sea surface cooling (SSC) were the factors critical for simulating the extraordinary intensity of Haiyan. Without SSC, Mike might have become stronger than Haiyan. To evaluate uncertainties of TC intensity predictions under different oceanic initial conditions, ensemble simulations for thirty-three oceanic conditions were performed with a 7-km mesh NHM and its CPL for the two TCs. Uncertainties of preexisting oceanic conditions directly affected the central pressures simulated by the NHM. In addition, uncertainties of simulated central pressures were reduced via modification of the secondary circulation due to reduction in the uncertainties of sea surface temperature, irrespective of geographical location, even though wave coupling resulted in some uncertainties of drag coefficients, surface winds, and latent heat fluxes near the TC centers. The ensemble simulations also indicate the importance of TC moving speed and thereby sea surface cooling on TC predictions.

Keywords: Tropical cyclone-ocean interaction , Atmosphere-wave-ocean coupled model, sea surface cooling, Oceanic environment

Interaction of storm surge and waves along the Indian coastline using a coupled atmosphere-ocean-wave model

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Interaction between the tropical cyclone (TC) induced waves, storm surge, and associated coastal inundation along the east coast of India investigated using a coupled atmosphere-ocean-wave model. The fully coupled Ocean-Atmosphere-Wave model (COAWST model components) was configured over the Bay of Bengal (BoB), a semi-enclosed basin in the northern Indian Ocean. To understand the impact of waves on storm surge, two numerical experiments were performed with different coupling configuration. In the experiment with wave model coupled to atmosphere and ocean models, the ocean circulation model includes depth dependent wave stress terms, Stokes drift, vertical transfer of wave-generated pressure transfer to the mean momentum equation, wave dissipation as a source term in the turbulence kinetic energy equation, mean current advection, and refraction of wave energy. Wave induced forces were considered to affect the cyclone induced storm surge. Role of storm surge on the nearshore wave-field was analysed from coupled model simulations. Model results showed that the extent of simulated inundation area increased when the effects of waves were included. The study highlights importance of inclusion of the wave effects for the hindcast of the water levels during the storm surge.

Keywords: tropical cyclone, COAWST, surge-wave interaction

Development of the stretch-atmosphere and ocean model to study air-sea interaction associated with tropical cyclones

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The tropical cyclones have the large impacts on our lives. While the track of tropical cyclone is mainly controlled by wind fields associated with the Pacific high, development is influenced by heat flux from the oceans. A global nonhydrostatic atmospheric model (NICAM) can simulate the tropical cyclones and deep convection in the tropical regions. In order to understand the interactions between atmosphere and ocean associated with tropical cyclone, we need develop the atmosphere-ocean coupling model.
We select the stretched-version NICAM (Tomita et al., 2008) as an atmospheric model and also select the CCSR Ocean Component Model (COCO) as an ocean model. The Stretch-NICAM saves computational resources by focusing on a specific region at high resolution. However, the horizontal resolution becomes coarser for the region outside of the target region. The horizontal spacing of stretched-version NICAM and COCO is about 6 km and 1 degree grid, respectively. This is the first time to use the stretched atmospheric model as a coupling model. Hereafter we call this new coupling model as stretched-version NICOCO. The horizontal grid configuration is difference between stretched-version NICAM and COCO. Here we insert the coupler model (called Jcup) between the two models and exchange fluxes with every 1 hour. The initial condition of the NICAM is prepared by NCEP Tropospheric Analysis data.
In this study, we chose the tropical cyclone generated at 28 August 2004 near Japan and investigate the air-sea interaction associated with the tropical cyclone. The model integration was performed with 7 days. To compare the real ocean, we also use the 4-dimensional Ocean Reanalysis dataset (FORA) and Argo floats data. For a comparison, we also performed simulation by only oceanic model (COCO) with 33 days (18 Aug. 2004 to 19 Sep. 2004). In this simulation, atmospheric forcing is given by ERA-Interim (1.25degree). Horizontal resolution of atmospheric forcing is different from stretched-version NICOCO. Our new model shows that sea surface temperature near tropical cyclone drops and which is 1 K colder compared with FORA data. The sea surface height (SSH) and mixed layer depth (MLD) are also changed. These variables decreased associated with tropical cyclone. Mei et al. (2013) showed that SSH decreases associated with tropical cyclone. The negative anomaly reached 6 cm at maximum. While FORA shows the good results, stretched-version NICOCO shows the rapid recovery of SSH compared with observations. In stretched-version NICOCO and FORA, MLD becomes deepen associated with tropical cyclones. However, similar with SSH, recovery is rapid in stretched-version NICOCO. Compared with COCO, stretched-version NICOCO shows the large amplitude of SSH and MLD variation, it may be caused by difference of horizontal resolution of atmospheric forcing.
In the presentation, we will discuss the results about the boundary layer and state in the sea.

Keywords: stretch-atmosphere and ocean coupling model

Improvement in TWRF and Its Impact on Tropical Cyclones Predictions over the Western North Pacific

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With violent wind and severe rainfall, the tropical cyclone is one of the most disastrous weather system over ocean and the coastal area. To provide accurate tropical cyclone track and intensity forecasts is one of the most important task of the national weather service of countries affected. Taiwan is one of the area frequently influenced by tropical cyclones. Improving the tropical cyclone forecast is the highest priority task of Taiwan's Central Weather Bureau (CWB).

Recent improvement of the tropical cyclone forecast is due to the improvement of the numerical weather prediction. A version of the Advanced Research Weather Research and Forecasting Model (ARW WRF), named TWRF (Typhoon WRF), was developed and implemented in CWB for operational tropical cyclones forecasting from 2011. During the years, partial update cycling, cyclone bogus scheme, relocation scheme, 3DVAR with outer loop, field blending scheme, new trigger Kain–Fritsch cumulus scheme, and so on have been studied and applied in TWRF (Hsiao et al. 2010, 2012, 2015) to improve the model. The averaged 24/48/72 hours cyclone track forecast errors of TWRF are 91/152/210, 91/147/223, and 84/133/197km in year 2013, 2014, and 2015 respectively.

In this study, we try to improve the model by changing the TWRF configuration from a triple nested to a double nested one, and increasing the model resolution from 45/15/5 km, 45-levels (here TWRFd5) to 15/3 km, 52-levels (here TWRFd3). Results of the track, intensity, and rainfall predictions from both TWRFd5 and TWRFd3 for tropical cyclones over the Western North Pacific Ocean in 2016 are analyzed and compared. The quantitative rainfall predictions over high terrain area are also studied. The preliminary results show increasing the model resolution improving the track, intensity and rainfall forecast. However, the 3 km resolution model TWRFd3 has a tendency to over predict the intensity of the tropical cyclones. The detail will be presented in the conference.

Keywords: tropical cyclone forecast, Typhoon WRF, rainfall predictions

Additional Arctic observations improved forecast skill of a typhoon over midlatitude

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In summer and autumn 2016, a remarkable meandering of the jet stream occurred over the Northern Hemisphere. During August, the special radiosonde observations were made on the German RV Polarstern, Korean RV Araon and Russian land station Baranova although these data were not sent to the Global Telecommunication System. The impact of the additional radiosonde data on forecasting the atmospheric circulations over the Arctic and beyond, in particular a case of typhoon1610 (LIONROCK) over East Asia, was investigated using the AFES-LETKF data assimilation system and its ensemble reanalysis data set (ALERA2). We used the ALERA2 as the reference reanalysis (CTL) and the observing-system experiment (OSE) reanalysis in which the same observational data set was assimilated, including the radiosonde data obtained by the RVs and land station. Using these CTL and OSE reanalysis data as initial values, ensemble forecasting experiments were conducted as the CTL and OSE forecasts, respectively. Comparing these ensemble forecasts, there were large differences in the position of the predicted typhoon over Japan. The OSE forecast well predicted the northward movement of the typhoon which is controlled by a trough with strong wind at the upper level. In the CTL forecast, in contrast, the more southward shift of the trough was found over west of Japan, which caused failure of predicting of the typhoon position. Moreover, it is found that forecasting the trough was affected by the special observations in the Arctic regions. This result suggested that the radiosonde observations over the Arctic would improve the skill of weather forecasts at midlatitude during summer.

Keywords: Arctic, Radiosonde, Ensemble forecast

Global 7-km mesh nonhydrostatic Model Intercomparison Project for improving TYphoon forecast (TYMIP-G7)

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The Global 7-km mesh nonhydrostatic Model Intercomparison Project for improving TYphoon forecast (TYMIP-G7; Nakano et al. 2016) is designed to understand and statistically quantify the advantage of high-resolution nonhydrostatic global atmospheric models for improvement of tropical cyclone (TC) prediction. The 137 sets of 5-day simulations using three next-generation nonhydrostatic global models with horizontal resolution 7 km, and conventional hydrostatic global model with horizontal resolution 20 km are run on the Earth Simulator. The three 7-km mesh nonhydrostatic models are the nonhydrostatic global spectral atmospheric Model using Double Fourier Series (DFSM; Yoshimura, 2012), Multi-Scale Simulator for the Geoenvironment (MSSG; Takahashi et al., 2006, 2013), and Nonhydrostatic ICosahedral Atmospheric Model (NICAM; Satoh et al. 2014). The 20-km mesh hydrostatic model is the operational Global Spectral Model (GSM; Japan Meteorological Agency, 2013) of the Japan Meteorological Agency. Compared with the 20-km mesh GSM, the 7-km mesh models reduce systematic errors in the TC track, intensity and wind radii predictions. The benefits of the multi-model ensemble method were confirmed for the 7-km mesh nonhydrostatic global models. While the three 7-km mesh models reproduce the typical axisymmetric mean inner-core structure, including the primary and secondary circulations, the simulated TC structures and their intensities in each case are very different for each model. In addition, the simulated track is not consistently better than that of the 20-km mesh GSM. These results suggest that the development of more sophisticated initialization techniques and model physics is needed to further improve the TC prediction.

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Keywords: typhoon, numerical weather prediction

Effects of the Coriolis Force on Intensity of Hurricane PALI in Ensemble Experiments

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Tropical cyclones (TCs) observations are unusual in the equatorial region from 5°N to 5 °S. Therefore, previous studies studied the effects of the Coriolis force on TC in ideal experiments. These studies, however, have not shown the mechanisms for the TC intensification for realistic settings. Thus, the aim of this study is to clarify the mechanisms of the intensification of Hurricane PALI and the effects of the Coriolis force using a regional atmospheric model. PALI occurred at 4.4°N where is nearly 200 km southeast of Oahu island, USA, on 18Z 7 January 2016 and developed to 43.7 m×s^{-1} at the mature stage (Category-2) on 18Z 12.

We conducted ensemble downscale experiments to deal with initial uncertainty. The non-hydrostatic mesoscale numerical model, WRF, with horizontal resolution of 10 km is used in the present study. To identify the effects of the Coriolis force, sensitivity experiments with Coriolis parameters are conducted. The sensitivity experiments were conducted by inputting the Coriolis forces relatively north to 10° every 1° from the calculation domain. The initial states were derived from 11 ensemble members of NOAA's 2nd-generation global ensemble reforecast dataset. NCEP FNL (Final) Operational Global Analysis data is used as common soil data for all ensemble members and sea surface temperature fixed at the initial time. Among other settings, we used the Kain-Fritsch scheme for cumulus convection parameterization. For the initial time of 00Z 6 January, 36 hours before PALI genesis, all ensemble members forecast a cyclone with TC intensity of 17 m×s^{-1}. The simulated Hurricanes move continuously toward the northwest and locate from the equator to 10°N during forecast time.

We examined the differences of the intensity of simulated Hurricanes among different Coriolis forces. By changing Coriolis force, the intensity of hurricanes changed, but the tracks were almost the same. The result of sensitivity experiments show that larger Coriolis force does not necessarily make TCs stronger. Furthermore, it is found that the spread of TC intensity varies with the Coriolis force.

Keywords: Tropical cyclone, Hurricane, WRF, Ensemble forecast, Coriolis force

The influence of asymmetric convection on typhoon motion near Taiwan

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This study focus on the influence of asymmetric convection on typhoon motion near the east coast of Taiwan. Eighty-four typhoons that made landfall on the east coast of Taiwan are analyzed. There are 49 cases which experience deflection tracks turning to the left-hand side relative to the typhoon moving direction before landfall. Eighteen of them are with very large deflection angles (DA) (> 20°) and another 7 cases are with looping tracks (LTs). We found most of the large DA and LT cases are occurred north of 23 °N near Taiwan and has significant stronger convection in the north of the storm. The Weather Research and Forecasting (WRF) Model was used to simulate the typhoon motion approaching Taiwan. We use the potential vorticity (PV) tendency diagnosis to analyze the mechanisms which affect the storm movements. The wave number one component (WN1) of PV tendencies are decomposed into horizontal advection (HA), vertical advection (VA) and diabatic heating (DH) terms. The northern landfall typhoons have significant heating asymmetries for the storm structure before landfall, and thus modify the storm track through the DH PV tendency. The vorticity stretching effect also occurred to south of the storm. This vorticity stretching (VA effect) and diabatic heating asymmetries (DH effect) lead to the track deflections before landfall. Our results highlight the importance of asymmetric convection and its impact to typhoon track deflections which occurred north of 23 °N near the east coast of Taiwan.

Keywords: Typhoon track, Potential vorticity tendency diagnosis, Diabatic heating asymmetries

Interannual variation and prediction of spring precipitation over southeast China

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The interannual variations and the prediction of the leading two empirical orthogonal function (EOF) modes of the spring (April-May; AM) precipitation over southeast China for the period from 1951 to 2014 are examined using both observational data and the output from six atmosphere-ocean coupled climate models. A positive phase of the leading EOF mode of the spring precipitation over China (EOF1-prec) features enhanced rainfall in southern China. The ENSO-related tropical Pacific SST anomalies in the previous season can serve as a precursor for EOF1-prec. The second EOF mode of spring precipitation (EOF2-prec) over China is characterized by a dipole structure with one pole near the Yangtze River and another one with opposite sign over the Pearl River Delta. An equivalent barotropic Rossby wave train pattern associated with EOF2-prec can be observed, originating from the Ural Mountains across the Eurasian continent reaching the Japan Sea, causing anomalous moisture convergence over the Yangtze River alongside divergence conditions in southern China. A North Atlantic sea surface temperature (SST) dipole in the preceding March can contribute to the wave train-like pattern. An empirical model, constructed based on the observational analysis, can significantly improve the seasonal forecast skill of spring precipitation over China, especially over the Yangtze River area.

Keywords: precipitation, spring, numerical model

Interannual variations of tropical cyclone frequency over South China Sea

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This study attempts to investigate the interannual changes of tropical cyclone (TC) frequency over South China Sea (SCS) in the different seasons of summer (May-August) and winter (September-December) during 1977-2012. The spectral analysis indicate that during the summer, there is a periodicity of 4-8 years between 1993-2003 and an obvious interdecadal signal while during the winter the periodicity of 2-8 yeas is dominated between 1980 and 1992. The differences of characteristic between the summer and winter is related to the role of Indian Ocean. During the winter the subtropical Indian Ocean Dipole (IOD) around 20ºS induces a cyclone circulation over the North Indian Ocean that leads to a upper-level divergence and low-level cyclone with updraft over SCS that is favorable for TC formation. The impact of subtropical IOD becomes weaker during the summer, however the colder sea surface temperature still can be found in the western part of Indian Ocean. Meanwhile western North Pacific warm pool also results in an ascending flow over the SCS and enhances MJO activity there that increases the numbers of SCS TCs.

Keywords: tropical cyclone , interannual change, South China Sea

How well do global climate models simulate the variability of Western North Pacific Tropical Cyclones Associated with ENSO?

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An assessment on the simulations of interannual variability of tropical cyclones (TCs) over the western North Pacific (WNP) and association with El Niño–Southern Oscillation (ENSO), as well as a subsequent diagnosis for possible causes of the model biases generated from simulating the large scale climate conditions, are documented in the paper. The model experiments are carried out by the Hurricane Work Group under the U.S. Climate Variability and Predictability Research Program (CLIVAR) using five global climate models (GCMs) with a total of 16 ensemble members forced by the observed sea surface temperature, and spanning 28-yr period from 1982 to 2009. The results show GISS and GFDL model ensemble means best simulate the interannual variability of TCs and the multi-model ensemble mean (MME) follows. Also, the MME has the closest climate mean annual number of WNP TCs and the smallest root-mean-square error to the observation.

Most GCMs can simulate the interannual variability of WNP TCs well, with stronger TC activities during two types of El Niño, namely eastern Pacific (EP) and central Pacific (CP) El Niño, and weaker activity during La Niña. However, none of models captures the differences in TC activity between EP and CP El Niño as shown in observations, which may be due to the bias of the circulations in models in response to the westward shift of tropical heating associated with CP El Niño. In addition, a general unrealistic scene exists in model simulations with the underestimated intensities of the convection anomaly over the maritime continent in the western tropical Pacific during each ENSO phase of whatever warm or cold, which may be the important source of biases in simulating WNP TC associated with the ENSO events.

Keywords: Simulations, tropical cyclones, variability, ENSO, global climate models

Unusual growth in intense typhoon occurrences over the Philippine Sea in September after the mid-2000s

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During the global warming hiatus period (1998–present), a pronounced increase in the number of intense typhoon occurrences was identified over the Philippine Sea (PS: 5˚–25˚N, 125˚–140˚E) in September after the mid-2000s. Comparing two periods before and after the mid-2000s indicates that intense typhoons rarely occurred over the PS in September before the mid-2000s, with a frequency of fewer than 0.4 per year, but reached up to nearly 1.5 per year after the mid-2000s. The abrupt increase in intense typhoon occurrences over the PS was primarily attributed to increased tropical cyclone (TC) genesis and favorable large-scale conditions for TC intensification. The increase in TC genesis number over the PS was caused by contributory dynamical conditions, including positive low-level relative vorticity anomalies and anomalous ascents, which corresponded to a southwestward shift and strengthening of the monsoon trough. In addition, among the favorable large-scale conditions, the increased relative humidity that resulted from intensified moisture flux convergence exerted essential effect on the TC intensification.

These changes in atmospheric environmental conditions

favoring intense typhoon occurrences over the PS

were primarily associated with the change in the tropical

Indo-Pacific sea surface temperature (SST) around the mid-

2000s. Besides that, the positive feedback TCs exerted on

the circulation was also conducive to the unusual growth in

intense typhoon occurrences over the PS. And note that the

role of SST anomalies in the air–sea interaction is the key

to interpret why the unique phenomenon only occurred in

September

Keywords: tropical cyclone, decadal change

Influence of the IOD on the relationship between El Nino Modoki and the East Asian-western North Pacific summer climate

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The relationship between El Nino Modoki and the East Asian-western North Pacific summer monsoon (EA-WNPSM) has been revealed to be under the influence of Indian Ocean Dipole (IOD). When a pure El Nino Modoki occurs without a positive IOD, a strong EA-WNPSM is observed with a significant anomalous low-level cyclone over the western North Pacific (WNP), excessive rainfall there and deficient Meiyu–Baiu rainfall. In contrast, when an El Nino Modoki happens simultaneously with a positive IOD, the anomalous EA-WNPSM tends to be much weaker. This difference is attributed to a positive IOD effect. The results demonstrate that a positive IOD usually leads to a strong South Asian summer monsoon heating, which further causes easterly anomalies in the western Pacific. These anomalous easterlies tend to strengthen the WNP anticyclonic vorticity leading to a weak EA-WNPSM. Therefore, a positive IOD weakens the relationship between the El Nino Modoki and the EA-WNPSM. In addition, numerical experiments verified that the strong low-level WNP cyclonic anomaly is built through the off-equatorial heating associated with the local cyclonic circulation. The anomalous WNP anticyclonic vorticity induced by a positive IOD weakens this off-equatorial heating, thus leading to a weak EA-WNPSM.