Science Bulletin 65 (2020) 1849–1858

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

Article

# A high-resolution Asia-Pacific regional coupled prediction system with dynamically downscaling coupled data assimilation

Mingkui Li [a,b], Shaoqing Zhang [a,b,c,d,*], Lixin Wu [a,b,*], Xiaopei Lin [a,b], Ping Chang [c,e], Gohkan Danabasoglu [c,f], Zhiqiang Wei [b], Xiaolin Yu [a,b], Huiqin Hu [b], Xiaohui Ma [a,b], Weiwei Ma [a], Dongning Jia [b], Xin Liu [g], Haoran Zhao [a], Kai Mao [a], Youwei Ma [d], Yingjing Jiang [d], Xue Wang [a], Guangliang Liu [g], Yuhu Chen [b]

[a] *Key Laboratory of Physical Oceanography, Ministry of Education/Institute for Advanced Ocean Study/Frontiers Science Center for Deep Ocean Multispheres and Earth System (DOMES), Ocean University of China, Qingdao 266100, China*
[b] *Pilot National Laboratory for Marine Science and Technology (Qingdao), Qingdao 266100, China*
[c] *International Laboratory for High-Resolution Earth System Model and Prediction (iHESP), Qingdao 266100, China*
[d] *The College of Oceanic and Atmospheric Sciences, Ocean University of China, Qingdao 266100, China*
[e] *Department of Oceanography, Texas A&M University, College Station, TX 77843, USA*
[f] *National Center for Atmospheric Research, Boulder, CO 80301, USA*
[g] *National Supercomputing Jinan Center, Jinan 250101, China*

ARTICLE INFO

*Article history:*
Received 6 March 2020
Received in revised form 20 June 2020
Accepted 22 June 2020
Available online 12 July 2020

*Keywords:*
High-resolution coupled models
Dynamically downscaling coupled data assimilation
Improved weather and typhoon forecasting
Extended-range predictability

ABSTRACT

A regional coupled prediction system for the Asia-Pacific (AP-RCP) (38°E–180°, 20°S–60°N) area has been established. The AP-RCP system consists of WRF-ROMS (Weather Research and Forecast, and Regional Ocean Model System) coupled models combined with local observational information through dynamically downscaling coupled data assimilation (CDA). The system generates 18-day forecasts for the atmosphere and ocean environment on a daily quasi-operational schedule at Pilot National Laboratory for Marine Science and Technology (Qingdao) (QNLM), consisting of 2 different-resolution coupled models: 27 km WRF coupled with 9 km ROMS, 9 km WRF coupled with 3 km ROMS, while a version of 3 km WRF coupled with 3 km ROMS is in a test mode. This study is a first step to evaluate the impact of high-resolution coupled model with dynamically downscaling CDA on the extended-range predictions, focusing on forecasts of typhoon onset, improved precipitation and typhoon intensity forecasts as well as simulation of the Kuroshio current variability associated with mesoscale oceanic activities. The results show that for realizing the extended-range predictability of atmospheric and oceanic environment characterized by statistics of mesoscale activities, a fine resolution coupled model resolving local mesoscale phenomena with balanced and coherent coupled initialization is a necessary first step. The next challenges include improving the planetary boundary physics and the representation of air-sea and air-land interactions to enable the model to resolve kilometer or sub-kilometer processes.


## 1. Introduction

Skillfully monitoring and predicting weather and climate states is of the utmost importance to ensure the safety of human living environments. Combined with instrumental measurements from the Earth observing system, a numerical model that discretizes dynamics equations with physics onto an Earth mesh system provides a platform that integrates the advances in geofluid science with observations and information technology. At present, climate models can assess climate change due to changes in anthropogenic climate process drivers by simulating the interactions among the atmosphere, ocean, land, and sea ice [1]. The development of coupled model data assimilation (CDA) allows the balanced and coherent incorporation of an Earth system model and the Earth observing system [2–4].

Currently, the most concerning question is: what are the impacts of global warming on local weather and climate anomalies, which directly influence the daily lives and societal production of local people? Climate science and societal needs require climate studies to better resolve and evaluate regional changes and/or variations as well as extreme events. Two important scientific questions require urgent clarification: (1) how do global change and/or large-scale fluctuations influence local weather and climate

* Corresponding authors.
*E-mail addresses:* szhang@ouc.edu.cn (S. Zhang), lxwu@ouc.edu.cn (L. Wu).

https://doi.org/10.1016/j.scib.2020.07.022
2095-9273/

anomalies? (2) How do local weather-climate perturbations provide feedback to the large-scale background? To address these questions, seamless weather-climate studies are an important research topic [5–8]. Thus, coupled modeling and CDA must simultaneously resolve higher resolutions and local meso- and small-scale physical processes in increasingly greater details [9] to assess the impacts on the local living environment and the environment's vulnerability. However, due to limited computing resources and knowledge on the local details of mesoscale physical processes, implementing such a numerical system at a global scale is currently implausible. Dynamic downscaling is usually an efficient approach [10–13], but most dynamical downscaling focuses on model simulations.

Here, we combine dynamical downscaling with CDA and design a computationally efficient extended prediction system over 10 d, which consists of multilevel high-resolution regionally coupled models and CDA systems nested with a coarse-resolution global prediction system. The dynamic downscaling coupled data assimilation approach is used to initialize the regional high-resolution coupled model in a balanced and coherent manner, where background information from the coarse-grid model and high-resolution observational information in the local domain are incorporated into the coupled model. This dynamic downscaling method optimally utilizes computational resources and enables efficient studies on meso- and small-scale activities. While such a framework efficiently advances our understanding of the attribution and impact of large-scale phenomena on local conditions, it also provides an opportunity to link scientific advances with severe weather alerts at the local level. This seamless weather-climate monitoring and prediction system with persistently improved modeling and assimilation processes will progressively advance climate sciences and promote local societal services.

A high-resolution regional coupled prediction system for the Asia-Pacific (AP-RCP) (38°E–180°, 20°S–60°N) area has been developed and run in a quasi-operational mode at QNLM. The model domain covers such a large area (roughly 1/3 of the global surface) that the core concern region has a minimized boundary effect in the prediction. Our high-resolution AP-RCP system is designed to overcome the following two deficits in the present weather and ocean forecasts: (1) as weather forecasts are based on atmosphere stand-alone models and use persistent rather than forecasted sea surface temperature (SST) as a forcing at the lower boundary, these models often encounter problems with representing important physical processes during extreme weather events, such as typhoons, over the oceans, which is where intense ocean-atmosphere exchange occurs. As a result, forecast uncertainties during such extreme weather events can grow quickly as the forecast lead time increases. With the exclusion of frontal and mesoscale air-sea interactions, the coarse-resolution coupled climate models have uncertainties caused by systematic errors and deficient resolutions. (2) Based on the weather forecast data and constrained by practical predictability of the numerical weather prediction, the ocean forecasts from an ocean stand-alone model have limited predictability in terms of forecast accuracy and lead time. While evaluation of the complete benefits of coupled model forecast system compared to atmosphere and ocean stand-alone systems still requires a great number of parallel numerical experiments, as the first step, here we report the development of the AP-RCP system, which is constructed by an advanced coupled regional forecast system and is expected to overcome the pitfalls of both atmosphere and ocean stand-alone systems. This system consists of a state-of-the-art cloud-permitting/eddy-resolving coupled atmosphere-ocean model capable of explicitly resolving small-scale air-sea processes.

The AP-RCP system consists of different resolution (the highest to 3 km) WRF (weather research and forecast) and ROMS (regional ocean model system) coupled models with dynamically downscaling coupled data assimilation to incorporate local detailed atmospheric and oceanic observational information. With the high-resolution and coherent coupled model initialization, the AP-RCP system improves weather forecasting over 10 d and can predict the genesis of typhoons in advance by a few days. With simultaneous multiresolution predictions, the results of the AP-RCP system offer opportunities to understand the impact of enhanced resolutions on coupled modeling and predictions.

The intent of this article is to document the feature and forecasting capabilities of the high-resolution AP-RCP system and to evaluate the impact of enhanced coupled model resolutions on mesoscale activity modeling and predictions by comparing two settings of resolutions on the same coupled model structure. We focus on the high-resolution coupled model behavior, improved precipitation and typhoon forecasting as well as certain important aspects of oceanic mesoscale activities, leaving the evaluation of the benefit of coupled model compared to atmosphere and ocean stand-alone models in the future studies when the constraint of computational resources is significantly relaxed.

## 2. The performance of high-resolution coupled models

The main region of the prediction system covers the Asia-Pacific area (AP, i.e., 38°–178°E, 16°S–63°N), which includes the Northwest Pacific and the north Indian Oceans (Fig. 1). The three coupled model versions with different resolutions are named 27v9 (27 km WRF coupled with 9 km ROMS), 9v3 (9 km WRF coupled with 3 km ROMS) and 3v3 (3 km WRF coupled with 3 km ROMS). The vertical layers of 27v9 WRF and ROMS are 28 and 33, and the ROMS maximum and minimum water depths are 5300 and 10 m, respectively. The time step for both WRF and ROMS is 60 s, and the coupled time step is 600 s. The 9v3 and 3v3 ROMS vertical layers and maximum water depth are changed to 40 and 5760 m, respectively. For the 3 km WRF, the cumulus convection parameterization scheme is turned off. The detailed coupled model settings are listed in Table S1 (online), and corresponding description can be found in the section of *Description of regional coupled model setting* in the Supplementary materials (online).

Both the 27v9 and 9v3 coupled models are initialized from the Climate Forecast System Version 2 (CFSv2) reanalysis [14] at 00 UTC 1 January 2016 and spun up for two years with the CFSv2 background boundary conditions. The following model performance analysis is based on the simulation results of 2017. Compared to the ERA-Interim reanalysis, both the 27v9 and 9v3 coupled models can reasonably simulate the intensity and position of the storm track in the area (Fig. S1 online). The higher-resolution 9v3 model simulates stronger storm tracks that are closer to the reanalysis, although the mean U velocities of 300 hPa in both the 27v9 and 9v3 simulations are slightly weaker than that of the reanalysis. Generally, in both the 27v9 and 9v3 simulations, the tropical cyclones (TCs) are more active (the TC count is much greater than in the observation data), but the capability to simulate super-strong typhoons is weak, although the number of typhoons with a maximum 10 m wind speed beyond 40 m/s increases significantly in the 9v3 model compared to the 27v9 model (Fig. S2 online). Both the 27v9 and 9v3 coupled models can simulate the Kuroshio path similar to the AVISO observations (Fig. S3a–c online), but while the 9v3 simulation is closer to the observations, the variability in the 27v9 (9v3) simulation is too weak (strong) (Fig. S3d–f online). Specifically, compared to the 27v9 system, the 9v3 can simulate the Kuroshio Large Meander (KLM) in the southeast of Japan as in the AVISO, but the Kuroshio Extension is too far north compared to the AVISO. Both the 27v9 and 9v3 coupled models simulate the mesoscale atmosphere-ocean coupling processes well, and the 9v3 higher-resolution model gives a more detailed structure, including smaller scales (Fig. 2 [15]) and a slightly stronger coupling strength (3.51 W $m^{-2}$ °$C^{-1}$ more in the 9v3 model than the 27v9). In addition, both the 27v9 and 9v3 models can capture the mesoscale and sub-mesoscale processes with seasonal variability (Fig. S4 online). We see that the simulation of the 9v3 higher-resolution model is stronger and has more detailed scales. In particular, the KLM in the 27v9 is too weak.

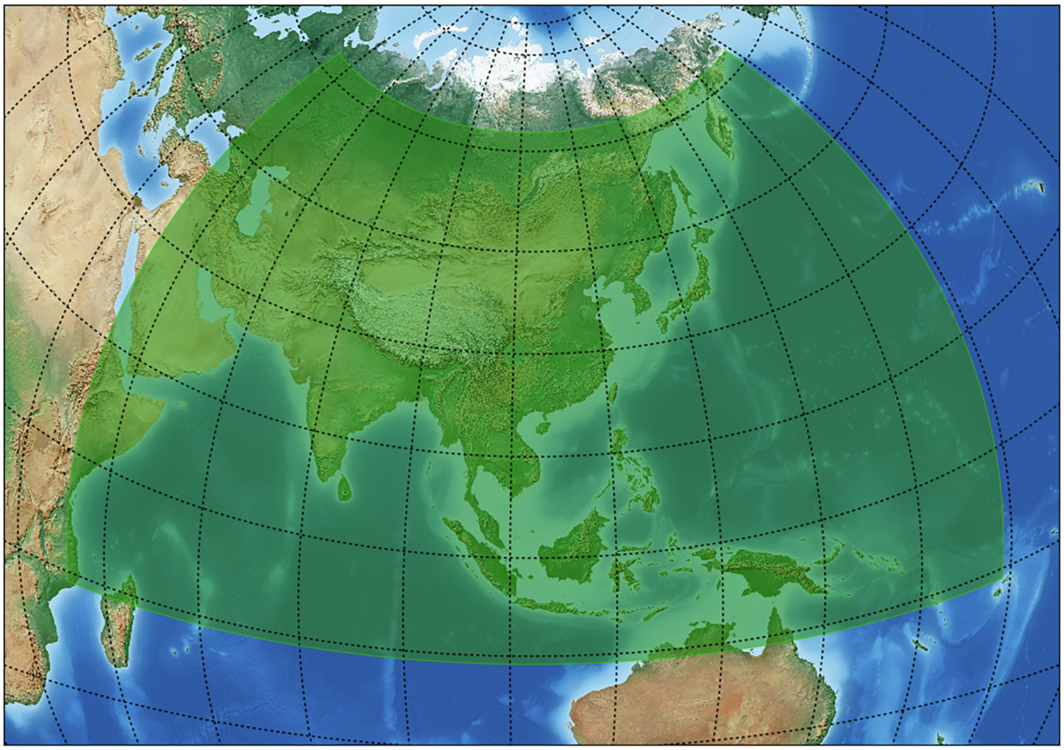

**Fig. 1.** Model domain in the AP-RCP system (38°–178°E, 16°S–63°N), covering the Northwest Pacific and the North Indian Oceans.

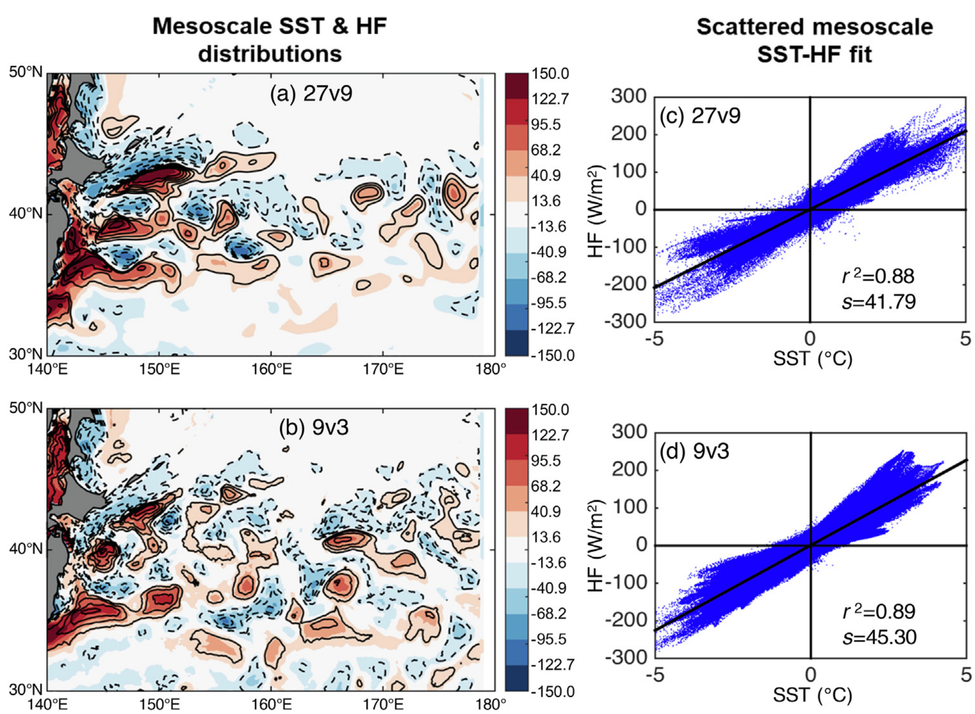


**Fig. 2.** Coherent distributions of mesoscale information in the AP-RCP coupled models. (a, b) The mesoscale SST (contour interval: 0.5 °C) and heat flux (HF, color-shaded; unit: W $m^{-2}$); (c, d) scattered point fitting in the SST-HF space (corresponding to *x*-axis and *y*-axis) in the 27v9 (a, c) and 9v3 systems (b, d). Both (c) and (d) show the correlation square ($r^2$) and the slope (*s*, unit: W $m^{-2}$ °$C^{-1}$) of the fitting lines. Here, following the same fashion to gain the mesoscale oceanic fronts and eddies [15], mesoscale SSTs and heat fluxes are derived by applying a high-pass filter of 5° × 5° running mean box.

## 3. Initialization of high-resolution coupled models

Initialization of the AP-RCP coupled system takes the weakly coupled data assimilation (WCDA) approach; i.e., within the coupled model framework, the atmosphere and ocean components conduct their own data assimilation procedure. After the 2-year spin up of the coupled models, the WCDA begins on 00 UTC 1 January 2018. Then, the atmosphere/ocean state is constrained by cycling through the real-time operational atmosphere/ocean data assimilation (ADA/ODA) processes with 6-h/daily updated observations, providing initial conditions for the routine forecasts. The forecasts also use the atmospheric (oceanic) boundary conditions interpolated from the CFSv2 forecast data. It's worth mentioning that the current use of CFSv2 is mainly for the real-time availability to meet the need of routine forecasts. More tests on ECMWF products and QNLM-running global forecasts are under evaluation for future usage.

### *3.1. Atmosphere initialization*

The WRF model uses the standard 3-dimensional variational data assimilation (WRF3D-Var) [16,17] further incorporates the local atmospheric observations (an example of the network at 00 UTC on October 1, 2017, is shown in Fig. S5 online) to update the atmospheric states and impact the whole coupled system through flux exchanges at a 6-h assimilation frequency. Through the ADA, the model fitting to the observations gains significant improvement [18]. With the Noah land model [19] setting in all resolution, the WCDA is expected to constrain the land state by some degree through the planetary boundary processes, although there is no direct land data assimilation for land model initialization.

### *3.2. Ocean initialization*

In ODA, the ocean model temperature and salinity (TS) are filtered through two steps. First, the TS profiles are vertically adjusted on each model column that has available sea surface height (SSH) observations. Second, a multiscale 3-dimensional variational assimilation (M3D-Var) analysis process is used to assimilate *in situ* T and S profile data, which first works horizontally, then loops by level with a high-efficiency multiscale scheme. With the multiscale ODA scheme, the AP-RCP system was run in a test mode starting from October 15, 2017. As discussed in details in Li et al. [18], the ODA incorporates the local ocean observations and significantly improves the ocean initial conditions as well as SST forecasts. The major SST error after ODA is in the KLM and Kuroshio Extension area. More detailed evaluation of the coupled initial conditions can be found in the section of *Additional analysis of the AP-RCP initial states* in the Supplementary materials (online).

### *3.3. The coupled prediction system with different resolution models*

The AP-RCP system uses 4500 processing element (PE) cores of Intel Xeon E5-2667 CPU and runs routinely with an Intel® Omni-Path Architecture. Currently, there are three forecasting systems to make forecasts (Fig. S6 online), including a relatively low-resolution 27v9 (27 km WRF coupled with 9 km ROMS), a high-resolution 9v3 (9 km WRF coupled with 3 km ROMS) and a higher-resolution 3v3 (3 km WRF coupled with 3 km ROMS). The system development begins from the forecast using the 27v9 system. Considering the computational efficiency, the coupled restart states of the 9v3 are regridded for the 3v3 forecasts, as shown in Fig. S6 (online). There are 6 daily-based ensemble members for 27v9 with slightly different atmospheric initial conditions (±6-h) and one member for 9v3, while the 3v3 forecasting system runs on an irregular timeline when a severe weather event such as a strong TC emerges due to the constraint of computational resources. All the evaluations in this study are based on the unperturbed forecast member (the first member). All the forecast schedules can be found in the section of *Description of AP-RCP forecasting schedule* in the Supplementary materials (online). Since the required computational resource of 9v3 is more than 10 times of 27v9, from a view of operational feasibility, the 27v9 system is more appropriate as a routinely-operational system, while the 9v3 system can serve as a research testbed. For the 3v3 system, it even requires 10 times of computational resources of the 9v3. Then the constraint of computational resource is a major obstacle on the development of high-resolution coupled prediction system. We will discuss more on this point in Section 6. We also have some comparisons between different resolution model data and observations to help people better understand the AP-RCP system (Figs. S7–S14 online).

The Luzon Strait and South China Sea (SCS) has complex topography and multiscale dynamical processes [20], thus being special challenging in modeling. While the major characteristics of circulations at the Luzon Strait and South China is shown in *Meso and small-scale characteristics in the Luzon Strait and South China Sea* under the section of *Additional analysis of the AP-RCP initial states* in the Supplementary materials (online), here we examine the overflow structures of the Luzon Strait in 27v9 and 9v3 DA results (Fig. 3 [21]) as an example to demonstrate the importance of model resolution. The overflow structures of the Luzon Strait in the HYCOM ocean reanalysis data and the 27v9 and 9v3 initial conditions, overall, all have a similar south-in (easterly) and north-out (westerly) patterns, but in terms of detailed strength and position, the 9v3 is the best fitting to the observations, although variability is still weak (compare Fig. 3a–c to Fig. 3i and Fig. 3d–f to Fig. 3j, respectively). Comparing Fig. 3g with Fig. 3h, we can see that with the resolution of the detailed bathymetric structure of the Luzon Strait, the 3 km ROMS can more realistically represent the deep-ocean (up to 3270 m at the Luzon Strait) water exchange flows between the West Pacific and SCS than the 9 km ROMS (up to 2750 m at the Luzon Strait). It's worth mentioning that considering there is no 2012 model result or 2018 observation, and that the annual mean may not change too much (which is supported by the HYCOM annual means of 2012 and 2018), this comparison of 2018 model annual mean and 2012 observational annual mean is expected to give us an overall understanding, not quantitatively though. The comparison of the SCS interior U and V velocities among the CFSv2, 27v9 and 9v3 AP-RCP systems as well as the HYCOM ocean reanalysis product (Fig. S14 online for U velocities) reveals similar characteristics, i.e., the CFSv2 is the weakest due to having the coarsest resolution, while the 9v3 product gives stronger and more detailed structures, especially for the deep ocean from 500 to 3000 m. However, even in the 3 km ocean model, the structures of the Bashi Channel and Heng-Chun Ridge in the Luzon Strait are still not sufficiently accurate. More studies need to be performed to clarify the impact of the more realistic Bashi Channel and Heng-Chun Ridge structures on the SCS deep ocean circulations. Here, the results of 3 km versus 9 km models on the Luzon Strait may have an implication on the importance of kilometer level modeling for the Atlantic meridional overturning circulation for which strait overflows of Denmark Strait and Faroe Bank Channel play critical roles [22].

## 4. TC forecasts and upper ocean responses on TC passing

### *4.1. TC genesis, lifecycle intensity and track forecasts*

Considering that a TC is an atmospheric response to a warm ocean surface [23,24], when the coupled model can resolve the

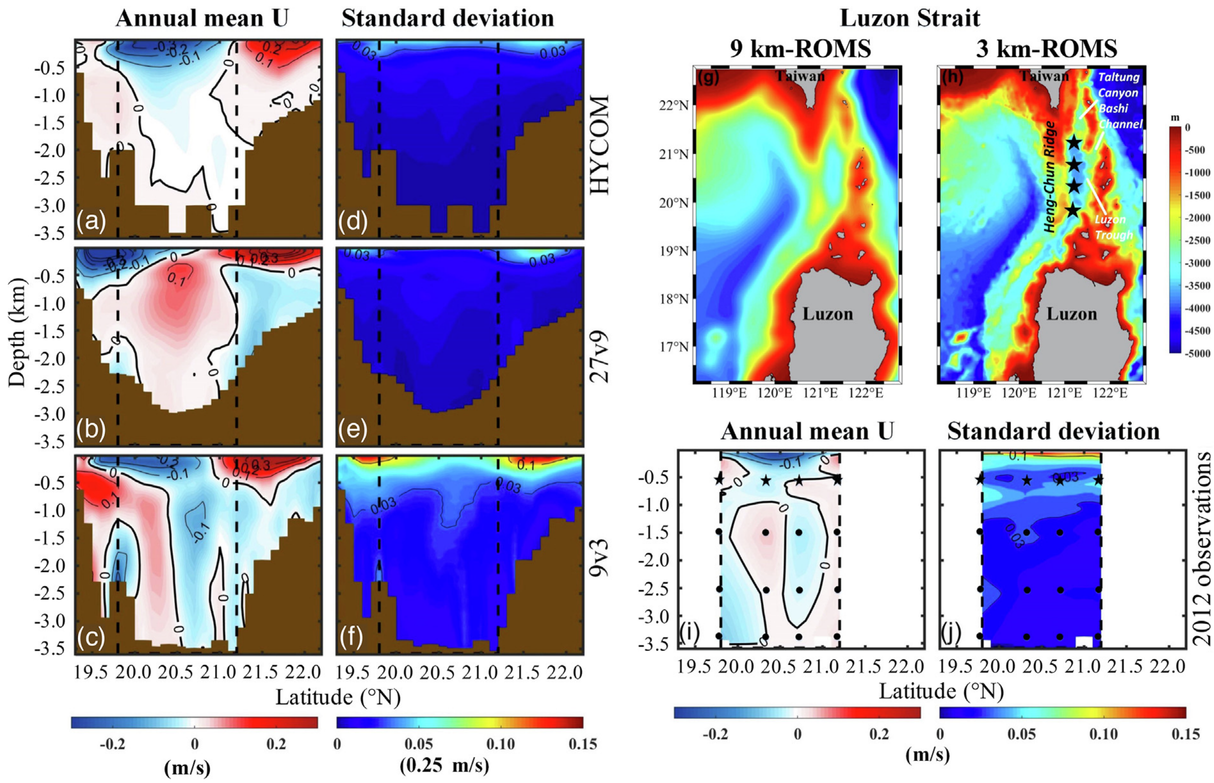


**Fig. 3.** Better representation of higher-resolution model for the Luzon Strait flows. The distribution of the 2018 annual mean of the U velocities in the Luzon Strait (a–c) and their standard deviations (d–f) in (a), (d) HYCOM ocean reanalysis, (b, e) 27v9 and (c, f) 9v3 AP-RCP system initial conditions. (g), (h) The bathymetry of the Luzon Strait in the 9 km (3 km) ROMS model. (i) and (j) are taken from Zhang et al. [21] for the 2012 observed annual mean U velocities and standard deviation at the 4 locations marked in (h). The observational locations marked in (c) and (f) are for convenience of comparison with (i) and (j). Note that model variability is much weaker than the observation.

detailed air-sea interactions, it is expected that a properly initialized high-resolution coupled model can predict TC genesis on a reasonable time scale [25]. The examination of the 21 (20) TC cases detected in the 27v9 (9v3) initial conditions in the 2018 typhoon season has shown that 18 (80%) and 19 (95%) onsets can be predicted two days in advance by 27v9 and 9v3 respectively [18]. But the number of predicted onsets drops by 60% for both systems with a forecast lead time of 3 d, and continuously drops up to 5% (for the 27v9) and 10% (for the 9v3) with a forecast lead time of 5 d. While the error of the onset times in the initial conditions in the 27v9 and 9v3 systems is roughly within the uncertainty range between the CMA (China Meteorological Administration) and JMA (Japan Meteorological Agency) data, the error increases with the forecast lead time, but within a 48-hour range. Similarly, the errors of onset position and maximum wind speed increase with the forecast lead time, while the errors of onset minimum pressure do not increase significantly with the forecast lead time. Regarding TC track forecasts, both the 27v9 and 9v3 systems can generally trace the TC tracks for approximately 8 d (50% of the initialized TCs still survive). While the higher-resolution 9v3 system always shows a notably lower maximum wind speed error than the 27v9 system throughout the forecast period, the minimum center pressure errors behave indistinguishably between the 27v9 and 9v3 systems. For the forecast errors of the TC positions, both the 27v9 and 9v3 systems exhibit similar behaviors, but after 5 d, the error of the higher-resolution 9v3 system is a little higher, suggesting the complexity and uncertainty of TC track predictability.

These results suggest that the enhanced model resolution can consistently improve the TC intensity forecasts, but the impact of the enhanced model resolution on the TC track forecasts tends to be more complex and requires further studies for clarification. In addition, the impact of physics scheme (with cumulus parameterization and cloud resolving schemes, as well as the underneath land condition in detailed features, for instance) on TC track and intensity is also an important aspect that needs further examinations in the high-resolution coupled simulations in the future studies.

*4.2. Upper ocean responses to typhoon passing*

As the first step to study the impact of an enhanced model resolution on the typhoon position forecasts, we show the track forecasts of two strong typhoons: Mangkhut (the 22nd in 2018) and Kong-Rey (the 25th in 2018) in Fig. 4. The 6 h locations in the 27v9 (blue) and 9v3 (red) AP-RCP systems are shown, which were initialized at 00 UTC 6 September (for Mangkhut) and 00 UTC 29 September (for Kong-Rey). For the Mangkhut case, we can see that in terms of track locations, the 27v9 and 9v3 forecasts are very close. For the Kong-Rey case, the 27v9 forecast changes direction slightly early, while the 9v3 overshoots toward the west. In both cases, the 27v9 and 9v3 forecasts are close to the observations before the decay phases of the typhoons but begin departure from the observed tracks after approximately 8–10 d. We also observed that the lifetimes of the predicted typhoons are longer than those of the actual typhoons, especially in the 27v9 system. Subsequent analyses of the detailed TC structure and associated environment will show that the enhanced-resolution system can describe the interaction process between the TC and environment with more detailed structures, which may help to enhance the accuracy of the simulated TC intensity and lifetime.

We use Mangkhut and Kong-Rey as examples to examine the differences between models with different resolutions to simulate the detailed environment and internal structures of the atmosphere/ocean around/underneath the typhoon (Figs. 5 and S15–S18 online).

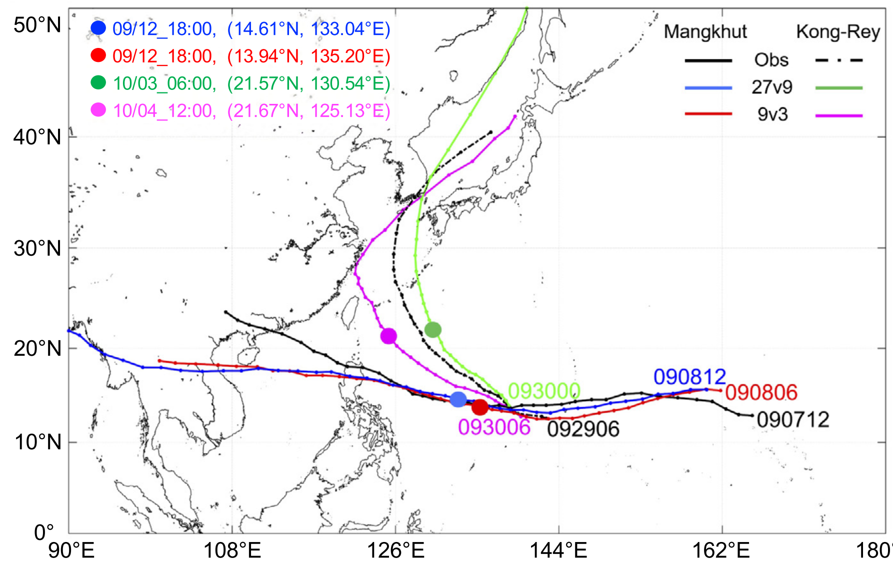


**Fig. 4.** The examples of forecasted typhoon tracks in the AP-RCP system. The forecasted (color) tracks of Typhoon Mangkhut (onset on 12 UTC of September 7; the 22nd of 2018) and Kong-Rey (onset on 06 UTC of September 29; the 25th of 2018) compared to the corresponding satellite observations (black, from the IBTRACS data, International Best Track Archive for Climate Stewardship). The blue and green (red and purple) line represents the forecast results produced by the 27v9 (9v3) AP-RCP system for Mangkhut and Kong-Rey, while the corresponding big dots on the tracks mark the time and location of the 27v9-forecasted (9v3-forecasted) typhoons Mangkhut and Kong-Rey, for which the vertical/horizontal atmosphere and/or ocean conditions are shown in Figs. 5 and S15–S18 (online). Here the small dots along the tracks are the positions of the typhoons with 6-hourly intervals, while the big red/green dots represent the strongest time/location. The numbers in the same color as the track at the starting position of each track line denote the onset time (for example, "090712" means 12UTC, September 7).

In the strongest phases of the typhoons (Mangkhut at 00 UTC on September 13 and Kong-Rey at 06 UTC on October 4), we found distinguishable differences between the 27v9 and 9v3 systems, besides different locations of typhoon center. First, following a deeper and drier eyewall passing in the 9v3 system, clearly delayed upper ocean mixing is observed (compare Fig. 5b to a and Fig. S15 online, respectively). Due to enhanced mixing, both systems show a deeper mixing layer underneath the typhoons, and stronger downwelling is observed immediately following the typhoon passing in the 9v3 system with different 50–100 m temperature-salinity structures. It's worth mentioning that since the locations of the typhoon center at their strongest phase are a little different in the two systems, all comparisons above only can provide an overall qualitatively understanding instead of a precisely quantitative comparison.

The 27v9 and 9v3 systems both show strong precipitation at the front of the typhoon eye (Fig. S16 online), but the 9v3 system has a clearer spiral cloud rain belt structure (compare Fig. S16b, d to Fig. S16a, c online). We also see that the upper ocean water becomes cold after the typhoon passes in both systems, probably due to the lagged mixing [26] (Figs. 5 and S15 online), but the 9v3 shows a more asymmetric structure (Figs. S17 and S18 online). Consistent with the precipitation distribution and current structures, considering freshwater transport, salty/fresh water is located on the right/left hand side of the typhoon passing track in both systems, but again, the 9v3 system shows clearly asymmetric characteristics, while the 27v9 system shows roughly symmetric distributions. In addition, as the ocean responds to the typhoon, a slightly rear-slanted eddy is observed at the rear of the typhoon. These common and different characteristics of ocean structures in the 27v9 and 9v3 systems can be traced down to a depth of 50 m (Figs. S17c, f and S18 online), which shall be further studied in the future to examine the detailed response of ocean mixing with meso- and small-scale activities during strong TCs. For example, the cross-experiments using the 3 km (9 km) ROMS with 27v9-produced (9v3-produced) fluxes can increase our understanding of the response of ocean meso- and small-scale activities to different scale atmospheric forcings. In addition, given the importance of a more accurate initial structure of the vortex with balanced and coherent environmental conditions for the evolution of a TC track and intensity [27,28], the TC forecast skill of the AP-RCP system could be improved with a more advanced initialization technique [29], especially convection-permitting initialization scheme [30].

## 5. Precipitation forecasts

To evaluate the capability of the 27v9 and 9v3 systems for rainfall forecasts over the Asia-Pacific area, we compare the rainfall forecast skills of both systems with the NCEP-GEFS (global ensemble forecast system) and ECMWF-EPS (ensemble prediction system). Due to the enhanced model resolution, the 9v3 AP-RCP system forecasts the precipitation closest to the observations, and the 27v9 system performs better than the other 3 systems (Fig. S19 online). Consistently, the 9v3 AP-RCP precipitation forecast in China has higher equitable threat score (ETS) and lower false alarm ratio (FAR) than the 27v9 system, and both are much better than the CFSv2 forecast (Fig. 6, [31,32]). Here both ETS and FAR (the definition is given in the section of *Definition of ETS and FAR* in the Supplementary materials (online)) are station-based statistical skills in the China mainland area. In the current AP-RCP system, except for grid spacing, neither specific initialization scheme nor fine-grid match land surface information has been applied to land processes. Given the land processes being an important part of planetary boundary layer processes, once the representation of land processes is improved through initialization and/or addition of detailed feature information, it is expected that the NWP forecast skills of the AP-RCP system can be further improved.

## 6. Summary and discussions

A high-resolution regional coupled prediction (RCP) system for the Asia-Pacific (38°E–180°, 20°S–60°N) area has been developed

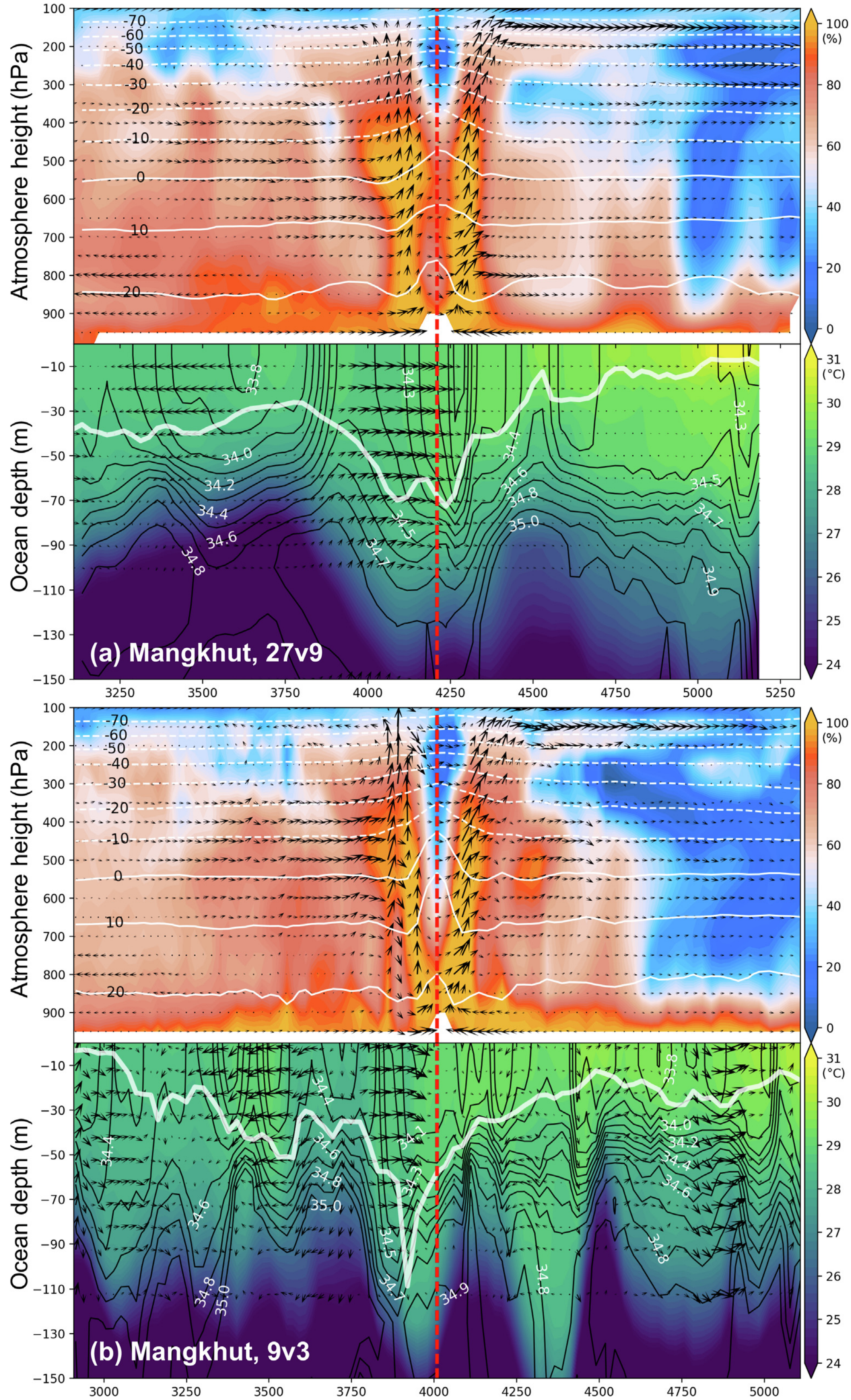


**Fig. 5.** The coherent vertical structure of atmosphere and ocean conditions of strong typhoon passing. The atmosphere and ocean conditions on the air-sea interface (vertical section) along with the Typhoon Mangkhut track in the strongest phases (at 18 UTC on September 12) in the 27v9 (a, marked by the blue dot in Fig. 4) and 9v3 (b, marked by the red dot in Fig. 4) AP-RCP systems. The dashed red vertical line represents the center of the typhoon; the atmosphere (ocean) relative humidity (%) (temperature: °C) is color shaded, while the atmosphere (ocean) temperature (°C) (salinity: psu) is contoured, and the vector arrows always represent the atmospheric winds (m/s) (ocean currents: 0.04 m/s) along the track. The white line represents the mixing layer depth, and the long red arrow marks the movement direction of the typhoon.

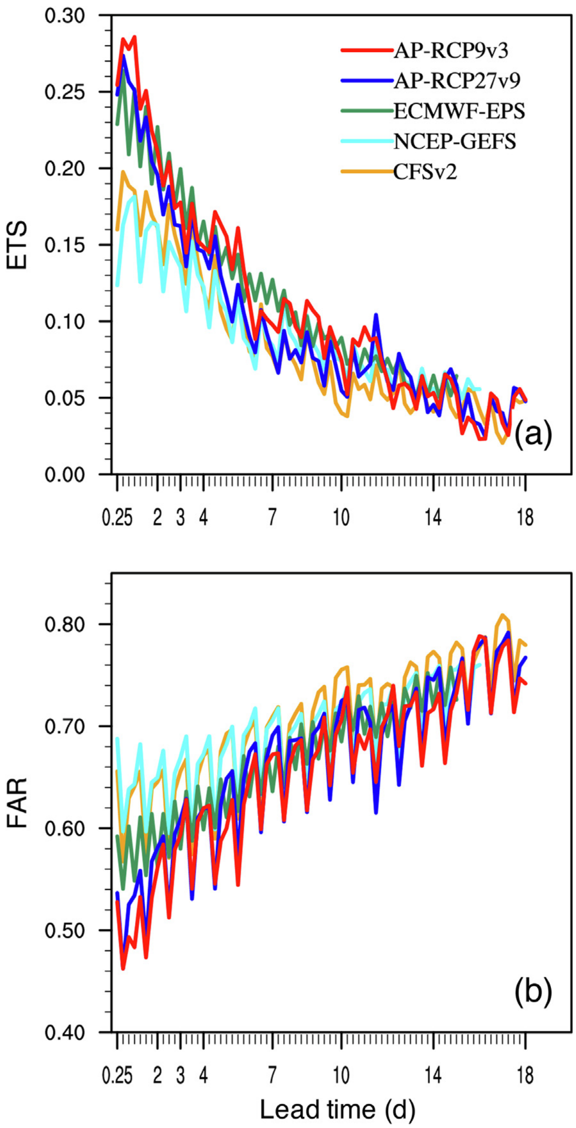


**Fig. 6.** The rainfall forecast skill of the AP-RCP system. The variation in ETS (a, equitable threat scores) and FAR (b, false alarm ratios) for the precipitation forecasts in the AP-RCP system with the 9v3 (red) and 27v9 (blue) models and ECMWF-EPS (ensemble prediction system, green), NCEP-GEFS (global ensemble forecast system, cyan) and CFSv2 (yellow) with the forecast data statistics shown against the station observation data over the China mainland in August and September of 2018 (CMORPH CMA data, http://data.cma.cn/data/cdcdetail/dataCode/SEVP_CLI_CHN_MERGE_CMP_PRE_HOUR_GRID_0.10.html [31,32]).

by combining the WRF + ROMS coupled model with dynamically downscaling coupled data assimilation. The current version of the AP-RCP system uses the CFSv2 product as the background. The system is set to configurations with 3 different resolutions—27 km WRF + 9 km ROMS (27v9), 9 km WRF + 3 km ROMS (9v3) and 3 km WRF + 3 km ROMS (3v3)—and provides a large amount of high-resolution coupled model prediction data (https://pan.baidu.com/s/1hG5tMbJ3p7qOJLWPLDuh2Q). This system serves as an effective research platform to study the impact of model resolution on typical mesoscale atmospheric and oceanic phenomena in this area, such as the West Pacific typhoons and the eddies along with Kuroshio and Kuroshio Extension (KE). While the 3v3 prediction system is run in an irregular need-based mode due to the constraint of computational resources, the 9v3 and 27v9 systems are in a quasi-operational mode. The first version of the system consists of multiscale atmosphere and ocean data assimilations implemented by a 3D-Var method on a daily assimilation cycle. The evaluation analysis of this study focuses on the results of 27v9 and 9v3 predictions with statistics of a whole year of data series. The overall reasonable behavior of the system is described, and the impact of enhancing model resolution on the simulations of Kuroshio, KE and KLM (Kuroshio Large Meander), local basin circulations in the SCS and Luzon Strait overflows, and so on are evaluated. Then, the forecast capabilities for the West Pacific typhoons, East Asia precipitation and mesoscale eddies in the Northwest Pacific are also assessed. The 3v3 system is under systematic evaluation, and the preliminary comparison with the 9v3 result shows the highter-resolution atmospheric model can reduce the upper-ocean forecast errors (Fig. S20 online). We found that although many issues associated with the high-resolution coupled model require further study, enhancing the coupled model capability to resolve many local details is a necessary step to extend the predictability of the atmosphere and ocean environmental conditions beyond 10 d.

We evaluated the initial conditions and forecasted results of the 27v9 and 9v3 systems by comparing to the products of CFSv2 and HYCOM and established the following findings:

(1) Among the model-based analysis products – CFSv2, 27v9, 9v3 and HYCOM, the 9v3 and HYCOM have similar qualities in temperature and salinity properties, verified against Argo observations.
(2) The 9v3 and HYCOM have similar structures in the KLM and KE, while the 27v9 has a smooth but overly strong West Boundary Current (WBC), and the CFSv2's WBC is too weak.
(3) The eddy counts in the 27v9 and 9v3 systems as well as HYCOM are closer to the AVISO, but have more eddies in the short lifetime band and fewer eddies in the long lifetime band (10 d or beyond).
(4) All the model-based products (CFSv2, 27v9, 9v3 and HYCOM) have overall similar westerly-in-north and easterly-in-south patterns in the Luzon Strait, but 9v3 has the best fit to the HYCOM reanalysis in terms of detailed strength and overflow positions, while CFSv2 is too weak. The same characteristics hold for the SCS interior U (V) velocity distributions.
(5) Overall, both 27v9 and 9v3 systems can predict the genesis of a tropical cyclone (TC) in advance by a few days with an onset time uncertainty of less than 48 h. In describing the interaction process between the TC and environment with greater detail, the 9v3 system can more accurately forecast the TC intensity and lifetime.
(6) Among the CFSv2, NCEP-GEFS, ECMWF-EPS, 27v9 and 9v3 predictions, the 9v3 rainfall forecast skill is the highest, and overall speaking, the 9v3 and 27v9 precipitation forecasts are both better than the others.

This study is a preliminary evaluation of the high-resolution coupled prediction system with only one-year quasi-operational runs, serving as a catalyst for studies on the impacts of km-level resolution coupled models on the simulation and prediction of the atmosphere–ocean environment. While further analyses will be conducted with more forecast data, specific research that will improve our understanding of seamless weather-climate simulation and prediction will include the following topics:

(1) How to properly set the dissipation when the model resolution is higher? The current 9v3 system produces stronger mesoscale activities, which may be responsible for the large error in the KE area.

(2) How to improve the planetary boundary layer (PBL) physics and increase representation of the air-sea and air-land interactions as the model resolution is increasingly higher? What is the impact of PBL processes with the underlying surface resolved in details on simulation of the meso- and small-scale atmospheric activities?
(3) When the high-resolution observations are unavailable and previous understanding is based on studies of relatively coarse-resolution models, how to evaluate the different characteristics of high-resolution simulation and prediction? For example, the current 9v3 system produces more detailed flow structures in the Luzon Strait and SCS than the 27v9 and HYCOM, although with similar background patterns. These detailed flows may add more insights on the previous studies on the structures of the "traditional" 3-layer [33] and overturning [34] circulations in the SCS basin since such circulations represent the integral effect of detailed flows in the whole interior of the basin.
(4) Given that predictability of the TC onset and intensity as well as its track is strongly dependent on the individual TC properties, how to use multiple-resolution coupled prediction systems to further study the impact of detailed structures of TCs on TC predictions, thus sorting out the source of such predictability?
(5) Given the importance of resolving more realistic strait structures for representing overflows/throughflows between ocean basins and resolving more accurate boundary processes for simulating mesoscale weather phenomena, a 3v1 (3 km WRF + 1 km ROMS) coupled prediction system may be necessary to address the issues raised in this study. How can we overcome the constraint of computational resources? One of the solutions is the Escala heterogeneous many-core Sunway machine, which will soon be installed at QNLM. Once the AP-RCP system is optimized on the Escala Sunway machine (currently, the system has been ported on the pretest Sunway machine), another door for seamless weather-climate simulation and prediction studies will be opened.
(6) Once the constraint of computational resources is relaxed by the home-growth Escala Sunway machine, we can thoroughly examine the role of high-resolution atmosphere–ocean coupled model on predictability of mesoscale atmospheric and oceanic phenomena compared to atmosphere and ocean stand-alone models. We also need to detect the relative benefits of atmospheric and oceanic resolutions for achieving a specific goal by testing the system with different resolution combinations on atmosphere and ocean model components. For that regard, a 9v9 system may be the first step to get results compared to 27v9 and 9v3. Through the comparison of simulation/prediction on typical weather phenomena such as TCs and/or ocean mesoscale eddies/fronts, we can gain insights on the relative importance of the model components for the analysis and prediction.

## Conflict of interest

The authors declare that they have no conflict of interest.

## Acknowledgments

This work was supported by the National Key Research and Development Program of China (2017YFC1404100, 2017YFC1404104), the National Natural Science Foundation of China (41775100, 41830964), and the Shandong Province's "Taishan" Scientist Project (2018012919). This work was also within the collaborative project between the Ocean University of China (OUC), Texas A&M University (TAMU) and the National Center for Atmospheric Research (NCAR) and completed through the International Laboratory for High Resolution Earth System Prediction (iHESP) – a collaboration among QNLM, TAMU and NCAR. Authors thank anonymous reviewers for their thorough examinations and useful and helpful comments on the early version of the manuscript. The reanalysis data and observations used to do the comparison are from HYCOM (https://www.hycom.org), NOAA AVHRR (https://www.ncdc.noaa.gov/oisst/data-access), IBTrACS (https://climatedataguide.ucar.edu/climate-data/ibtracs-tropical-cyclone-best-track-data), NCEP-GEFS (https://www.nco.ncep.noaa.gov/pmb/products/gens/), ECMWF-EPS (https://www.ecmwf.int/en/forecasts/datasets), CMORPH (https://www.cpc.ncep.noaa.gov/products/janowiak/cmorph_description.html), and GDAS (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-data-assimilation-system-gdas). The data used to produce the figures and analyses in this work are available through the link https://pan.baidu.com/s/1hG5tMbJ3p7qOJLWPL-Duh2Q (password: 25jz) or by sending a written request to the corresponding author (Shaoqing Zhang, szhang@ouc.edu.cn).

## Author contributions

Mingkui Li is responsible for all plots, initial analysis and some writing; Shaoqing Zhang and Lixin Wu lead the project, organize and refine the paper; all other co-authors make equal contributions by wording discussions, comments and reading proof.

## Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.scib.2020.07.022.

## References

[1] Randall DA, Wood RA, Bony S, et al. Climate change 2007: the physical science basis. Cambridge: Cambridge University Press; 2007. p. 589–662.
[2] Zhang S, Harrison MJ, Rosati A, et al. System design and evaluation of coupled ensemble data assimilation for global oceanic climate studies. Mon Weather Rev 2007;135:3541–64.
[3] Saha S, Moorthi S, Pan HL, et al. The NCEP Climate Forecast System Reanalysis. Bull Amer Meteorol Soc 2010;91:1015–57.
[4] Laloyaux P, de Boisseson E, Balmaseda M, et al. Cera-20c: a coupled reanalysis of the twentieth century. J Adv Model Earth Sys 2018;10:1172–95.
[5] Wang B, Rui H. Synoptic climatology of transient tropical intraseasonal convection anomalies - 1975–1985. Meteorol Atmos Phys 1990;44:43–61.
[6] Kim OY, Wang B, Shin SH. How do weather characteristics change in a warming climate? Clim Dyn 2013;41:3261–81.
[7] Zhang S, Zhao M, Lin SJ, et al. Impact of having realistic tropical cyclone frequency on ocean heat content and transport forecasts in a high-resolution coupled model. Geophys Res Lett 2015;42:5966–73.
[8] Alley RB, Emanuel KA, Zhang FQ. Advances in weather prediction. Science 2019;363:342–4.
[9] Zhang S, Zhao M, Lin SJ, et al. Retrieval of tropical cyclone statistics with a high-resolution coupled model and data. Geophys Res Lett 2014;41:652–60.
[10] Rockel B, Castro CL, Pielke RA, et al. Dynamical downscaling: assessment of model system dependent retained and added variability for two different regional climate models. J Geophys Res-Atmos 2008;113:D21107.
[11] Hostetler SW, Alder JR, Allan AM. Dynamically downscaled climate simulations over North America: methods, evaluation, and supporting documentation for users. US Geological Survey Open-File Report 2011;2011–1238:64.
[12] Gula J, Peltier WR. Dynamical downscaling over the great lakes basin of north america using the WRF regional climate model: the impact of the great lakes system on regional greenhouse warming. J Clim 2012;25:7723–42.
[13] Komurcu M, Emanuel KA, Huber M, et al. High-resolution climate projections for the northeastern United States using dynamical downscaling at convection-permitting scales. Earth Space Sci 2018;5:801–26.
[14] Saha S, Moorthi S, Wu XR, et al. The NCEP Climate Forecast System Version 2. J Clim 2014;27:2185–208.

[15] Ma X, Jing Z, Chang P, et al. Western boundary currents regulated by interaction between ocean eddies and the atmosphere. Nature 2016;535:533–7.
[16] Courtier P, Thepaut JN, Hollingsworth A. A strategy for operational implementation of 4D-Var, using an incremental approach. Q J R Meteorol Soc 1994;120:1367–87.
[17] Barker DM, Huang W, Guo YR, et al. A three-dimensional variational data assimilation system for MM5: implementation and initial results. Mon Weather Rev 2004;132:897–914.
[18] Li M, Zhang S, Wu L, et al. An examination of the predictability of tropical cyclone genesis in high-resolution coupled models with dynamically downscaled coupled data assimilation initialization. Adv Atmos Sci 2020. https://doi.org/10.1007/s00376-020-9220-9.
[19] Niu GY, Yang ZL, Mitchell KE, et al. The community Noah land surface model with multiparameterization options (Noah-MP): 1. model description and evaluation with local-scale measurements. J Geophys Res 2011;116:D12109.
[20] Zhang Z, Zhao W, Qiu B, et al. Anticyclonic eddy sheddings from Kuroshio Loop and the accompanying cyclonic eddy in the northeastern South China Sea. J Phys Oceanogr 2017;47:1243–59.
[21] Zhang Z, Zhao W, Tian J, et al. Spatial structure and temporal variability of the zonal flow in the Luzon Strait. J Geophys Res 2015;120:759–76.
[22] Danabasoglu G, Large WG, Briegleb BP. Climate impacts of parameterized Nordic Sea overflows. J Geophys Res 2010;115:C11005.
[23] Emanuel KA. On thermally direct circulations in moist atmospheres. J Atmos Sci 1995;52:1529–34.
[24] Emanuel KA. The behavior of a simple hurricane model using a convective scheme based on subcloud-layer entropy equilibrium. J Atmos Sci 1995;52:3960–8.
[25] Emanuel KA. 100 Years of progress in tropical cyclone research. Meteorol Monogr 2018;59:15.11–68.
[26] Lee CY, Chen SYS. Symmetric and asymmetric structures of hurricane boundary layer in coupled atmosphere wave ocean models and observations. J Atmos Sci 2012;69:3576–94.
[27] Fudeyasu H, Wang YQ, Satoh M, et al. Multiscale interactions in the life cycle of a tropical cyclone simulated in a global cloud-system-resolving model. Part i: large-scale and storm-scale evolutions. Mon Weather Rev 2010;138:4285–304.
[28] Fudeyasu H, Wang YQ, Satoh M, et al. Multiscale interactions in the life cycle of a tropical cyclone simulated in a global cloud-system-resolving model. Part ii: system-scale and mesoscale processes. Mon Weather Rev 2010;138:4305–27.
[29] Cha DH, Wang YQ. A dynamical initialization scheme for real-time forecasts of tropical cyclones using the WRF model. Mon Weather Rev 2013;141:964–86.
[30] Schwartz CS, Liu ZQ. Convection-permitting forecasts initialized with continuously cycling limited-area 3DVAR, ensemble Kalman filter, and "hybrid" variational-ensemble data assimilation systems. Mon Weather Rev 2014;142:716–38.
[31] Yu J, Shen Y, Pan Y, et al. Comparative assessment between the daily merged precipitation dataset over China and the world's popular counterparts. Acta Meteorol Sin 2015;73:394–410 (in Chinese).
[32] Sun R, Yuan H, Liu X, et al. Evaluation of the latest satellite-gauge precipitation products and their hydrologic applications over the Huaihe River basin. J Hydrol 2016;536:302–19.
[33] Gan JP, Liu ZQ, Hui CR. A three-layer alternating spinning circulation in the South China Sea. J Phys Oceanogr 2016;46:2309–15.
[34] Shu Y, Xue HJ, Wang DX, et al. Meridional overturning circulation in the South China Sea envisioned from the high-resolution global reanalysis data GLBa0.08. J Geophys Res Oceans 2014;119:3012–28.

Mingkui Li is an associate professor at Key Laboratory of Physical Oceanography, Ministry of Education, Ocean University of China. He received his Ph.D. degree from the Institute of Oceanology, Chinese Academy of Sciences in 2005. The major research interest includes regional climate modeling, developing data products from high-resolution model simulations and developing automated data visualization tools.

Shaoqing Zhang is a professor at Key Laboratory of Physical Oceanography, Ministry of Education, Ocean University of China (POL/OUC), and Pilot National Laboratory for Marine Science and Technology (Qingdao). He received his Ph.D. degree from the Florida State University, USA, in 2000. The major research interest includes coupled Earth system modeling, seamless weather-climate predictability, coupled model data assimilation and parameter estimation.

Lixin Wu, Fellow of Chinese Academy of Sciences, American Geophysical Union, and the World Academy of Sciences, heads Pilot National Laboratory for Marine Science and Technology (Qingdao). He also serves as the vice president of the Ocean University of China and the director of Key Laboratory of Physical Oceanography, Ministry of Education. His research focuses on dynamics of ocean circulation and air-sea interaction.