Rainfall and Tropical Cyclone Activity over Vietnam Simulated and Projected by the Non-Hydrostatic Regional Climate Model – NHRCM

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(Manuscript received 7 December 2014, in final form 1 October 2015)

Abstract

This study uses the non-hydrostatic regional climate model (NHRCM) to simulate and project rainfall and tropical cyclone (TC) activity over Vietnam. The simulated precipitation shows that climatic heavy rainfall centers are well captured in the seasonal march. In near and far future, the projected rainfall by NHRCM using outputs of the Meteorological Research Institute atmospheric general circulation model 3.2 with RCP8.5 scenario will clearly decrease in Northwest and Central Vietnam in June–August, while it will remarkably increase in Northeast and Central Vietnam in September–November. The model underestimates TC number and activity area in the first half of the TC season but slightly overestimates in the second half as compared to the best track. Projected TCs indicate a decrease in both TC number and activity area in near and far future. Moreover, the maximum TC number occurs one month late as compared to the present climate, whereas TC number remarkably decreases in July–August in far future. Rainfall induced by TCs increases in North Vietnam in the projected climate as compared to the baseline period. It also increases in mid-Central Vietnam in near future but decreases in southern Central Vietnam in near and far future. Conversely, non-TC rainfall is likely to decrease in North Vietnam in future and in mid-Central Vietnam in near future but increase in southern Central Vietnam in far future.

Keywords  dynamical downscaling; projected rainfall; projected tropical cyclone; NHRCM model

1. Introduction

In recent years, atmospheric general circulation models (AGCMs) are the most advanced tools for global climate simulations and projections (Oouchi
Statistical downscaling is the establishment of empirical statistical relations between local climate variables and large-scale predictors, which is then applied to AGCM outputs to simulate or project future local climate features (Kim et al. 1984; Wilby et al. 1998). This approach has the advantage of computational efficiency but a disadvantage in being able to capture extreme phenomena and physically consistent variables (Lim et al. 2007). Dynamical downscaling is the use of higher resolution regional climate models (RCMs) to reproduce local climate using AGCM outputs as initial and boundary conditions (Giorgi and Mearns 1999; Wang et al. 2004).

According to Shiogama et al. (2008), mean and extreme precipitation will increase in the tropics and higher-latitude regions, while it will decrease in the subtropics up to the year 2030. As climate projections are available from AGCMs, several studies have been carried out for various regions using higher resolution RCMs for more detailed future climate (Christensen et al. 2007). Higher resolution models require stronger computational facilities; however, mesoscale disturbances can be better reproduced. For example, Tsunematsu et al. (2013) dynamically downscaled MIROC3.2 projections and indicated that mean daily rainfall amounts increase in windward sides of the mountainous regions of Japan in summer months. Gao et al. (2006) pointed out that increasing model resolution is important to improve the simulation of monsoon precipitation over East Asia.

Under the context of climate change, there have been several studies related to 2-m air temperature and rainfall trends in historical data as well as climate projections by RCMs in Vietnam and adjacent regions. Endo et al. (2009) showed that precipitation extremes increase in the south while they decrease in the north of Vietnam based on daily rainfall data of the second half of the 20th century. In the study by Ho et al. (2011), the Regional Climate Model version 3.0 (RegCM3) is utilized to project extreme climatic events over Vietnam in the years 2001–2050 using the A1B and A2 emission scenarios. It can be found that hot days will increase in summer and cold nights will decrease in winter due to global warming. Heavy rainfall events tend to decrease over all sub-regions except Northwest and South Central Vietnam. In terms of mean rainfall, Ngo-Duc et al. (2014) used three regional climate models and showed that projected rainfall varies inconsistently from South Central Vietnam northward in summer, while it increases consistently in fall in the 2000–2050 period.

Previous dynamical downscaling studies for Vietnam region were mostly done by hydrostatic models, where information on tropical cyclone (TC) activity is also deficient. Moreover, all of them are limited to the middle 21st century that could limit the applicability of climate change information. It is noteworthy that the climate in lower-latitude regions, such as the Vietnam-East Sea, is strongly modulated by deep convection systems (Truong et al. 2009; Chen et al. 2012). In the latest years, however, the non-hydrostatic regional climate model (NHRCM) has been widely used in Japan as a productive tool to project local climate. For example, Sasaki et al. (2012, 2013) indicated that temperature and heavy rainfall are projected to increase while snow depth will decrease over Japan in future. As the first step to evaluate NHRCM’s ability to simulate and project climate in the tropics, the primary aim of this study is to apply the model to assess changes in rainfall and TC activity over Vietnam both in near and far future climate. In the next section, numerical experiments and data are given. Section 3 describes results and discussions. Concluding remarks are given in Section 4.

2. Methods and data

2.1 Methods

NHRCM used in this study is the extended version of Non-Hydrostatic Model (NHM) wherein the soil model is replaced by MRI-Simple Biosphere model (MRI-SiB; Hirai et al. 2007), and lateral boundary conditions are replaced by spectral nudging boundary conditions. The detail descriptions of NHM can be found in Saito et al. (2006). The model is able to simulate regional climate and dynamically downscale AGCM outputs for Japanese geophysical domain (Kitoh et al. 2009; Sasaki et al. 2012, 2013).

The model domain extends for about 91.4°E–128.4°E and 1.6°S–30.3°N (Fig. 1) with a 20-km grid spacing and 40 vertical levels. The Truong Son Mountains are clearly seen in the model topography along the border between Laos and Vietnam. Initial and boundary conditions for NHRCM are the
MRI-AGCM3.2 outputs with a 60-km grid spacing supplied by the SOUSEI Program. The AGCM3.2 was jointly developed by Japan Meteorological Agency (JMA) and Meteorological Research Institute (MRI) of Japan based on a numerical weather prediction model operationally used by JMA, wherein several modifications are implemented in radiation and land surface processes for use in climate simulation (Mizuta et al. 2012). NHRCM is integrated for the baseline period from 1979 to 2003 and for the near (2015–2039) and far (2075–2099) future period (i.e., 25 years for each period) under the RCP8.5 scenario. Details on sea surface temperatures used in these experiments can be found in Mizuta et al. (2012). Lateral boundary conditions are updated every 6 h.

2.2 Data

The APHRODITE (Asian Precipitation Highly-Resolved Observational Data Integration towards Evaluation) daily gridded precipitation (Yatagai et al. 2012) is used to validate distributions of the simulated rainfall over the whole domain. In addition, daily rain gauge data observed at 59 selected meteorological stations during the baseline period are used to estimate the seasonal march of the simulated rainfall in three sub-regions of Vietnam. The observation sites, including 21 stations in North Vietnam (NVN), 31 stations in Central Vietnam (CVN), and 7 stations in South Vietnam (SVN), are shown in Fig. 2. The number of stations in SVN is smaller than the other sub-regions since the terrain is flat there. Most stations in CVN are located to the east of the Truong Son Mountains.

It is observed that rainfall in NVN is governed by early summer TCs, northward migration of the intertropical convergence zone (ITCZ), and mesoscale convective systems. Southwesterly summer monsoon is the predominant precipitating mechanism in SVN (Pham et al. 2010). CVN, however, has rainy season delayed until fall and early winter due to fall TCs, southward-migration ITCZ, and cold surges and interactions among them and topography (Yokoi and Matsumoto 2008; Yen et al. 2011). Therefore, the present study climatic rainy season in CVN includes September, October, and November (SON), while the other two sub-regions have the rainy season in June, July, and August (JJA). Presented in Fig. 3 are mean rainfall and 850 hPa winds produced by the MRI-AGCM3.2 for the baseline and future period, where simulated and projected heavy rainfall centers are found to be located along the Thai–Laotian border and over most of NVN in JJA when the summer monsoon prevails (Figs. 3a, c, e). Conversely, heavy rainfall centers are distributed in the form of narrow belts to the east of the Truong Son Mountains in CVN due to the reversal of the prevailing winds (Figs. 3b, d, f). Compared to the baseline and near future period, the projected rainfall clearly increases...
over Southeast Asia and southeastern coastal region of China in far future SON (Fig. 3f).

Because TCs climatically make landfall to Vietnam from May to December, we divide the TC season in Vietnam into two halves. The first half includes May–August (MJJA) when TCs frequently affect NVN, while the second one includes September–December (SOND) when TCs often hit CVN. TCs detected by NHRCM satisfy the criteria for grid-point variables, including minimum surface pressure in $7^\circ \times 7^\circ$ grid box, 850-hPa maximum relative vorticity, maximum wind speed at 850- and 300-hPa level, temperature structure in the lower troposphere, and TC duration. Refer to Oouchi et al. (2006) for more details. The best track and intensity of TCs in the Northwestern Pacific are collected from the website http://weather.unisys.com for the period 1979–2003. Such data source is used because it includes tropical depressions (TDs) that are also able to produce heavy rainfall in Vietnam.

3. Results and discussions

3.1 Projected rainfall

Figure 4 shows distributions of the JJA mean APHRODITE rainfall, JRA-25 850 hPa winds and the corresponding NHRCM rainfall, and 850 hPa winds during the baseline period of 1979–2003 (Figs. 4a, b). It can be seen that the southwesterly summer monsoon is well reproduced to dominate in South Indochinese Peninsula that then curves east of the Philippines to create the monsoon trough, whose axis crosses NVN in the northwest–southeast direction. Even though meridional winds are somewhat underestimated in South China and around Hainan Island. Precipitation simulated by NHRCM is overestimated on the windward side of the Truong Son Mountains in Laos and along the coast of the Malaysian Peninsula and Cambodia as compared to the reanalysis. However, the heavy rainfall centers given by the model are in much better agreement with the APHRODITE than those given by the MRI-AGCM3.2, including an overestimate of rainfall over NVN (i.e., Fig. 3a). This could be due to the better representation of topography in NHRCM (Xie et al. 2006).

To assess future rainfall changes during the 2015–2030 and 2075–2099 periods in the RCP8.5 scenario, the ratio of the future and baseline rainfall are illustrated in Figs. 4c and 4d. The ratio greater than 100% indicates increasing precipitation and vice versa. It is realized that precipitation will decrease to about 70–90% compared to the baseline in Northwest and Central Vietnam and a large part of Southeast China in near future. There will be little changes in rainfall amount in Northeast and South Vietnam while precipitation increases noticeably in the Malaysian Peninsula. It will be therefore expected that dry and hot weather will increase in summer months in CVN, where the Föhn effect often occurs due to the summer monsoon impinging on topography (Nguyen-Le et al. 2014). The decreasing trend of precipitation continues to be maintained and enhanced in Northwest and Central Vietnam in the far future period. However, precipitation shows increasing trends to ~140% in SVN, especially in the Malaysian Peninsula and north of the Yangtze River.

The SON mean APHRODITE rainfall, JRA-25 850 hPa winds, and the corresponding NHRCM rainfall and 850 hPa winds are given in Figs. 5a and 5b. Although a cyclonic circulation covering the East Sea between Vietnam and Philippines is captured by the model, it is stronger as compared to that of the JRA-25 winds. The trade winds are clearly observed to the north of the cyclonic circulation. Northeastery winds prevailing from south China to NVN indicate early winter cold surges that merge with the...
Fig. 3. JJA (a, c, e) and SON (b, d, f) mean rainfall and 850 hPa winds given by the MRI-AGCM3.2 during 1979–2003 (a, b), 2015–2039 (c, d), and 2075–2099 (e, f) period.
trade winds to the north of 16°N over the East Sea and CVN. It is clear that a simulated intensive rain belt occupies most of CVN to the east of the Truong Son Mountains in a similar fashion to the reanalysis. However, the rainfall amount given by NHRCM is again overestimated. This intensive rain belt is induced by a convergence of the northeasterly moisture flow nearly normal to the Truong Son Mountains. During fall in near future, precipitation tends to increase in NVN and northern CVN while shows a remarkable decrease over the Yangtze River basin (Fig. 5c). The increasing pattern is dramatically extended westward to North Thailand and southwestward to West Cambodia and the peninsular part of Thailand in far future, except for southern CVN. An increasing trend is also observed in a large part of Southeast China, including the Yangtze River basin (Fig. 5d). As previously mentioned, such trends are also found in the projected rainfall produced by the MRI-AGCM3.2 (i.e., Fig. 3f). Therefore, this could be a result of a much warmer climate in the late 21st century that may more often favor conditions to form clouds and precipitation, such as instability in the lower troposphere, moisture supplies, etc.

Distributions of the annual mean rainfall, 850 hPa winds, and future change ratios of rainfall are shown in Fig. 6. Accordingly, the simulated winds and some heavy rainfall centers such as in Northwest, Central, and South Central Vietnam are in good agreement with the JRA-25 and APHRODITE data (Figs. 6a, b). It is noteworthy that although the APHRODITE data provides convenient pictures of spatial rainfall
distribution, it may underestimate the rainfall amount in comparison with the rain gauge data observed at meteorological stations in Vietnam (Fig. 2). Annual precipitation seems to be unchanged over the whole domain in near future (Fig. 6c). Conversely, it slightly increases in limited areas of the northeastern and southeastern coastal zone of Vietnam and the southwestern coastal zone of Cambodia and detectably increases in the Malaysian Peninsula and north of the Yangtze River in far future (Fig. 6d). This suggests a more severe separation of wet and dry season in CVN in the projected climate.

Monthly rainfall of the rain gauge data and NHRCM in the three sub-regions and the whole of Vietnam during the baseline and future periods are plotted in Fig. 7. The model well simulates precipitation in December–April in NVN during the baseline period, but it underestimates rainfall in May–November, especially in MJJA—the first half of the TC season (Fig. 7a). It is interesting that NHRCM well captures the increasing tendency of rainfall amount, though little overestimated, in CVN in May–June when early summer floods frequently happen. The simulated maximum rainfall occurs in September instead of October as in the observed rainfall (Fig. 7b), leading to an overestimate in August–September and an underestimate in October–November. For SVN, the simulated rainfall shows rather good agreement with the observed rainfall from December to May. However, NHRCM overestimates rainfall from June to September when the summer monsoon prevails in the region (Fig. 7c). This is probably due to the NHRCM physics that are not well consistent with monsoonal processes in low latitudes.

For the whole of Vietnam, the simulated rainfall of 50 to 180 mm per month is in a good agreement...
with the rain gauge amount of 50 to 200 mm per month from December to May, when precipitation is normally produced by moisture flows associated with the northeast winter monsoon and/or easterly winds from the Western Pacific. NHRCM reproduces somewhat lower or higher rainfall for an intensive amount of 200 to 350 mm per month during the remaining months of the year (Fig. 7d). In the seasonal march, precipitation in CVN decisively contributes to the maximum rainfall for the whole of Vietnam. The projected rainfall shows a little decrease in early summer (i.e., May and June) but detectable increase in September–November as compared to the baseline period.

3.2 Projected TC activity

Because TC activity is important information for climate change adaptation and mitigation, this subsection focuses on TC activity through analyzing changes in the TC number detected by the criteria previously mentioned. Figure 8 illustrates distributions of the mean TC number in the first half of the TC season (MJJA) during the baseline and future periods. It is clear that the area of TC frequency \( \geq 0.25 \) (hereafter briefly called TC activity area) of the best track is larger than that of NHRCM over the East Sea (Figs. 8a, b). The maximum TC number area given by the model is qualitatively consistent with the observations but smaller in both scale and frequency. However, detected TCs that have the potential to make landfall to CVN seem reasonable in comparison with the best track. To some extent, less appearance of TCs in eastern NVN (Figs. 8a, b) probably contributes to underestimation of rainfall there (Figs. 4a, b). Compared to the baseline period, the mean TC number reduces little in near future, except NVN and

Fig. 6. Same as Fig. 4 but for annual values.
northern CVN but remarkably in far future (Figs. 8c, d).

Similar analyses are done for the second half of the TC season and presented in Fig. 9. Unlike the MJJA case, the TC number detected by NHRCM in SOND is higher than that of the best track in the baseline SOND (Figs. 9a, b), except eastern NVN where rainfall underestimate is again observed (Figs. 5a, b). The maximum TC number area given by the model is again consistent with the observations. Compared to MJJA, the TC activity area shifts southward presumably due to the southward migration of ITCZ. The projected TC number and activity area slightly increase over the East Sea and middle CVN in near future (Fig. 9c) but it remarkably decreases in far future in comparison with the baseline period (Fig. 9d). Annually, NHRCM underestimates the TC number over the East Sea but overestimates in CVN (Figs. 10a, b). Annual TC number slightly decreases in near future (Fig. 10c) but significantly in far future climate (Fig. 10d). The reduction of TC frequency in the western North Pacific in future periods is also found in other studies. For example, Murakami et al. (2012) conducted an ensemble experiment using the MRI-AGCM and found that TC frequency decreases in the western North Pacific but increases in the central Pacific for the 2075–2099 period; this could be attributed to differences in large-scale dynamical parameters and SST anomalies. On analyzing outputs of seven general circulation models, including the MRI-AGCM, Yokoi et al. (2013) also found similar future changes in TC frequency in sub-basins of the Pacific.

The frequency of the annual mean maximum wind speed and monthly TC number of the best track and NHRCM during the baseline and future periods are described in Fig. 11, where the maximum wind speed is divided into 5 m s$^{-1}$ interval ranges. The annual values are just statistics of numbers in each range and month. It can be seen that the model detects much higher TC intensity frequency in range of the maximum wind speed 15–25 m s$^{-1}$ than the observations and vice versa at stronger maximum wind speed. This can be partly explained that 20-km grid spacing cannot help NHRCM well capture TC inner core and eyewall structure. Projected TC maximum wind speed shows little changes compared to the baseline period (Fig. 11a). As previously mentioned, the model underestimates the TC number in MJJA; therefore, it cannot detect the first pick of the observed TC number in July. Unlike simulated TCs detected most in September, the projected maximum TC number

![Figure 7](https://example.com/fig7.png)

Fig. 7. Monthly rainfall of the rain gauge data and NHRCM in North (a), Central (b), South (c) and whole Vietnam (d) during 1979–2003, 2015–2039, and 2075–2099 period.
occurs in October as in the best track. However, in far future, the projected TC number clearly declines from June to December, especially in July and August (Fig. 11b).

3.3 Projected rainfall induced by TCs

To clarify contributions of TCs to the projected rainfall in future climate, this subsection discusses projected rainfall induced by TCs [hereafter called TC rainfall, refer to Nguyen-Thi et al. (2012) for its calculation]. Because MJJA is the time when TCs often move along the southwestern rim of the Western Pacific Subtropical High across the Philippines and make landfall to NVN and South China, TC rainfall is mostly confined between 16°N–24°N in near future (Fig. 12a). It is interesting that MJJA is the TC season of NVN, but TC rainfall is not the largest there. This is probably due to weakening of TCs after they collide with Hainan Island. Conversely, it appears to be large on the eastern side of the Truong Son Mountains in northern CVN. TC rainfall shifts northward and clearly decreases in northern CVN for the 2075–2099 period (Fig. 12b), because the TC number decreases in this region in far future (Fig. 8d). For example, it may come up to 180 mm to the south of Vinh station in near future (Fig. 12a) but decreases much less than 80 mm in far future MJJA (Fig. 12b). Compared to the baseline period, TC rainfall basically increases in NVN and South China in the projected climate, where its magnitude is large (Figs. 12c, d).

TCs favorably originate from southward migration of the ITCZ and then make landfall to CVN in SOND. That is why TC rainfall concentrates in CVN in this season, whereas it is very small in other regions (Figs. 13a, b). The Truong Son Mountains plays the role of a natural barrier to rainfall extending more westward. Similar to the MJJA case, it decreases in far future as a result of the reduction of TC number as previously mentioned (Fig. 9d). TC rainfall increases in middle CVN in near future and in a small area of northern

Fig. 8. (a) Mean TC number in MJJA during 1979–2003 period of the best track. (b) Same as (a) but given by NHRCM. (c) Same as (b) but during 2015–2039 period. (d) Same as (b) but during 2075–2099 period.
CVN in far future in comparison with the baseline period (Figs. 13c, d). TC rainfall in CVN is larger than that in NVN, because it is expectedly induced by cooperative interactions between TC circulation, cold surges, ITCZ, and topography (Yokoi and Matsumoto 2008; Truong et al. 2009).

4. Concluding remarks

Vietnam is located in the Asian monsoon region, where the seasonal march of prevailing large-scale circulations and interactions between them with tropical mesoscale disturbances and topography lead to strong spatial separations in TC and rainfall climate. Therefore, better understanding and projections of rainfall and TC activity are essential to the country for natural disaster mitigations and adaptations. In such a context, we try to apply NHRCM to simulate and project rainfall and TC activity over Vietnam.

Compared to the APHRODITE data, NHRCM well reproduces the heavy rainfall centers on the windward side of the Truong Son Mountains in North-west Vietnam and along the coast of the Malaysian Peninsula and Cambodia in JJA when the summer monsoon prevails and produces large-scale moisture convergence. In fall, the simulated precipitation distributes to the east of the Truong Son Mountains in CVN because precipitating mechanisms are primarily forced convection. Specifically, the northeasterly winds originating from cold surges frequently converge with the trade winds north of the ITCZ or TCs to create huge moisture flows normal to the topography. However, the model overestimates rainfall in comparison with the APHRODITE data. Compared to the rain gauge data, NHRCM underestimates rainfall in NVN but overestimates rainfall in SVN in JJA when the summer monsoon gets mature. The model overestimates rainfall in September but underestimates it in October–November in CVN.

The annual projected rainfall remains almost unchanged over the whole of Vietnam in near future, but increases little in the northeastern and southeastern coastal zone in far future. At first glance,
therefore, projected rainfall climatology seems to be the same as the present climate. However, seasonal analyses reveal that the projected mean rainfall noticeably decreases in Northwest and Central Vietnam in JJA, while it remarkably increases in Northeast and Central Vietnam in SON in near and far future. As a result, the rainy season in NVN is expected to be longer and is expected to shift to fall in future, whereas CVN will suffer more hot and dry weather in JJA and will have heavy rainfall and
flooding in fall. In other words, a more severe separation of wet and dry season is expected in CVN in future.

In the first half of the TC season, NHRCM captures less TC number and activity area as compared to the observations. In the second half, the TC activity area is extremely well reproduced, but the maximum TC number area is somewhat overestimated. It is worthy to realize that the model can reproduce the southward migration of the TC activity area as well as the maximum TC number area. For future climate, the annual projected TCs manifest to reduce in both number and activity area, especially in far future. In terms of annual means, NHRCM reproduces much larger weak-TC number, while it detects smaller strong-TC number as compared to the best track. The reason should be that NHRCM cannot help capture TC inner core dynamics and eyewall structure with 20-km grid spacing (e.g., Gentry and Lackmann 2010 suggested that to generate TC core properties, model grid spacing should be 3 km or less). Compared to the present climate simulation, it is indicated that the maximum TC number occurs in October in the projected climate with a dramatic decrease in TC number in June–August in far future. In future, Vietnam will suffer less annual TC activity.

TC rainfall appears to be confined in the 16°N–24°N latitude band in NVN and South China in near future MJJA. However, it is displaced northward to cover a vast region of South China in far future.

Fig. 12. (a) MJJA mean rainfall induced by TCs during 2015–2039 period. (b) Same as (a) but during 2075–2099 period. (c) Ratio of MJJA mean rainfall induced by TCs during 2015–2039 and 1979–2003 period. (d) Same as (c) but during 2075–2099 and 1979–2003 period.
This suggests that TC steering flow is likely changed with time in the projected climate. It is noteworthy that while TCs produce more rainfall in NVN in future, the total projected rainfall in JJA decreases as compared to the baseline period. This implies that non-TC rainfall probably plays a less important role in the projected climate (i.e., TC rainfall gets more dominant in future). Though TC rainfall increases in middle CVN in near future fall, the total projected rainfall remains unchanged or reduced in SON there (i.e., non-TC rainfall is expected to decrease). Conversely, the total projected rainfall increases in southern CVN in far future SON, though TC rainfall basically decreases in comparison with the baseline period. Therefore, non-TC rainfall is likely to increase in this situation.

**Acknowledgment**

This study is supported by the Vietnam Ministry of Natural Resources and Environment (BDKH-01 Project) and the SOUSEI Program of the Ministry of Education, Culture, Sports, Science, and Technology (MEXT) of Japan. This study is presented in AS-36 of AOGS2014.

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