Section 9

Development of and studies with coupled ocean-atmosphere models

3D Ocean Coupling for the North Western Pacific Typhoon Forecasts

Hyun-Sook Kim*, Vijay Tallapragada, and Avichal Mehra
*Environmental Modeling Center, NCWCP, College Park, Maryland 20740, USA
hyun.sook.kim@noaa.gov

1. Introduction

Under the auspices of development of the next generation hurricane forecast model at U. S. NWS/NCEP/EMC, , 3D eddy-resolving HYbrid Coordinate Ocean Model (HYCOM) has been coupled to the Hurricane Weather Research Forecast (HWRF) model.. The atmospheric component of this new system (HYCOM-HWRF) is the same model that has been providing numerical guidance to the Joint Typhoon Warning Center (JTWC) in a non-coupled configuration since 2012. This new system has been extensively tested in real-time for the North Atlantic and Eastern Pacific hurricanes starting in 2009. The coupled system exhibits intensity improvements by reducing absolute mean errors and bias, but shows little impact on the track forecasts (Kim et al., 2014). With the availability of global Real-Time Ocean Forecast System (RTOFS) operational products from October 2011, application of this coupled system is now possible without any geographic limitations. For the first time in 2012, HYCOM-HWRF was employed to conduct Typhoon forecasts in the Western North Pacific. This report documents its performances for the 2012 and 2013 season in comparison to the non-coupled HWRF.

2. Experimental design

Coupled simulations were produced at 6-h cycles for the entire lifetime of the individual storms. Initial and boundary conditions for HYCOM are provided from daily operational products of global RTOFS by subregioning but at the same $1/12^{o}$ horizontal and 32-level vertical resolutions. Ocean initialization is obtained from a 24-h free run using RTOFS nowcasts forced by Global Data Assimilation System forcing. The atmospheric physics and air-sea parameters used are identical to the non-coupled HWRF system (ref. Tallapragada et al., 2014). Homogeneous verifications are prepared for both coupled and non-coupled runs using the National Hurricane Center verification tools for comparisons. Figure 1 shows tracks for all 31 TCs encompassing the 2012 (A) and 2013 (B) seasons.

3. Results

Comparisons of track forecasts between coupled (cpl) and non-coupled (ctl) runs (Fig. 2) show little difference in absolute mean error (Fig. 2A) and bias (Fig. 2B) for either season or for the two seasons combined together. Intensity differences, on the other hand, exhibit a seasonal variation where coupled runs retained smaller mean errors by < 5 kt (< 6 hPa) in 2013 than 2012, as compared to the non-coupled runs. The season intensity improvement is more notable at late lead times, with the error decreasing from ~17 kt (14 hPa) at 48 h to ~13 kt (10 hPa) at 120 h, whereas the error for non-coupled forecasts is relatively flat for the same lead hours (Fig. 2C and 2E). The intensity bias (Fig. 2D and 2F) suggests two significant differences: First, there is a distinct offset between the two runs, with largest bias at mid lead times, which then is reduced (for V_{max}) or kept at the same difference (for P_{min}). The pattern, however, is indistinguishable for the two seasons. Second, the coupled HYCOM-HWRF system under-predicts intensity. The intensity forecast by the non-coupled HWRF show little bias at early lead times (≤ 48 h), but then undergo a rapid change afterwards (negative for 2012 and positive for 2013), which results in an overall small bias by cancelling out for the two seasons put together. Meanwhile, coupled forecasts are biased to the negative (positive) for V_{max} (P_{min}), showing no apparent seasonal dependency.

4. Concluding remarks

HYCOM-HWRF coupling persistently reduces intensity forecast errors with seasonal variability, but shifts intensity bias with respect to the non-coupled runs regardless of season. It suggests that dynamic HYCOM coupling alters the gradient wind balance in the atmospheric model. One plausible explanation is that coupling realizes storm-driven sea surface temperature cooling, which in turn results in weakening thermodynamic instability in the atmospheric boundary layer. Efforts are underway to increase skill of the coupled system by identifying the responsible primary processes and determining an optimum air-sea interaction configuration.

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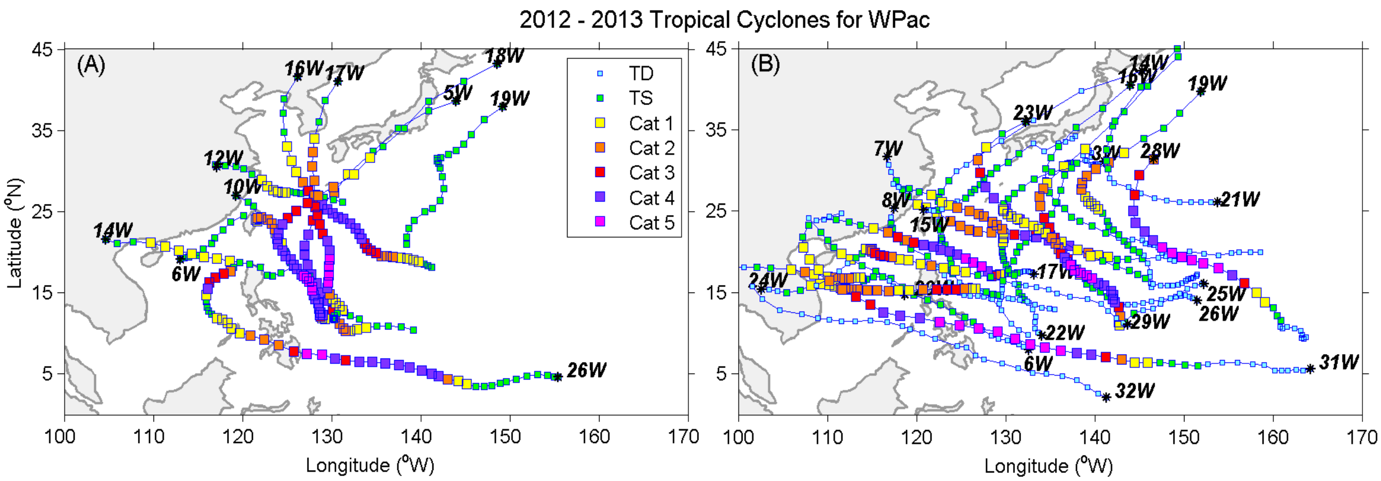

Figure 1. 2012 (A) and 2013 (B) Tropical Cyclones of study.

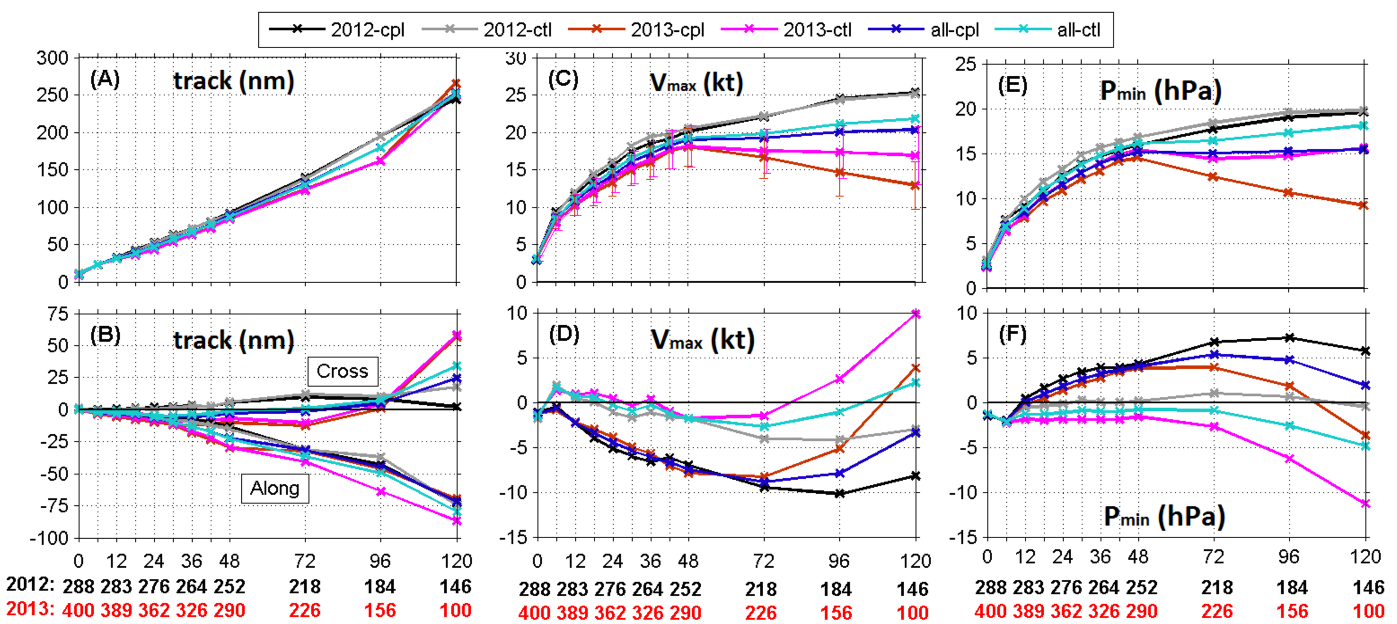

Figure 2. Comparisons of run verifications between coupled (cpl) and non-coupled HWRF (ctl): Absolute mean track error (A); along- and cross-track error (B); absolute mean error of maximum velocity (C) and its bias (D); and central pressure error (E) and its bias (F). Along the x-axis, top labels denote forecast hours, two lines below (middle and bottom) represent number of cases for 2012 (black) and 2013 (red), respectively. Vertical bars in panel (C) are intervals at the 95% confidence.

NOAA/NCEP Operational Hurricane Weather Research and Forecast (HWRF) Modeling System

V. Tallapragada, Z. Zhang, S. Trahan, W. Wang, Q. Liu, and M. Tong

Environmental Modeling Center (EMC), NCEP/NOAA/NWS, College Park, MD, USA

Prediction of track and intensity of a tropical cyclone (TC) is one of the many challenging problems in meteorology, but is very important for issuing timely warnings for many agencies engaged in disaster preparedness and mitigation. Hurricane forecasting is one of the most important areas of modeling at the Environmental Modeling Center (EMC) of the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP). The Hurricane Weather Research and Forecast (HWRF) modeling system for hurricane prediction, developed by scientists at EMC, in collaboration with various academic and government agencies, is a sophisticated, high-resolution, atmosphere-ocean-land coupled model designed to resolve inner-core features of hurricanes for providing accurate forecast guidance through improved representation of multi-scale, spatio-temporal interactions of storm circulations within the large-scale environment. The HWRF modeling system became operational at NCEP starting with the 2007 hurricane season. The HWRF model provides high-resolution track, intensity, and structure forecast guidance to the operational forecasters at the National Hurricane Center (NHC) and Central Pacific Hurricane Center (CPHC) for all tropical cyclones in their areas of responsibility (North Atlantic and Eastern North Pacific, and Central North Pacific, respectively). Recent efforts supported by NOAA's Hurricane Forecast Improvement Project (HFIP) allowed the HWRF team to expand the applications of the HWRF modeling system (henceforth to be referred to simply as 'HWRF') for tropical cyclone forecasts in all global oceanic basins, providing real-time forecast guidance to the operational forecasters at the Joint Typhoon Warning Center (JTWC), National Weather Service (NWS) Pacific Region (PR) and several international tropical cyclone forecast agencies across the world.

HWRF has undergone annual upgrades and continuous improvements since 2007 through a carefully designed testing, evaluation and implementation plans. A series of significant and foundational improvements were made to the operational HWRF in terms of resolution and physics improvements implemented in 2012 (Figure 1) as a result of collaboration with many NOAA

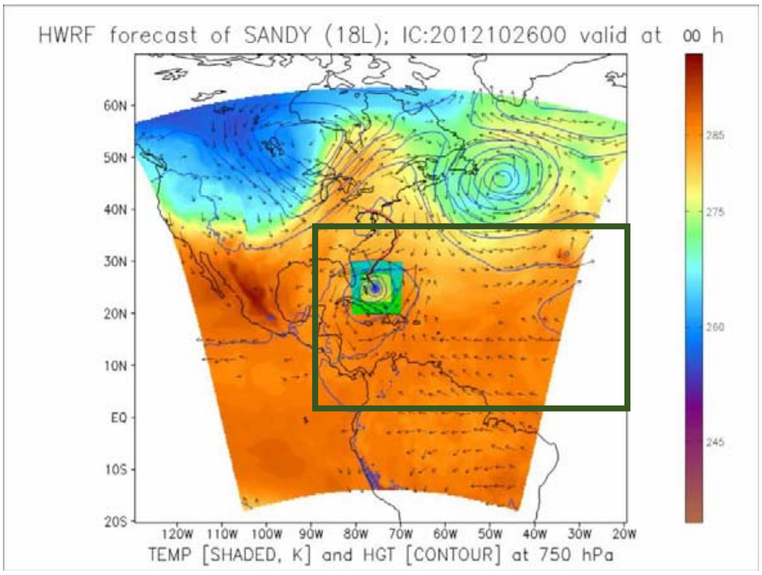

Figure 1: Triple nested configuration of NCEP Operational HWRF Model consisting of two high-resolution telescopic storm-following two-way interactive nests operating at 9 km and 3 km near the storm center embedded in a storm-centric outer domain (27 km). Dark green box indicates the location of the MPIPOM Ocean Model coupled to HWRF.

agencies under Hurricane Forecast Improvement Project (HFIP). For the first time, a very high resolution air-sea coupled model operating at a cloud permitting resolution of 3km near the storm center was implemented during the 2012 hurricane season, paving way for significant improvements in hurricane intensity forecasts that have been stagnated for more than two decades. In 2013, for the first time, real-time assimilation of Tail Doppler Radar (TDR) data collected by NOAA P3 aircraft reconnaissance missions was made possible through the implementation of an advanced regional hybrid (Ensemble-3 Dimensional Variational) data assimilation system. In 2014, HWRF upgrades included increased vertical resolution to 61 levels and raising the model top to 2 hPa, and coupling to a modern Message Passing Interface Princeton Ocean Model (MPIPOM) for all operational basins.

The current version (FY15) of operational HWRF system proposed for operational implementation in May 2015 is an advanced coupled system including ocean and land models. The model resolution is further increased to have the triple-nest capability (18/6/2km) that includes a cloud-resolving innermost grid operating at 2 km horizontal resolution and 61 vertical levels. In the FY15 HWRF upgrades, the physics schemes are further improved based on observational findings and advanced vortex initialization data assimilation techniques for better representation of the inner core storm structure of the storms. In order to better represent deep convection, micro-physics is upgraded to the Ferrier-Aligo scheme; the GFDL slab model is replaced by the multi soil level NOAH Land Surface Model which will improve track and intensity forecasts of landfalling hurricanes; the scale-aware Rapid Radiative Transfer Model for General Circulation Models (RRTMG) is introduced to HWRF physics with partial cloudiness, replacing the old GFDL radiation scheme; and FY15 upgrades also include well-tuned PBL, momentum and enthalpy exchange coefficients in the surface physics based on observations. The newly upgraded data assimilation system allows us to assimilate more observations, such as satellite data, Tail Doppler Radar (TDR), and tcvitals MSLP data along with dropsonde data in real time, using advanced 40-member HWRF ensembles.

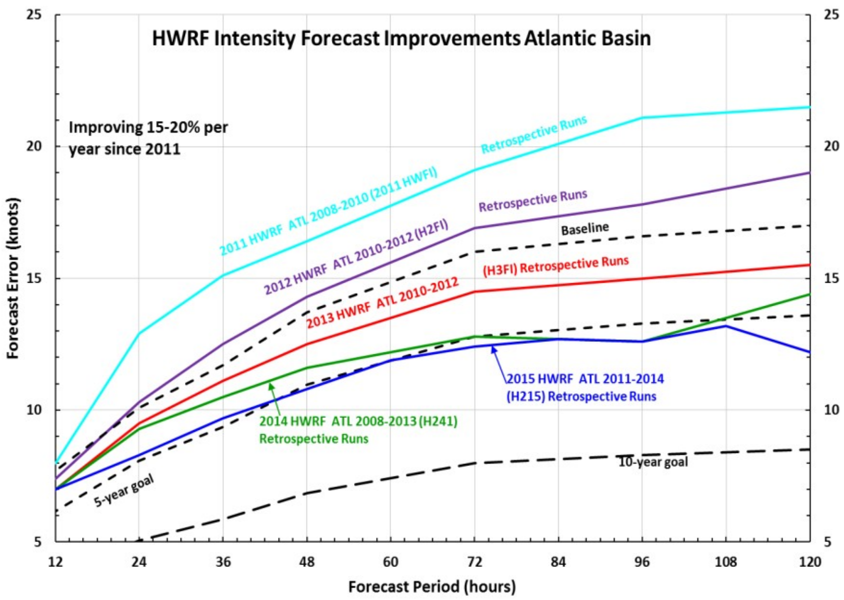

Figure 2: Progress of intensity improvements from HWRF over the years

Real time and retrospective experiments have demonstrated that HWRF track and intensity forecasts have constantly improved and outperformed other dynamic models, and beginning for the first time since 2013, it outperformed the statistical models and NHC's official forecasts for tropical cyclone intensity (subjectively made by the hurricane specialists) by about 15%, with track forecast skills competitive to the best performing NCEP GFS global model skills. In additional to steady improvements in the track forecast skill every year, the operational HWRF has conclusively demonstrated the positive impact of resolution on storm size and structure forecasts. Figure 2 illustrates the steady but significant intensity forecast improvements from the operational HWRF as evaluated through several seasons of retrospective evaluation of model upgrades.

HWRF emerged as a state-of-the-art hurricane modeling system outperforming many regional dynamic hurricane models; and became one of the best regional hurricane forecast models in the world. It has gained worldwide reputation for its accurate track and intensity forecasts. It has been run by many tropical cyclone forecast centers for all ocean basins worldwide for both research and operational purposes. HWRF is also implemented at the India Meteorological Department (IMD) in New Delhi for operational tropical cyclone forecasts over the North Indian Ocean basin. Several international tropical cyclone forecast agencies, including Vietnam's Institute for Meteorology, Hydrology, and Environment (IMHEN), China's Shanghai Typhoon Institute (STI), Taiwan's Central Weather Bureau (CWB), and Oman's Directorate General of Meteorological Affairs and Air Navigation (DGMAAN) have also adopted HWRF for their operational needs. The concept of an operational hurricane model available as a research tool and supported through a dedicated community modeling framework at NOAA's Developmental Testbed Center (DTC) allowed further expansion and outreach of the HWRF modeling system to many academic and research organizations across the world, facilitating accelerated model development, research, and transition to operations.

Starting from 2015, HWRF forecasts will be running operationally at NCEPEMC and will provide tropical cyclone forecast guidance for all global oceanic basins, including Northern Atlantic, Eastern North Pacific, Central North Pacific, Western North Pacific, Northern Indian Ocean, and Southern Hemispheric basins. Real-time HWRF forecast products are disseminated through the Automated Tropical Cyclone Forecast (ATCF) system, the NCEP EMC Website (http://www.emc.ncep.noaa.gov/gc_wmb/vxt), NCEP ftp servers (ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/hur/) and NCEP Model Analysis and Guidance website (http://mag.ncep.noaa.gov/tropical-guidance-model-storm.php).

A single deterministic hurricane model can only provide one of the many possibilities of tropical cyclone evolution. It is imperative that we need adopt the ensemble approach for representing the uncertainty and improve the predictability of the tropical cyclone path, intensity, structure, and rainfall forecasts. HWRF team at EMC have started experimenting with a 20-member high-resolution ensemble forecasts starting with the 2013 hurricane season. The HWRF based ensemble prediction system (HWRF-EPS) takes into account un- certainties in storm initial position and intensity, large scale environment, model physics including stochastic sub-scale convective triggers, and PBL height. As expected, the ensemble mean outperformed the single deterministic forecasts from the operational HWRF. Future plans include further development of HWRF ensembles for operational purposes.

The impact of a sea-spray parameterization on the assimilation of Typhoon Sinlaku (2008)

Akiyoshi Wada* and Masaru Kunii
*Meteorological Research Institute, Tsukuba, Ibaraki, 305-0052, JAPAN
awada@mri-jma.go.jp

1. Introduction

The effect of the ocean on tropical cyclone (TC) intensity and intensification is important for predicting TC intensity accurately. Wada and Kunii (2014) previously reported the construction of data assimilation system based on the local ensemble transform Kalman filter (LETKF) and the nonhydrostatic atmosphere model (NHM) coupled with the multilayer ocean model and the third generation ocean surface-wave model (Wada et al. 2010). The coupled system was able to analyze a TC affected by sea surface cooling caused by upwelling and vertical turbulent mixing. However, the NHM-LETKF system was not able to analyze realistic TC intensification (particularly rapid intensification) due to relatively coarse horizontal resolution (15 km in Wada and Kunii 2014). The TC-induced sea surface cooling excessively suppressed TC intensification in the assimilation system so that TC intensification was poorly assimilated when the coupled atmosphere-ocean prediction system was used.

In order to improve the analysis of TC intensification in the coupled atmosphere-ocean prediction system, a sea-spray parameterization is introduced into the atmosphere-wave-ocean coupled model. The impact of the sea-spray parameterization (Bao et al. 2000) on TC intensification has been already investigated by using the atmosphere-wave-ocean coupled model (e.g., Wada 2013, 2014). The studies suggested that the sea-spray parameterization helped TC intensification by increasing turbulent heat fluxes near the atmospheric surface-boundary layer. The purpose of this study is to understand the impact of the sea-spray parameterization on the assimilation of TCs by using the coupled atmosphere-ocean prediction system. Numerical experiments were conducted by the coupled NHM-ocean assimilation system for Typhoon Sinlaku in 2008.

2. Experimental design

The experimental design was almost the same as Wada and Kunii (2014) except that this study used the coupled model incorporating the sea-spray parameterization of Bao et al. (2000).

The coupled atmosphere-wave ocean model consists of the NHM, the third generation ocean-wave model, and a multilayer ocean model (Wada et al., 2010). Sea surface temperature calculated by the coupled model in the prediction part was not used in the subsequent sea surface temperature analysis, which is the same as Wada and Kunii (2014). The analysis component of the LETKF system was not changed from Kunii (2014). The ocean state (wave conditions) was assumed to be motionless at the initial time every analyses.

The analysis and prediction for the storm covered a ~3600 km x ~1900 km computational domain with a horizontal grid spacing of 15 km. The system had 40 vertical levels with variable intervals from 40 m for the near-surface layer to 1180 m for the uppermost layer. The system had maximum height approaching ~23 km. The analysis period was from 1200 UTC 1 to 1800 UTC 19 September in 2008. The number of ensemble member was 20.

3. Results and concluding remarks

The original NHM-LETKF system used merged satellite and in situ data global daily sea surface temperature (hereafter CNTL experiment). To conduct the numerical prediction by the coupled model, daily oceanic reanalysis data calculated by the Meteorological Research Institute multivariate ocean variational estimation (MOVE) system (Usui et al. 2006) was used, too. When the atmosphere model and MOVE dataset were used, the experiment calls “MOVE”, whereas it calls “MOVECP” when the atmosphere-wave-ocean coupled model was used. Moreover, when the atmosphere-wave-ocean coupled model incorporating the sea-spray parameterization was used, the experiment calls “MOVECSP”. The analyzed center positions of Typhoon Sinlaku in the MOVECSP experiment is more close to those of the Regional Specialized Meteorological Center (RSMC)-Tokyo best track and the CNTL experiment than those of MOVE and MOVECP.

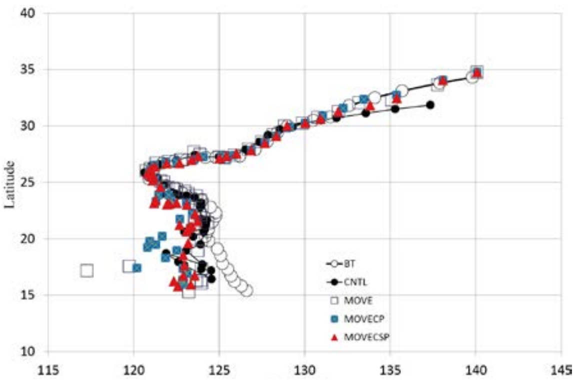

Figure 1 Results of analyzed center positions of Typhoon Sinlaku in CNTL, MOVE, MOVECP and MOVECSP along with the RSMC-Tokyo best track.

Figure 2 depicts the evolutions of analyzed central pressures along with the RSMC-Tokyo best-track central pressure. In the MOVECSP experiment, the falling rate of the analyzed central pressure was more rapid than that in the MOVECP experiment even though sea surface cooling induced by the storm was calculated in the forecast part for each cycle. The falling rate was similar to that in the CNTL experiment. TC intensification in the MOVECSP experiment occurred earlier than that in the MOVE experiment. The results suggest that the improvement of atmospheric surface boundary scheme is effective for the analysis of TC intensification in the NHM-LETKF system.

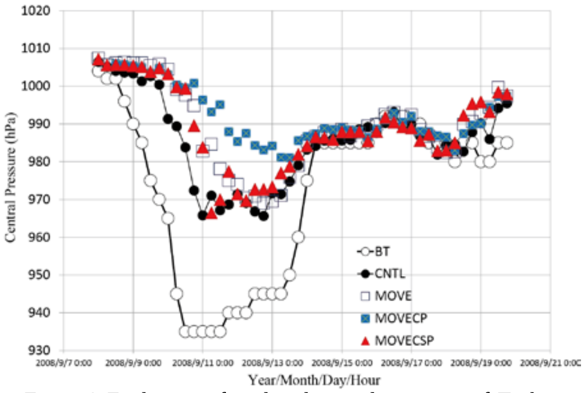

Figure 2 Evolutions of analyzed central pressures of Typhoon Sinlaku in CNTL, MOVE, MOVECP and MOVECSP along with the RSMC-Tokyo best track central pressure.

Figure 3 shows radial-height profiles of axisymmetrical mean radial and tangential flows in the MOVECSP and MOVECP experiments. Mean radial inflow and tangential flow in the MOVECSP experiment were stronger than those in the MOVESP experiment. This result suggests that the enhancement of turbulent heat fluxes near the atmospheric surface-boundary layer directly affect the inner-core structure of the TC and TC intensity analysis.

In Figure 3, a few peaks of radial inflow and tangential flow are analyzed. The distance of each peak from the storm center was longer than the analysis in Wu et al. (2012) and Huang et al. (2012). This is due to relatively coarse horizontal resolution (15 km) in the present experiments compared with 5 km in Wu et al. (2012) and Huang et al. (2012). However, the amplitude of radial inflow and the outer maximum tangential flow became greater due to the sea-spray parameterization in the NHM-LETKF system.

This study reveals that the impact of the sea-spray parameterization is effective to resolve the inner-core structure of the TC and thus improve the TC intensity analysis. However, high horizontal resolution (at least 5 km) is required to analyze the inner-core structure of the TC more accurately. In addition, the analysis in the ocean part needs to be developed.

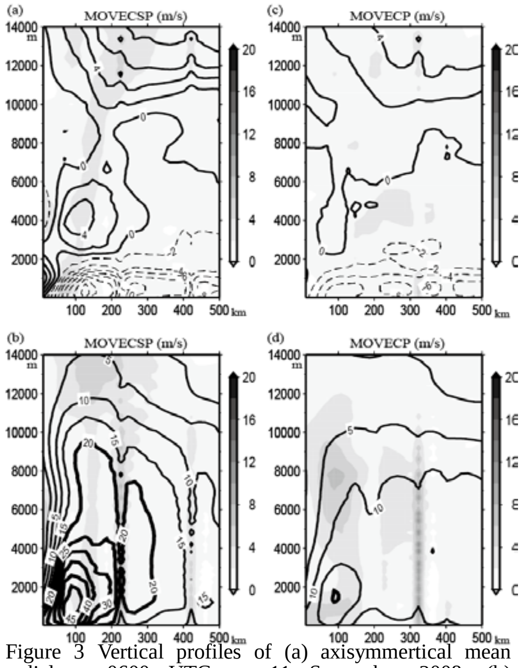

Figure 3 Vertical profiles of (a) axisymmertical mean radial at 0600 UTC on 11 September 2008, (b) axisymmertically mean tangential flow (contours) and the standard deviations (shades) in the MOVECSP experiment and (c) same as (a) except in the MOVECP experiment and (d) same as (c) except for axisymmertically mean tangential flow.

Acknowledgement

This work was supported by MEXT KAKENHI Grant Number 25106708 and by JSPS KAKENHI Grant Number 26800247.

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Roles of the ocean on extremely rapid intensification and the maximum intensity of Typhoon Haiyan in 2013

Akiyoshi Wada

Meteorological Research Institute, Tsukuba, Ibaraki, 305-0052, JAPAN

awada@mri-jma.go.jp

1. Introduction

Typhoon Haiyan was one of extremely intense tropical cyclones ever recorded. Lin et al. (2014) suggested that piling up warm subsurface water to the western part of the North Pacific Ocean and resultant subsurface warming created a very favorable pre-existing oceanic condition for the extraordinary intensity of Haiyan. Wada (2014) reported that rapid intensification of Haiyan and the minimum central pressure were simulated reasonably well using a nonhydrostatic atmosphere model (NHM) with a horizontal resolution of 2.5 km. The purpose of this study is to understand roles of preexisting oceanic conditions and storm-induced sea surface cooling on extremely rapid intensification and the maximum intensity of Haiyan by using the result of numerical simulations by an atmosphere-wave-ocean coupled model (CPL) with a horizontal resolution of 2.5 km.

2. Model and experimental design

Numerical simulations were performed by CPL (Wada et al. 2010). The computational domain is displayed in Fig. 1. The coupled model had 55 vertical levels with variable intervals from 40 m for the near-surface layer to 1013 m for the uppermost layer.

NHM and CPL had maximum height approaching nearly 26 km. The integration time was 84 hours (84 h) with a time step of 4 seconds in NHM. The time step of the ocean model was 24 seconds, six times that of NHM. That of the ocean wave model was 10 minutes. These time steps were the same as those in Wada et al. (2010).

Physical processes used in the simulations were almost the same as those of Wada et al. (2010) except for a sea spray parameterization (Bao et al. 2000) in the atmospheric surface-boundary layer.

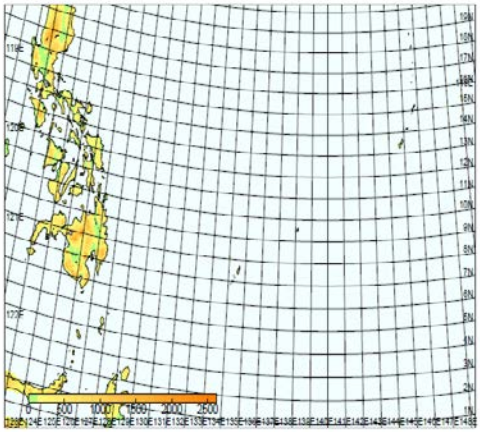

Figure 1 Computational domain with the horizontal resolutions of 2.5 km.

Oceanic initial conditions were obtained from the oceanic reanalysis datasets with a horizontal resolution of 0.5º calculated by the Meteorological Research Institute multivariate ocean variational estimation (MOVE) system (Usui, et al. 2006). This study used two data: One was daily oceanic reanalysis data on 5 November, 2013 and the other was the data on 5 November, 1993. In this study, the numerical experiment by NHM with the daily oceanic reanalysis data on 5 November 2013 calls NHM2013, while that by CPL calls CPL2013. The numerical experiment by NHM with the daily oceanic reanalysis data on 5 November, 1993 calls NHM1993, while that by CPL calls CPL1993.

3. Results and concluding remarks

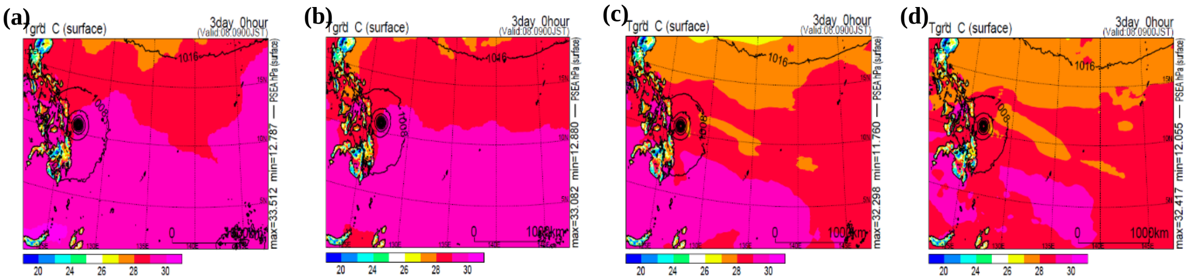

Figure 2 Horizontal distributions of sea surface temperature at 0000 UTC on 8 November (72 h integration time) in (a) NHM2013, (b) NHM1993, (c) CPL2013 and (d) CPL1993.

Figure 2 displays the horizontal distributions of sea surface temperature used in NHM2013 (Fig. 2a), NHM1993 (Fig. 2b), CPL2013 (Fig. 2c) and CPL1993 (Fig. 2d). The comparison between NHM2013 and NHM1993 reveals that the area at which sea surface temperature exceeded 30˚C was almost the same. In fact, sea surface temperature around 10°N, 140°E in NHM2013 near the track of Haiyan was lower than that in NHM1993. The comparison between CPL2013 and CPL1993 indicates that storm-induced sea surface cooling in CPL2013 was smaller than that in CPL1993. The result is consistent with Lin et al. (2014) in that subsurface warming in the northwestern Pacific Ocean played a role in suppressing vertical mixing in the upper ocean along the Haiyan's track.

The result of simulated tracks shows that preexisting oceanic conditions and storm-induced sea surface cooling had little impact on track simulations (not shown). In contrast, rapid intensification from 5 to 6 November was well simulated in the four simulations, irrespective of pre-existing oceanic conditions (Fig. 3). Rapid intensification in the CPL2013 and CPL1993 experiments was consistent with the Regional Specialized Meteorological Center (RSMC)-Tokyo Typhoon Center best track data. The impact of storm-induced sea surface cooling was remarkable: Storm-induced sea surface cooling did affect the simulated central pressure from 1800 UTC on 5 November. The difference of simulated central pressures between NHM and CPL increased during the intensification phase. The difference little changed after the storm reached the mature phase.

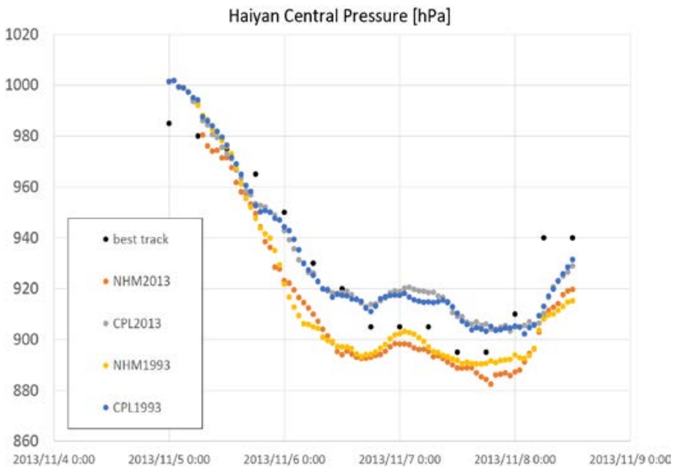

Figure 3 Results of simulated central pressure of Haiyan and RSMC-Tokyo best track central pressure.

Figure 4 displays axisymmetrical mean radial-height profiles of specific humidity and radial flow in the tropical-cyclone boundary layer. The height of the inflow layer exceeded 1000 m and the maximum inflow was located in around 25-50 km from the storm center. Above the edge of the inflow layer, the outflow was remarkable at around the height of 2000 m around the radius of 25 km. The axisymmetrical mean structure indicates that the simulated storm had a small inner-core structure. Simulated specific humidity was relatively high at around the height of 2000 m around the radius of 25 km in the NHM2013 experiment, indicating the occurrence of updraft at the eyewall. Storm-induced sea surface cooling simulated in the CPL2013 experiment affected the strength of the inflow in the tropical-cyclone boundary layer, that of the outflow, above the edge of the inflow layer, the updraft and the associated moisture transport to the upper layer.

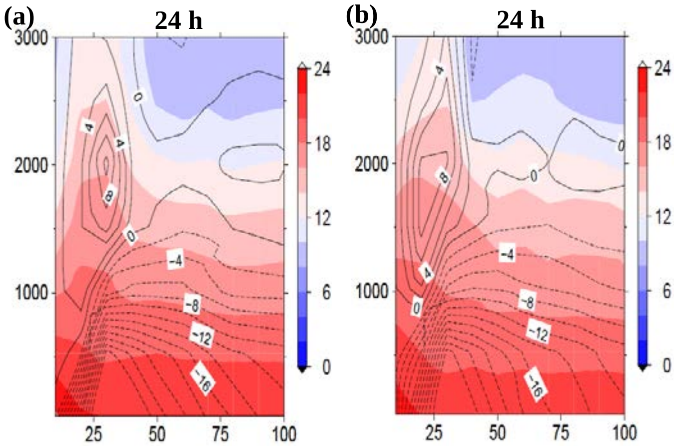

Figure 4 Axisymmetrical mean radial-height profiles of specific humidity (g/kg: Shades) and those of radial flow (m/s: contours) in (a) NHM2013 and (b) CPL2013. Soild contours indicate outflow, whereas dashed contours indicate inflow. Vertical axis shows heights (m) and horizontal axis shows a distance (km) from the storm center.

Therefore, the results of numerical simulations indicate that not only subsurface warming in the northwestern Pacific Ocean but also the ocean response to Haiyan should be considered to understand rapid intensification and resultant extremely strong intensity of Haiyan.

Acknowledgement

This work was supported by MEXT KAKENHI Grant Number 25106708.

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The effect of ocean coupling on torrential rains caused by Typhoon Man-yi in 2013

Akiyoshi Wada
Meteorological Research Institute, Tsukuba, Ibaraki, 305-0052, JAPAN
awada@mri-jma.go.jp

1. Introduction

Typhoon Man-yi (2013) underwent a rapid lowering of sea-level pressure near the coast of Japan, south of Shikoku Island, before it made landfall. The rate of lowering of sea-level pressures exceeded 2.5 hPa h^{-1} (60 hPa d^{-1}) over the ocean north of 30°N from 0600 to 1200 UTC on 15 September. The typhoon made landfall on 16 September near Toyohashi-city, Aichi Prefecture in Central Japan and caused torrential rains in Kinki districts. It was the first time that the special warming regarding torrential rains was issued around the region. Wada (2015) reported that both preexisting high sea surface temperature conditions and storm-induced sea surface cooling affected the extraordinarily heavy rainfall particularly in the northern Kinki districts, which was simulated reasonably well in the numerical experiments. However, Wada (2015) did not mention the background of the effect of ocean coupling on the extraordinarily heavy rainfall.

The purpose of this study is to clarify the effect of ocean coupling on the torrential rains occurred in Kinki districts due to the passage of Man-yi by using the results of numerical simulations, which is the same as the results of Wada (2015).

2. Model and experimental design

Numerical simulations were conducted by both a regional nonhydrostatic model (NHM) and a regional atmosphere-wave-ocean coupled model (CPL) developed by Wada et al. (2010). CPL covered a ~2000 km x ~2400 km computational domain with a horizontal grid spacing of 2 km. Hereafter, 'A' indicates the results by NHM, whereas 'AWO' indicates the results by CPL. The year is expressed by four digits, 2013. Both NHM and CPL had 40 vertical levels with variable intervals from 40 m for the near-surface layer to 1180 m for the uppermost layer. The top height was ~23 km.

The simulations used the Japan Meteorological Agency global objective analysis data for atmospheric initial and boundary conditions (with a horizontal grid spacing of ~20km) and the daily oceanic reanalysis data calculated by the Meteorological Research Institute multivariate ocean variational estimation (MOVE) system (Usui, et al. 2006) with the horizontal grid spacing of 0.1˚. The initial time was 0000 UTC on 14 September in 2013. The integration time was 60 hours. The model and experimental design are the same as Wada (2015).

3. Results and concluding remarks

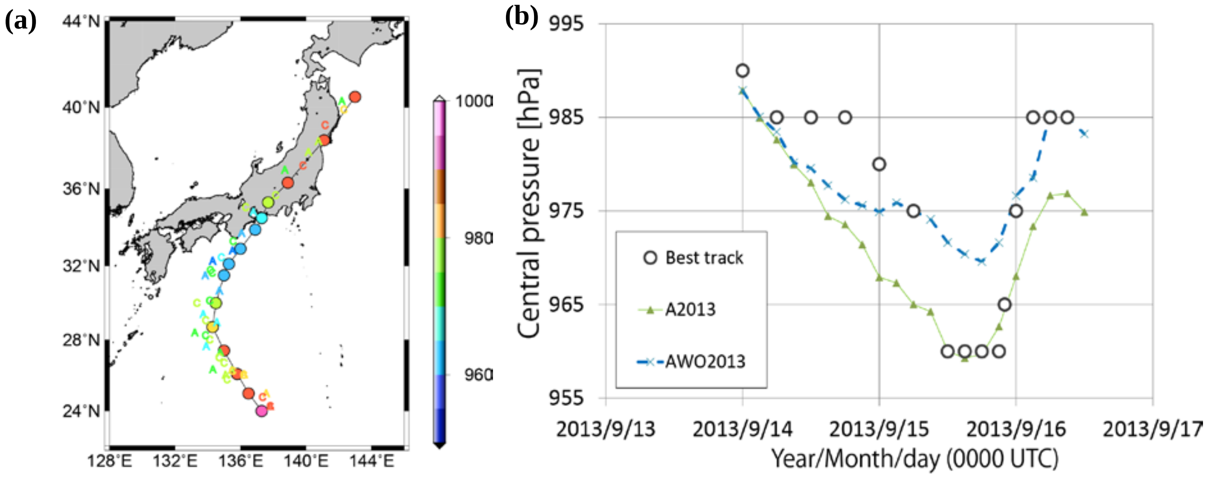

Figure 1 (a) Results of simulated tracks (A: NHM, C: CPL) and Regional Specialized Meteorological Center-Tokyo best track (b) Results of simulated central pressures and the best-track central pressure.

Figure 1 shows the results of simulated tracks (Fig. 1a) and central pressures (Fig. 1b). The coupling effect was negligible on the track simulation, whereas it was remarkable on the central pressure simulation. The A2013 experiment was able to simulate the minimum central pressure on 15 September reasonably well. However, the A2013 experiment indicated excessive intensification on 14 September. In that sense, the change in the simulated central pressure at the early integration time was improved in the AWO2013 experiment. An interesting issue in the simulations is the effect of the ocean coupling on the simulated precipitation.

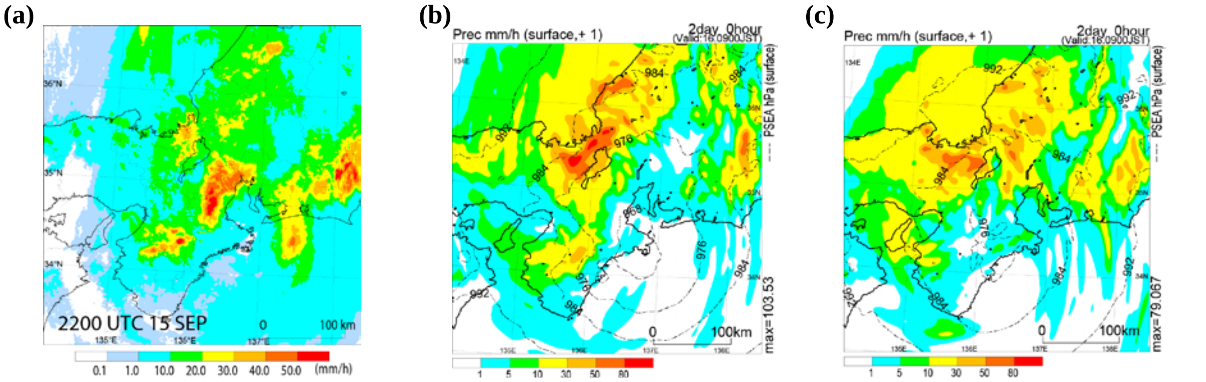

Figure 2 Horizontal distributions of accumulated hourly precipitation (a) by the Radar-Raingauge analyzed precipitation at 2200 UTC on 15 September, (b) in the A2013 experiment at 0000 UTC on 16 September and (c) in the AWO2013 experiment at 0000 UTC on 16 September. The unit is mm/hour.

Figure 2 displays the horizontal distribution of the Radar-Raingauge analyzed accumulated hourly precipitation and the results of numerical experiments. The corresponding time differed between the analysis and the results of numerical experiments because of the error of simulated track relative to the best track (Fig. 1a). Figure 2 reveals that the distribution of precipitation was asymmetric, indicating that the storm underwent axisymmetric-to-asymmetric transition. In particular, the precipitation was remarkable on the downshear left side of the northeastward moving direction of the typhoon (Wada, 2015). The feature was simulated reasonably well in both A2013 and AWO2013 experiments. However, the amount of the precipitation significantly reduced due to the ocean coupling.

Figure 3 shows the horizontal distribution of specific humidity at a height of 404 m in the atmospheric boundary layer at 0000 UTC on 16 September. The reduction of precipitation shown in Fig. 2 is consistent with the reduction of specific humidity in the boundary layer. Figure 3 indicates that specific humidity was relatively high around the storm center and on the right side of the moving direction. Around the Wakasa-Wan in the Sea of Japan, the linearly-aligned pattern apart from high specific humidity area on the right side of the moving direction was remarkable in both A2013 and AWO2013 experiments. The linearly-aligned pattern is closely related to extremely torrential rains in the northern Kinki districts (Fig. 1b-c). The results suggests that the ocean coupling did affect not only the rainfall around the storm center but also extremely torrential rains and the associated moisture distribution on the downshear-left side of the moving storm.

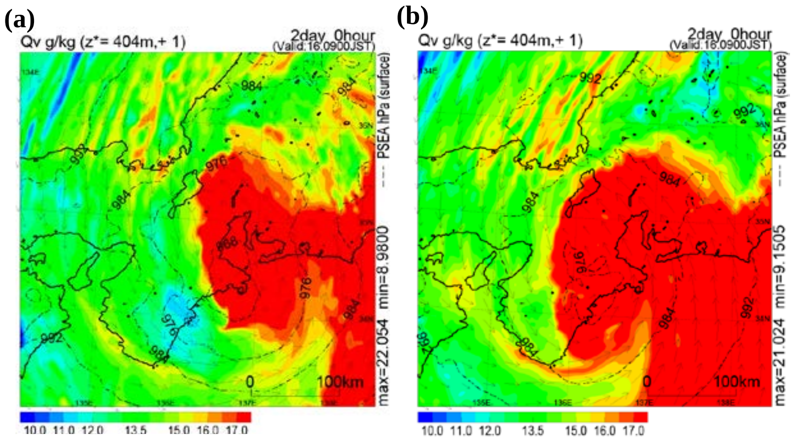

Figure 3 Horizontal distributions of specific humidity (g/kg) at a 404-m height at 0000 UTC on 16 September.

Acknowledgement
This work was supported by MEXT KAKENHI Grant Number 25106708

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The effects of ocean coupling and sea spray on the simulated track for Typhoon Muifa in 2011

Akiyoshi Wada
Meteorological Research Institute, Tsukuba, Ibaraki, 305-0052, JAPAN
awada@mri-jma.go.jp

1. Introduction

Previous studies have pointed out that the effect of ocean coupling on the simulated track of tropical cyclones was negligibly small compared with the effect of steering flow in the atmosphere. However, Wada (2014) demonstrated from the results of numerical simulations by using an atmosphere-wave-ocean coupled model that storm-induced sea surface cooling significantly affected the simulated track for Muifa in 2011 when the atmospheric steering flow was southwesterly and relatively weak. The question is whether the effect is caused by changes in the steering flow or by changes of the inner-core structure of a storm due to changes in turbulent heat fluxes near the air-sea interface from the ocean to the atmosphere.

The purpose of this study is to compare the simulated storm among different numerical experiments and to understand the effect of ocean coupling and increases in turbulent heat fluxes due to sea spray on the simulated track for Typhoon Muifa in 2011.

2. Model and experimental design

Numerical simulations were conducted by both a regional nonhydrostatic model (NHM) and a regional atmosphere-wave-ocean coupled model (CPL) developed by Wada et al. (2010). In addition, the sea spray parameterization (Bao et al. 2000) was incorporated into NHM (NHMSP) and CPL (CPLSP). The models covered a ~2200 km x ~2200 km computational domain with a horizontal grid spacing of 2 km. The models had 40 vertical levels with variable intervals from 40 m for the near-surface layer to 1180 m for the uppermost layer. The top height was ~23 km.

The simulations used the Japan Meteorological Agency global objective analysis data for atmospheric initial and boundary conditions (with a horizontal grid spacing of ~20km) and the daily oceanic reanalysis data calculated by the Meteorological Research Institute multivariate ocean variational estimation (MOVE) system (Usui, et al. 2006) with the horizontal grid spacing of 0.1˚. The initial time was 0000 UTC on 30 July in 2011. The integration time was 84 hours. The model and experimental design were the same as Wada et al. (2014) except for the sea spray parameterization.

3. Results and concluding remarks

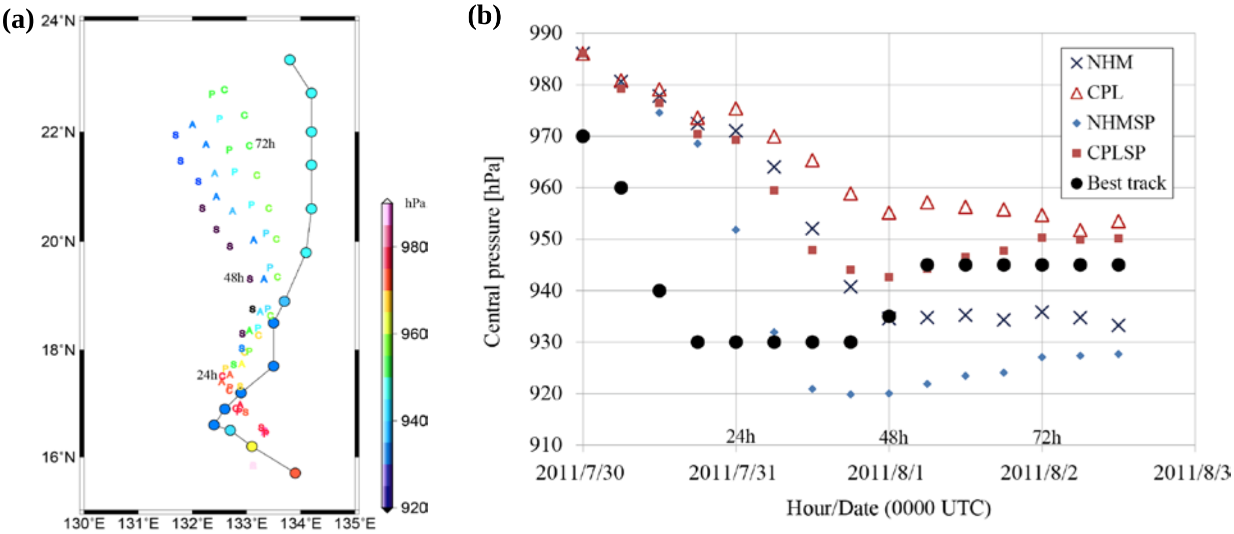

Figure 1 (a) Results of simulated tracks (A: NHM, C: CPL, S:NHMSP, P: CPLSP) and Regional Specialized Meteorological Center-Tokyo best track (b) Results of simulated central pressures and the best-track central pressure.

Figure 1 shows the results of simulated tracks (Fig. 1a) and central pressures (Fig. 1b) in the NHM, CPL, NHMSP and CPLSP experiments. The results of track simulations indicated that the track tended to shift westward as the simulated central pressure became low. All experiments poorly simulated rapid intensification of the storm occurred from 30 to 31 July in 2011. During the period, the simulated track showed the northward bias against the Regional Specialized Meteorological Center-Tokyo best track. Not only the ocean coupling but also sea spray parameterization did affect the simulated track through the change in turbulent heat fluxes near the air-sea interface.

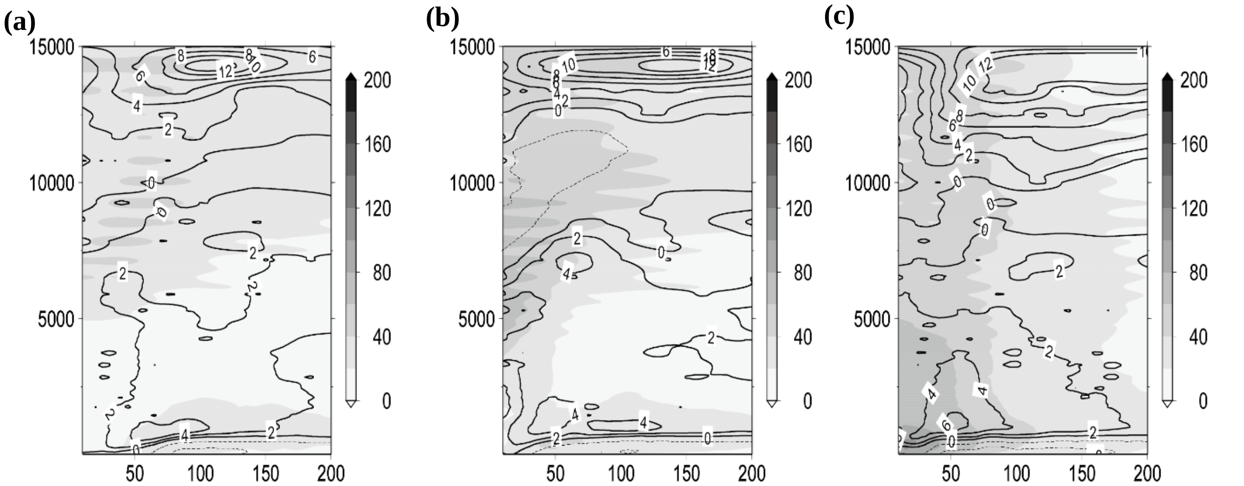

Figure 2 Axisymmetrical mean vertical profiles of radial flow (m/s: contours) and the standard deviation (m/s shades) in (a) NHM, (b) CPL and (c) NHMSP at 24 h, at 0000 UTC on 31 July. Soild contours indicate outflow, whereas dashed contours indicate inflow. Vertical axis shows heights (m) and horizontal axis shows a distance (km) from the storm center.

Figure 2 displays axisymmetrical mean radial-height profiles of radial flow and the standard deviation in the NHM, CPL and NHMSP experiments. In the tropical-cyclone boundary layer, the inflow became weak due to the effect of ocean coupling and resultant sea surface cooling (Wada et al. 2014). In addition, the location of the maximum outflow shifted outward from the radius of 120 km to that of 150 km. Even though the effect of the ocean coupling on the steering flow was small (Wada et al. 2014), the effect of ocean coupling on the inner-core structure of the simulated storm was remarkable.

The effect of sea spray parameterization on the inner-core structure of the simulated storm appeared not only in the tropical-cyclone inflow layer but also above the edge of the inflow layer and the outflow layer around the height of 14000 m. The effect of sea spray parameterization resulted in the asymmetry of the inner-core structure of the simulated storm. Above the edge of the inflow layer, the updraft became strong. The strong updraft was connected with the structure of the outflow layer. In this case, the location of the maximum outflow shifted inward compared with that in the NHM and CPL experiments.

Figure 2 also indicates that the amplitude of vertical shear was smallest in the CPL experiment, whereas that was greatest in the NHMSP experiment. However, the difference of the vertical shear on the simulated track was relatively small at 24 h and then became great after 24 h. Thus, the result of this study suggests that the changes of the inner-core structure resulted from the difference of turbulent heat fluxes lead to the changes of the steering flow and associated simulated tracks under the relatively weak atmospheric environmental flow.

As described in the introduction, this study addresses a rare case that storm-induced sea surface cooling significantly affected the simulated track. However, the result will contribute to improvement of "busts" of tropical cyclone track forecasts under a relatively weak steering flow. Further studies are needed to understand the role of ocean coupling and sea spray parameterization in track predictions.

Acknowledgement
This work was supported by MEXT KAKENHI Grant Number 25106708.

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