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Impact of climate change on sea surface wind in Southeast Asia, from climatological average to extreme events : results from a dynamical downscaling.

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Abstract

Southeast Asia (SEA) climate shows a large range of variability scales, from extreme events to interannual variability. Understanding its answer to climate change is of primary scientific and socio-economic importance. IPCC 5th assessment report however pointed the lack of knowledge in regional climate change and its impact in SEA. In particular little is known about the answer of wind to climate change. The impact of climate change on sea surface wind speed is investigated here, examining changes in daily and extreme event scales, interannual variability and climatological average between the 20th and 21st centuries. For that the RegCM4 regional model was used to perform a dynamical downscaling of CMIP5 simulations done with CNRM-CM5 global climate model under RCP4.5 and RCP8.5 hypothesis. Comparisons with QuikSCAT satellite data show that the downscaled simulations perform overall better than the global simulations. Both models produce regionally and seasonally contrasted results in terms of daily wind speed answer to climate change. Global simulations produce mostly weak and non-significant changes, only suggesting an intensification of northeast winter monsoon in the northern SEA. Conversely regional downscaled simulations suggest from March to November in the northern South China Sea and Pacific regions a significant weakening of wind speed from climatological to daily scales (summer monsoon to extreme values), for regions and periods of initially strong values, associated with a 40% to 50% decrease of tropical cyclones frequency. These changes result from the increase of mean meridional south to north sea surface pressure gradient and decrease its daily variability.

Key words : sea surface wind, climate change, dynamical downscaling, regional climate model, CORDEX-SEA, tropical cyclones

1. Introduction

Southeast Asia (SEA) gathers 8.6% of the world population (United Nations 2017). A large part of this population lives in low elevated and densely populated areas along the coasts of the Bay of Bengal, South China Sea (SCS), Indonesian Seas, Pacific Ocean and Indian Ocean. SEA is highly dependant on marine resources and is submitted to a wide range of climatic forcings. One of the major features of SEA atmospheric circulation is the monsoon system (see Loo et al. 2015 for a review), with the East Asia monsoon (Wang and LinHo 2002; Yihui and Chan 2005; Zhang et al. 2002; Nguyen-Le et al. 2014), the Northwestern Tropical Pacific monsoon (Wang et al. 2009) and the Indo-Australian monsoon (Meehl and Arblaster 2002; Neale and Slingo 2003; Izumo et al. 2013; Jourdain et al. 2013). This monsoon system induces a high seasonal variability of climate conditions, in particular of precipitations and winds. SEA climate, environment and society are also characterized by a strong influence of extreme events, including tropical cyclones (TC). Understanding the answer of the SEA climate system to climate change is therefore of primary scientific and socio-economic importance. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) however pointed the considerable lack of knowledge in regional climate change and its impact in SEA (IPCC 2013).

To answer this need, the Southeast Asia Regional Climate Downscaling / Coordinated Regional Climate Downscaling EXperiment (SEACLID/CORDEX-SEA) group was created (Tangang et al. 2018). It gathers atmospheric modeling groups from several countries with the objective of improving the understanding of climate change impact over the SEA region. The main frame for the study of climate change at the global scale is provided by the Coupled Model Intercomparison Project (CMIP) of the World Climate Research Programme (WCRP). CMIP partners run climate projections simulations with General Circulation Models (GCM) in order to understand climate changes arising from natural variability or changes in radiative forcing. To study regional impacts of climate change, downscaling of those GCMs simulations are performed using higher resolution regional climate models (RCMs), in the framework of the CORDEX project of the WCRP. In SEACLID/CORDEX-SEA, several GCMs simulations of CMIP 5th phase (CMIP5) have been dynamically downscaled over the SEA domain, using a number of RCMs, including RegCM4 (Giorgi et al. 2012). Juneng et al. (2016) investigated the performance of RegCM4 in simulating rainfall over SEA with different combinations of deep-convection and air-sea flux parameterization schemes. Ngo-Duc et al. (2017) assessed the performance of RegCM4 in simulating extreme rainfall and temperature indices over the SEA, showing a higher sensitivity to the RCM configuration over the Maritime Continent than over mainland Asia. Cruz et al. (2017) evaluated the skill of RegCM4 in representing temperatures over the SEA, revealing a predominant cold bias for the December-February period. Those authors underlined the importance in choosing RegCM4 appropriate configuration and physical parameterizations schemes for climate projections, and suggested that the MIT Emanuel convective scheme and the BATS1e air-sea flux scheme perform better overall.

Several studies assessed the long term evolution of SEA atmospheric circulation over the last and future decades. Most of those studies focused on temperatures, precipitations and TC activity, suggesting a large seasonal and regional variability of long term variations, both

over the past and future centuries. First, available observational datasets were analysed to study the past evolution over the 2nd half of the 20th century. Wu et al. (2005) showed that TC influence has increased over the subtropical East Asia but considerably decreased over the SCS. Kajikawa et al. (2012) revealed an advanced onset and a weakening of SEA summer monsoon. Manton et al. (2001) showed an increase in extreme temperature events and a decrease in the frequency of rainfall events, but Endo et al. (2009) and Takahashi (2011) then revealed a strong regional and seasonal variability in the trends of rainfall and TC activity. Second, numerical simulations, including RCM downscaling of IPCC GCM simulations, were performed to assess the regional impact of global climate change over the 21st century. Several studies projected an increase of precipitations over SEA, including extreme rainfalls (Lal et al., 2001; Chotamonsak et al., 2011; Tangang et al., 2018). Conversely Ashfaq et al. (2009) projected an overall suppression of summer precipitation and a delay in monsoon onset, and Yokoi et al. (2013) suggested a decrease in TC frequency caused by an eastward shift of TC development regions. Some studies focused on specific countries, showing regionally and seasonally contrasted changes. Manomaiphiboon et al. (2013) suggested heavy precipitation and dry spells to be intensified over Thailand. Loh et al. (2016) projected drier conditions in winter and spring and wetter conditions in summer and fall over Malaysia. For south-central Vietnam Ho et al. (2011), Ngo-Duc et al. (2014) and Raghavan et al. (2017) also showed an increase of precipitation extremes, while Ho et al. (2011) and Trinh-Tuan et al. (2019) projected a decrease of rainy season rainfall events over northern and central Vietnam, explained by a weakening of the southwesterly air flow.

Estimates of wind evolution would be highly relevant for risks studies, and are moreover of strong interest for the study of the evolution of ocean circulation and ecosystems. Winds are indeed a key factor of ocean dynamics, which trigger the biological productivity and ocean ecosystems through their impact on nutrient transport, mixing and availability. The SCS circulation is for example strongly related to the wind forcing, from the impacts of monsoon wind on SCS large scale circulation (Wyrski 1961) and the impact of seasonal wind on mesoscale and coastal processes (Da et al. 2019) to the impact of typhoons on ocean mixing (Pan and Sun, 2013). Several authors have consequently examined the influence of this wind-driven circulation on primary production (Shen et al. (2018) for the effect of monsoon on primary productivity in the Gulf of Tonkin, Liu et al. (2019) for the effect of typhoons in the South China Sea...). To our knowledge, very few studies were however dedicated to the answer of surface wind to climate change in SEA. Published results suggest a weakening of the large scale monsoonal circulation in the South Asia and SEA regions (Ashfaq et al. 2009; Ho et al. 2011; Manomaiphiboon et al. 2013; Loh et al. 2016). The goal of the present study is to propose a first evaluation, and the associated methodology, of the response of sea surface wind speed to climate change in the SEA region, using a RCM downscaling of GCM simulations. We investigate in details the case study of one couple of GCM and RCM, namely CNRM-CM5 and RegCM, used respectively in the framework of the CMIP5 and SEACLID/CORDEX-SEA projects. To estimate the added value of the downscaling, we assess the quality of GCM simulations and corresponding RCM downscaled simulations in terms of representation of sea surface wind speed spatial and temporal variability over SEA in the present period by comparison with available satellite daily data. We then analyse simulations performed under hypothesis of RCP4.5 and RCP8.5 IPCC scenarios to examine

the changes of sea surface wind speed, from daily and extreme event scale to interannual and climatological scales, between the end of the 20th and 21st centuries. Observations dataset and numerical models are presented in Sect 2. Simulations quality and downscaling added-value are evaluated in Sect 3. The answer of sea surface wind speed to climate change is investigated in Sect 4. Physical mechanisms explaining our results are proposed in Sect. 5, as well as the assessment of the robustness of those results regarding the choice of the reference periods. Final discussion and conclusions are presented in Sect 6.

2. Tools and methods

In this section we present the RCM, the CMIP5 GCM simulations and the observation datasets.

2.1. The Regional Climate Model : RegCM4

We use the hydrostatic, limited-area Regional Climate Model version 4.3 (RegCM4, Giorgi et al. 2012). RegCM4 is implemented with 18 vertical σ -levels with the top level set at 5 mb and with a horizontal resolution of 25 km, covering the [15°S - 27°N ; 89.5°E - 146.5°E] domain (Fig. 1a). The physical options used here are the radiative transfer scheme of the NCAR Community Climate Model (CCM3) (Kiehl 1996), the sub-grid explicit moisture (SUBEX) scheme for large-scale precipitation (Pal et al. 2007), the planetary boundary layer scheme of Holtslag et al. (1990), the MIT-Emanuel convective scheme (Emanuel and Živković-Rothman 1999) and the BATS1e ocean flux scheme (Dickinson et al. 1993). This setting is based on the sensitivity experiments conducted previously by the CORDEX-SEA community (Juneng et al. 2016; Ngo-Duc et al. 2017; Cruz et al. 2017).

Initial and lateral boundary conditions are provided by the outputs of the GCM described in Section 2.2. No spectral nudging was used. Over the lateral boundaries of the RegCM domain, atmospheric variables are relaxed toward GCM variables within the buffer zone (of 12 points \sim 300 km) and are therefore dominantly controlled by the GCM. To exclude the effect of this buffer zone from our analysis, we remove a \sim 3.5° band along the boundaries of our domain and perform our analysis over this reduced domain, called SEA hereafter (see black frame in Fig. 1a). We also indicate in Fig. 1a the main regions of interest for our analysis : IO (Indian Ocean), SCS (South China Sea), PAC (Pacific Ocean) and INDO (Indonesian seas).

2.2. GCM simulations : CNRM-CM5

For AR5, IPCC adopted 4 GHG trajectories, or Representative Concentration Pathway (RCP), labelled after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W.m⁻², respectively). In the framework of the CMIP5, GCMs simulations following the 4 RCPs were performed. They include simulations performed with the atmosphere-ocean GCM CNRM-CM5.1 developed jointly by CNRM-GAME and CERFACS (Voldoire et al. 2011). CNRM-CM5.1 includes the atmospheric model ARPEGE-Climat (v5.2), the ocean model NEMO (v3.2), the land surface scheme ISBA, the TRIP river routing model and the sea ice model GELATO (v5) coupled

through the OASIS (v3) system. The horizontal resolution is equal to $1.4^{\circ}\sim 150\text{km}$ for the atmosphere model, i.e. 6 times coarser than our RegCM resolution (see Fig. 1b), and $1^{\circ}\sim 110\text{km}$ for the ocean model. We used 3 simulations to provide initial and boundary conditions for RegCM : CNRM-HIST, CNRM-RCP4.5, CNRM-RCP8.5. The CNRM-HIST simulation covers the period 1850-2005 and is forced with a time-evolving historic reconstruction of observed GHG concentrations as specified by CMIP5. CNRM-RCP4.5 and CNRM-RCP8.5 are two projection simulations forced with specified GHG concentrations consistent with the medium (RCP4.5) and high (RCP8.5) scenarios, and follow the HIST simulation covering the period 2006-2100. We therefore performed 3 downscaled simulations over our SEA RegCM configuration : RCM-HIST over 1950-2005 then RCM-RCP4.5 and RCM-RCP8.5 over 2006-2100. Both RCM-RCP4.5 and RCM-RCP8.5 use the final state of RCM-HIST as initial conditions.

2.3. Observation data

Satellite observations of wind speed over the sea are provided daily by QuikSCAT LEVEL 3 dataset with a 0.25° resolution available over the period 19/07/1999-21/11/2009. These data are freely available on the Physical Oceanography Distributed Active Archive Center (PODAAC) server of NASA JPL at <ftp://podaac.jpl.nasa.gov/allData/quikscat/L3/jpl/v2/hdf/>. One of the strong advantage of QuikSCAT data is its high spatial and temporal coverage : Fig. 1c shows that the availability of QuikSCAT data over the period 2000-2008 exceeds 80% over most of the SEA region. The areas of lower coverage over a band of 1-2 pixels correspond to coastal areas, where the proximity of land hinders the quality of the data. For our analysis, we only consider points for which the data availability exceeds 80%. Time series of the observed yearly number of TC in SEA are obtained from Digital Typhoon database (<http://agora.ex.nii.ac.jp/digital-typhoon/>), based on the data from the Japan Meteorological Agency and the Joint Typhoon Warning Center.

3. Added value of RegCM4 dynamical downscaling of CNRM-CM5 simulations for the representation of sea surface wind speed in SEA

We evaluate and compare here the ability of CNRM-CM5 and RegCM models to reproduce realistically the sea surface wind speed in SEA and its spatio-temporal variability, from the daily and seasonal to the climatological scales, taking QuikSCAT data as a reference. Note that CNRM-CM5 and RegCM simulations are launched respectively from 1850 and 1950, and do not involve any real data assimilation. For each model, we concatenate the 2000-2005 period of -HIST simulation and 2006-2008 period of -RCP4.5 and -RCP8.5 simulations to produce two 9-year time series of daily sea surface wind over the 2000-2008 period that can be compared with QuikSCAT data. Those time series are named hereafter CNRM-HIST4.5, CNRM-HIST8.5, RCM-HIST4.5 and RCM-HIST8.5.

Absolute or relative biases and correlation of a given metric are always computed taking QuikSCAT as a reference. We use the average over 2000-2008 of the daily sea surface wind speed as metrics for the climatological state, and the daily standard deviation (*std_d*) and 95th and 99th percentiles (q95 and q99) for the daily variability, including intense and extreme

events. We compute the time correlation compared with QuikSCAT of the climatological monthly time series to assess the realism of the simulated seasonal cycle. To compare the modeled and observed distributions of daily sea surface wind speed, we also present in Fig. 2 quantile-quantile plots (QQplots) of the spatial average of daily wind speed field over the 5 boxes B1 to B5 shown in Fig. 1. Those boxes, of $\sim 3.2^\circ \times 3.2^\circ$, were chosen within the main regions of the SEA domain: IO, southern and northern SCN, southern and northern PAC. The values of observed and simulated value, bias and relative bias for std_d , q95 and q99 of daily wind are indicated in Fig. 2 and Tab. 1 for each box. Tab. 2 presents the average over the SEA domain of those metrics for QuikSCAT and for the average of both simulations for both models. For all the metrics presented above, the difference for a given model between the -HIST8.5 and -HIST4.5 time series (maps shown in Fig. ESM1) is indeed at least one order of magnitude smaller than the difference between RegCM and CNRM-CM5 simulations (Fig. 3, column iv). The time series -HIST8.5 and -HIST4.5 indeed only differ from year 2006 and do not have sufficient time to diverge over the period 2000-2008. For each CNRM-CM5 and RegCM model, we therefore compute the average of -HIST4.5 and -HIST8.5 time series and compare it with QuikSCAT to evaluate the model ability to represent sea surface wind speed over the area of study.

3.1. Climatological average

Fig. 3 shows the maps of sea surface wind speed averaged over 2000-2008 in QuikSCAT (Fig. 3.a.i), CNRM-CM5 (Fig. 3.a.ii) and RegCM (Fig. 3.a.iii), as well as the ratio of average bias between RegCM and CNRM-CM5 (Fig. 3.a.iv): an absolute value of ratio smaller than 1 indicates that RegCM performs better than CNRM-CM5, and a negative value indicates that biases are of opposite signs. Models output were projected on QuikSCAT grid to plot those maps.

Spatial patterns of average wind speed observed in QuikSCAT are qualitatively quite well represented in CNRM-CM5 and RegCM simulations, with a minimum region in the equatorial band, where average wind speed is lower than $\sim 5 \text{ m.s}^{-1}$ in QuikSCAT, and spatial maxima in the central and northern part of SCS, where average wind speed reaches $\sim 9 \text{ m.s}^{-1}$ in QuikSCAT (Fig. 3.a.i-iii). However CNRM-CM5 underestimates the mean wind speed. On average over the SEA domain CNRM-CM5 shows an average absolute/relative bias of $-1.5 \text{ m.s}^{-1} / -23\%$ (Tab. 2). This wind speed underestimation in CNRM-CM5 varies from ~ -0.5 to $\sim -1.5 \text{ m.s}^{-1}$ depending on the region, and is stronger in the regions of maximum wind, in particular in the northern SCS where it reaches about $-1.5 \text{ m.s}^{-1} / -20\%$ (Fig. 3.a.i-ii). B3, located in this region, indeed shows a 7.8 m.s^{-1} average wind in QuikSCAT and a $-1.4 \text{ m.s}^{-1} / -18\%$ average bias CNRM-CM5, stronger than the average biases obtained for other the 4 boxes, varying between -9% and -14% (Tab. 1).

RegCM downscaling corrects this underestimation in a large part of the SEA (Fig. 3.a.iii), resulting in a $\sim -0.3 \text{ m.s}^{-1} / -4\%$ average bias over the whole SEA (Tab. 2). The absolute value of the RCM/CNRM-CM5 ratio of average bias is lower than 1 over 66 % of the SEA area (Fig. 3.a.iv). Except for box B5, which shows a small 1% increase, the mean underestimation of the spatially averaged wind over the boxes is reduced by 3% (B2) to 14% (B3) in RegCM compared to CNRM-CM5 (Tab. 1). This correction of wind speed underestimation is

noticeably strong in the IO (B1 bias : smaller than -0.1 m.s^{-1} / -1% in RegCM vs. higher than -0.6 m.s^{-1} / -9% in CNRM-CM5, Tab. 1), in the northern SCS maximum wind region (B3 bias : 0.3 m.s^{-1} / 4% vs. -1.4 m.s^{-1} / -17%), and in the northwestern PAC (B4 bias : -0.4 m.s^{-1} / -5% vs. -0.9 m.s^{-1} / -12%). In some parts of the SEA domain however, RegCM performs worse than CNRM-CM5. The reduction of the underestimation indeed results in an overestimation in RegCM that is more than twice stronger than the CNRM-CM5 underestimation in the western coastal areas of the SCS and in the northern IO (Fig. 3.a.iv). In the southern parts of the SEA domain, in the southern SCS and in the southern PAC, on the contrary, the underestimation of wind speed is more than twice stronger in RegCM than in CNRM-CM5. Note that both RegCM and CNRM-CM5 strongly underestimate the (weak) average wind in the equatorial band.

In summary RegCM downscaling reduces the underestimation of average sea surface wind observed in CNRM-CM5 over 2/3 of the SEA domain and by 6% in average over the domain. It however worsens the bias in some specific regions : southern SEA and PAC, southwestern and northwestern SCS, northern IO.

3.2. Seasonal cycle

To assess the ability of the models to represent the seasonal cycle of the sea surface wind speed over the SEA domain, we compute the climatological monthly time-series over 2000-2008 in QuikSCAT and in the models, and the correlations between those observed and modeled time series. Fig. 2d,e,f,k,l shows the monthly climatological time-series for boxes B1-B5, and Fig. 3.e.ii-iii shows the maps of those correlations over the SEA.

CNRM-CM5 shows a relatively high correlation with QuikSCAT (from 0.7 up to 0.9) over most of the domain, with an average value of 0.66 over the SEA (Tab. 2) and values larger than 0.75 over 70% of the domain, in particular in the northern SCS and PAC and in the southern IO (Fig. 3.e.ii). Values lower than 40% (and even negative) are obtained over a small area in the southern PAC. RegCM shows spatial patterns similar as CNRM-CM5 (Fig. 3.e.iii), with a similar average value of 0.67 over the SEA (Tab. 2). However in general the correlation is improved over areas of high correlation whereas it is worsened in areas of low correlation (Fig. 3.e.iv). RegCM produces better correlation (exceeding 80%) in the northern SCS and PAC, southern IO and part of INDO : there the correlation improvement varies between $\sim 5\%$ and 10% (e.g. $+4\%$ for the wind average over B4, Fig. 2i). For the other regions, in particular over the equatorial area, southern SCS and northwestern SCS, the correlation is lower in RegCM than in CNRM-CM5, by 20% to 40%, and can be statistically not significant (e.g. $\sim -30\%$ for B2 with $p > 0.10$ for RegCM, Fig. 2e). The patterns of RegCM-CNRM-CM5 difference of correlations, i.e. of the quality of the seasonal cycle representation, correspond roughly to the patterns of average bias ratio (Fig. 3.e.iv). In particular, we obtain in general an improvement in RegCM compared to CNRM-CM5 of the representation of the seasonal cycle in the areas of strong wind (northern SCS and PAC and in southern SEA), and a worsening in the areas of weak wind (particularly over the equatorial band covering the southern SCS and PAC as well as the Northwestern SCS). In overall, the correlation decreases over 64% of the SEA domain in RegCM compared to CNRM-CM5.

3.3. Daily variability

To assess and compare the models ability to represent the variability of daily sea surface wind speed over its whole range of values, we examine the maps of the std_d (Fig. 3.b.i-iii), q95 (Fig. 3.c.i-iii), and q99 (Fig. 3.d.i-iii), and the distribution of spatial average of daily wind speed values for boxes B1-B5 (Fig. 2a,b,c,i,j).

3.3.1. Daily standard deviation

Both models reproduce the area of high daily standard deviation in the Northern SCS and PAC (near $\sim 18^\circ\text{N}$) and near the southern Vietnam coast ($\sim 10^\circ\text{N}$, 110°E). However, as observed for the climatological average, they both underestimate the high daily variability observed over the equatorial band, between $\sim 6^\circ\text{S}$ and 6°N . CNRM-CM5 underestimates the std_d over the whole domain, by more than $1.5 \text{ m}\cdot\text{s}^{-1}$ and between $\sim 15\%$ and $\sim 40\%$ in a large part of the domain (Fig. 3.b.i-ii), and in average over the SEA by $1.1 \text{ m}\cdot\text{s}^{-1}/33\%$ (Tab. 2). RegCM downscaling reduces this underestimation over 88% of the SEA domain, with an average bias over the SEA of $-0.4 \text{ m}\cdot\text{s}^{-1}$, i.e. reduced by 21% compared to CNRM-CM5 (Tab. 2). This bias is reduced by more than 50% in a large part of the domain, and by even more than 75% in particular in the northern SCS and PAC (Fig. 3.b.iv). However, as observed for the average, the CNRM-CM5 std_d bias is not reduced and can be even doubled in RegCM in some small parts of the domain (southern PAC, coastal areas of INDO, Fig. 3.b.iv), while in other parts RegCM overestimation is actually stronger than the CNRM-CM5 underestimation (coastal northwestern SCS, eastern PAC).

For spatial averages of daily wind over boxes B3 and B4, the downscaling reduces std_d bias (by 2 to 5%, from a bias range of -11% to -13% in CNRM-CM5 to a range of $+6\%$ to 9% in RegCM, Tab. 1). However for boxes B1,2,5, the downscaling increases std_d bias (by 0 to 13%, from a bias range of -7% to $+7\%$ in CNRM-CM5 to a range of $+7\%$ to 20% in RegCM). The increase of std_d bias in RegCM for those boxes, which is not observed at the pixel level on the maps of Fig. 3.b.iv, is actually related to effect of the box spatial averaging. For QuikSCAT, daily wind fields show a much higher spatial variability at very small spatial scales than for RegCM and CNRM-CM5 (see Fig. ESM2.b-d in Supplementary Materials), due to the coarser spatial resolution of the models and to the errors of satellite measurements. Spatially averaging daily wind field over boxes consequently results in a stronger smoothing in QuikSCAT than in models. This does not impact the climatological mean (the difference between climatological mean of timeseries at the center of the box and of timeseries of box average is smaller than 1% for QuikSCAT and the model for all boxes), but this induces a stronger reduction of daily variability in QuikSCAT than in the models : for boxes B1, 2, 5, the difference between timeseries at the center of the box and of timeseries of box average exceeds respectively 22%, 9% and 20% for std_d , q95 and q99 for QuikSCAT, while it is respectively lower than 8%, 4% and 5% for both models (see for example Fig. ESM2.a for B2). As a result, for boxes B1, B2 and B5, std_d bias, which is negative at the pixel level for both models (Fig. 3.b.ii-iv) becomes positive at the box level for RegCM, and larger than the CNRM-CM5 bias (Tab. 1).

3.3.2. Daily spectrum and extreme values

CNRM-CM5 underestimates sea surface wind in average, but also over the whole spectrum of the daily wind values (Fig. 2a,b,c,i,j). This underestimation is not constant over the spectrum but increases for high wind values, both in absolute and relatively, as shown by the stronger departure of QQ-plots from the identity line for boxes B2,4, (Fig. 2b,i). In average over the SEA, the bias is indeed equal to -23% for the average, -27% for q95 and -36% for q99 (Tab. 2). The bias varies spatially between 10% to 30% for q95 (Fig. 3.c.i-ii), and between 20% to 40% for q99 (Fig. 3.d.i-ii), whereas it is lower than 20% for the average wind (Fig. 3.a.i-ii),

RegCM significantly corrects this underestimation over the whole spectrum, i.e. for the average but also for high (q95 and q99) values, resulting for all boxes in QQ-plots closer to the identity line (Fig. 2a,b,c,i,j). The relative correction is generally stronger for high values : in average over the SEA, the bias is indeed reduced by 18% for the average, 21% for q95 and 23% for q99 (Tab. 2). This reduction of CNRM-CM5 q95 and q99 biases by RegCM occurs over a large part of the SEA (Fig. 3.c.iii-iv) : q95 and q99 biases are reduced in RegCM over respectively 89% and 93% of the SEA domain. Compared to CNRM-CM5, the q95 bias is reduced in RegCM for all the boxes B1-4 (Tab. 1), by 3% (B1) to 11% (B4). The q99 bias by also reduced for most of the boxes, by 1% (B1,3) to 19% (B4), though it slightly increases by 2% for HIST8.5 for B1 and 3% for HIST4.5 for B3. For B1 this q99 bias increase of box average wind, not observed on Fig. 3.d.iv at the pixel level, is related to the smoothing effect of the spatial averaging as explained in section 3.3.1. For B3, the 96-99th tail of the QQ-plots deviates in RegCM more strongly from the identity line than for the rest of the spectrum, the q99 bias (+20% for HIST4.5 and +16% for HIST8.5, Tab. 1) is consequently higher than the average bias (+4% for both simulations), and for RCP4.5 than the CNRM-CM5 q99 bias (-17%). As already observed for the average and std_d , the overestimation of q95 and q99 in RegCM is indeed twice higher than the CNRM-CM5 underestimation in the coastal northwestern SCS (Fig. 3.c-d.iv), close to B3. Conversely, the q95 and q99 underestimation is worse in RegCM than in CNRM-CM5 in some small areas of weak wind speed in the intertropical band.

3.4. Spatial variability

To assess the ability of the models to represent the spatial variability of the daily sea surface wind speed, we compute for each metric (average, std_d , q95 and q99) the spatial correlation over the SEA between the 2D fields of modelled values (CNRM-CM5 or RegCM) and the 2D fields of observed values (QuikSCAT), and plot them on the Taylor Diagram on Fig. 4. The downscaling decreases the spatial correlation by 0.09 for the average wind, from 0.88 in CNRM-CM5 to 0.79 in CNRM-CM5. For std_d and q99, the downscaling increases the correlation (+0.04 for std_d , from 0.52 to 0.56, and +0.07 for q99, from 0.25 to 0.32) and it very slightly increases it for q95 (+0.01, from 0.71 to 0.71). RegCM therefore does not improve the representation of the spatial pattern for the average sea surface wind speed (note however that the correlation remains higher than 0.8), but slightly improves the representation of the spatial patterns of daily variability.

The Taylor diagram on Fig. 4 also shows the ratio between the spatial standard deviation of modelled values and of the observed values for each metric. For CNRM-CM5, the relative bias associated with this ratio varies between -19% (for q99) and +5% (for q95). For RegCM, it is higher for the 4 metrics, increasing from 25% (for the average) to 39% (for q99). This higher spatial variability obtained for all metrics for RegCM is actually related to the overestimation of high wind speeds in the northern SCS and IO, which exceeds the CNRM-CM5 underestimation as discussed in sections 3.1 and 3.3 ; and to the underestimation of weak wind speeds in the equatorial part (southern PAC, IO and INDO) which can be also more severe than in CNRM-CM5 (Fig. 3.a.iv). As a result, the spatial range of wind speed values is stronger in RegCM than in CNRM-CM5 and QuikSCAT.

All metrics used to assess the added-values of the downscaling in terms of sea surface wind speed modeling are spatially consistent : locations where the representation of the seasonal cycle is improved (or not) roughly correspond to locations where the average and the daily variability (in terms of std_d , q95 and q99) are improved (or not). Overall, RegCM downscaling of CNRM-CM5 simulations allows to improve the representation of sea surface wind daily speed over most of the SEA. Those simulations can therefore legitimately used to study the answer of wind speed to climate change over the SEA.

4. Impact of climate change on sea surface wind

In this section, we examine for each model the impact of climate change on sea surface wind speed by comparing reference periods in the RCP4.5 and RCP8.5 simulations and in the HIST simulation. We take respectively 2070-2099 and 1961-1990, called XXI and XX hereafter, as reference periods for the 21st and 20th centuries. Those 30-year periods are long enough to be statistically representative from a climatological point of view. Tab. 3 gives for each model the values of the average over SEA of the average, the yearly coefficient of variation CV_y (equal to the ratio between the yearly standard deviation and the average, see e.g. Giorgi et al. 2004), the daily standard deviation std_d and percentiles q95 and q99 of the daily sea surface wind over XX, and of their relative change between XX and XXI. QQ-plots comparing the distribution over XX and XXI of daily sea surface wind speed averaged over for boxes B1-5 are shown in Fig. 5 for both models. For each box, we also indicate in Fig. 5. the value of the metrics listed just above, and of their relative variation.

4.1. Climatological average

We first examine the changes of average sea surface wind speed between the XX and XXI periods. Fig. 6 and 7 (column i) show respectively for CNRM-CM5 and RegCM the maps of average annual (line a) and seasonal (over December-February DJF, line b, March-May MAM, line c, June-August JJA, line d and September-November SON, line e) sea surface wind speed over XX, and the associated average vector field. Fig. 6 and 7 (columns ii and iii) show respectively for RCP4.5 and RCP8.5 the maps of relative variations of average annual (line a) and seasonal (lines b-e) sea surface wind speed between XX and XXI. Fig. 6 and

similar figures in the following follow the same organization, and are referred by the line and the column letters.

CNRM-CM5 produces weak changes in average. For both RCPs the yearly average change over the SEA is smaller than 1% and not significant (Tab. 3). We consider as significant a change for which the Student's t test associated with the difference between the 30-year time series over the XX and XXI periods gives a p-value lower than 0.05. Locally, CNRM-CM5 produces a significant but weak ~2-3% decrease of the yearly average over a small part of the IO and eastern PAC for both RCPs (Fig. 6.a.ii-iii). It produces for RCP8.5 only a significant yearly ~2-3% increase over the southern SCS - northern PAC (+2.5% for B4, Fig. 5d).

Changes are more significant at the seasonal scale. DJF in particular shows in average over the SEA a significant increase of 2% in RCP4.5 and 4% in RCP8.5 (Tab. 3). This is spatially related to a significant increase of initially strong northeast winter monsoon wind over the SCS and northern PAC (see vectors in Fig. 6.b.i), which locally reaches ~5-7% in RCP4.5 (Fig. 6.b.ii) and ~10-12% in RCP8.5 (Fig. 6.b.iii). A smaller area of weak but significant decrease of winter monsoon is observed in the eastern PAC (~2% and ~5% respectively for RCP4.5 and RCP8.5, Fig. 6.b.ii-iii). For the other seasons, from March to November, CNRM-CM5 simulations produce weaker and non significant changes of wind speed in average over SEA (Tab. 3) and for most of the regions (Fig. 6.c-e.ii-iii), for both RCPs.

However, significant decreases lower than 10% can be observed locally: a significant decrease for initially strong southwest wind for both RCPs in the southwestern IO of ~10% in MAM (Fig. 6.c.i-iii) and ~5% in SON (Fig. 6.e.i-iii), and decrease of the summer southwest monsoon wind in the northeastern PAC part in JJA of ~6% in RCP4.5 (Fig. 6.d.ii) and ~8% in RCP8.5 (Fig. 6.d.iii).

Contrary to CNRM-CM5, RegCM produces for both RCPs a significant 4% decrease of the wind speed in average over the year and the SEA (Tab. 3). Locally, this is mostly related to a significant ~5-10% decrease in the southern SEA (Fig. 7.1.ii-iii, with respectively -6% and -7% in RCP4.5 and RCP8.5 for B1, Fig. 5a) and northern SCS (-5% and -6% for B3, Fig. 5c). Seasonal patterns are also quite different in RegCM from those observed with CNRM-CM5. First, for DJF, the average SEA change is not significant for both RCPs (Tab. 3). Spatially, RegCM changes show overall the same spatial pattern as in CNRM-CM5 for DJF, with an increase of northeast winter monsoon over SCS and northwestern PAC and a decrease over the eastern PAC (Fig. 7.b.ii-iii). However, the northwestern PAC increase is much weaker in RegCM than in CNRM-CM5 and only significant in RCP8.5 (where it reaches ~6%), whereas the eastern PAC decrease is much stronger, covering a larger significant area and reaching respectively ~5% for RCP4.5 and ~9% for RCP8.5. Second, for the 3 other seasons (i.e. from March to November), RegCM produces for both RCPs a strong and significant decrease in average over the SEA (from 4% to 7%, Tab. 3). Spatially, this decrease occurs mainly in regions of high wind : southern SEA and northern SCS and PAC (Fig. 7.c-e.ii-iii). For the southern SEA, this is related to a strong decrease of southeast wind in MAM (~10% in RCP4.5 and ~20% in RCP8.5, Fig. 7.c.ii-iii) and JJA and SON (~8% for both RCPs, Fig. 7.d-e.ii-iii). For the northern SCS and PAC, patterns are quite similar for both RCPs, but RCP4.5 shows a large area of significant decrease of SON northeast wind (exceeding 12%, Fig. 7.e.ii) whereas RCP8.5 produces a stronger decrease of JJA summer southwest monsoon (exceeding ~20%, Fig. 7.d.iii), located slightly easter.

4.2. Interannual variability

The coefficient of variation CV_y , the ratio between the yearly standard deviation and the climatological average, quantifies the interannual variability of yearly sea surface wind relative to the climatological average. To examine the changes in interannual variability of sea surface wind speed, we compute CV_y of the 30-year time series of yearly and seasonal averages, and its change between XX and XXI (Fig. 8 and 9). Note first that for the XX period, CV_y is stronger in RegCM than in CNRM-CM5, as observed for the average (see Section 3.1). The RegCM/CNRM-CM5 ratio of CV_y over the SEA is indeed equal to 1.7 for the total year, varying seasonally from 1.3 to 1.6 (Tab. 3). In particular RegCM shows a strong interannual variability in JJA in a large part of the northern SCS (CV_y reaches $\sim 30\%$, Fig. 9.d.i), not observed in CNRM-CM5 (CV_y hardly exceeds $\sim 20\%$, Fig. 8.d.i).

For CNRM-CM5, both RCPs produce qualitatively similar spatial and seasonal changes of CV_y (Fig. 8). However in overall, changes are globally more positive in RCP4.5 : the RCP4.5-RCP8.5 difference of CV_y change varies in average over the SEA from 0.3% to 1% (Tab. 3); and between +0.8% (B4) and +3% (B1) for the 5 boxes (Fig. 5). In average over the SEA, CV_y increases for every season in RCP4.5 (by 0.5% to 1.1%, Tab. 3), whereas in RCP8.5 CV_y increases only for the whole year and DJF (CV_y changes vary from -0.5% to +0.2%, Tab. 3). Spatially, both RCPs produce first a null to positive change over the northern and southern PAC for all seasons, which reaches $\sim 2\text{--}4\%$ the whole year (Fig. 8.a.ii-iii), and is maximum in JJA for RCP8.5 ($\sim 6\%$, Fig. 8.d.iii). Second, they produce over the central PAC for all the seasons, a null to negative change, that reaches $\sim -4\%$ in MAM for RCP8.5 (Fig. 8.c.iii) and in $\sim -5\%$ JJA for RCP4.5 (Fig. 8.d.ii). Third, they produce over the southwestern IO a $\sim -5\%$ CV_y decrease for RCP8.5 in MAM, JJA and SON (Fig. 8.c-e.iii) and for RCP4.5 in MAM (Fig. 8.c.ii). In this region, RCP4.5 conversely produces for JJA a $\sim 2\%$ CV_y increase (Fig. 8.d.i).

For RegCM, the SEA averaged CV_y decreases for all the seasons for both RCPs, and are stronger than in CNRM-CM5 (between -4.0% and -1.1%, vs. +0.5% to +1.1% in CNRM-CM5, Tab. 3). As for CNRM-CM5, these changes are more negative in RCP8.5 : the SEA average changes vary seasonally from -4.0% to -1.4%, vs. -3.2% to -1.1% for RCP4.5. This stronger CV_y decrease in RCP8.5 is also seen for boxes B1-4 (0.3% to 3.1% higher in RCP8.5 than in RCP4.5, Fig. 5). Spatially, the most important changes are first a strong CV_y decrease over the SCS and northwestern PAC for the yearly average and from March to November for both RCPs, varying spatially and seasonally between 1% and 10% (Fig. 9.a,c,d,e.ii-iii and Fig. 5c,d : from -1.0% to -3.4% for B3,4). Second, a CV_y decrease for all the seasons over the southern SEA, covering the INDO and southern IO, varying between 1% and 15% (Fig. 9.a-e.ii-iii and Fig. 5a,e: from -0.8% to -5.9% for B1,5). Third, an null to positive change for all the seasons in the eastern PAC, in particular in MAM and DJF (0-3%, Fig. 9.b,c.ii-iii), and in JJA (up to 10%, Fig. 9.d.iii), resulting in a 1% (in RCP4.5, Fig. 9.a.ii) to 2% (in RCP8.5, Fig. 9.a.ii) increase in average over the year. As observed for CNRM-CM5, RCP4.5 and RCP8.5 produce for RegCM opposite results in the equatorial part of the IO and neighbouring INDO in JJA, with a $\sim 5\%$ increase for RCP4.5 and a $\sim 2\%$ decrease in RCP8.5 (Fig. 9.d.ii-iii). The other difference lays in the central SCS and northwestern PAC in DJF, with a weak ($\sim 2\%$) increase in RCP4.5, vs. a weak ($\sim 1\%$) decrease in RCP4.8 (Fig.

9.b.ii-iii). Note that those contrasted changes are not negligible compared to the initial CV_y values for XX, which vary spatially and seasonally between ~8% and 30% (Fig. 9.a-e.i).

4.3. Daily variability and extreme events

In this section, we examine the changes in daily variability of sea surface wind speed, examining the range of daily values and the intense and extreme values. For that, we compute std_d , q95 and q99 over the whole year and over the 4 seasons for the period XX and their relative change between XX and XXI. For a given model, initial values and changes of q95 and q99 show similar spatial and seasonal features, as well as changes of std_d , q95 and q99. We therefore describe together those metrics, and show here only the maps for std_d (Fig. 10,11) and q95 (Fig 12,13) whereas maps for q99 are available in the online resources (Fig. ESM3, ESM4).

For CNRM-CM5, the changes of std_d , q95 and q99 are very weak both for RCPs and for all the seasons. Changes in average over the SEA vary for all the seasons between -2% and +1% for std_d , -2% and +2% for q95 and -3% and +2% for q99 (Tab. 3). Regionally, they rarely exceed 10% for std_d and 5% for q95 and q99 (Fig. 10, 12, ESM3). Locally, the only noticeable change is an increase over the northern/eastern PAC for DJF, MAM and JJA, in regions and periods of initially low values (Fig. 10.b-d.ii-iii, 12.b-d.ii-iii, ESM3.b-d.ii-iii). This regional increase reaches seasonally ~10% for std_d and ~6% for q95 and q99. It results in a low increase for the whole year in this region : for B4, std_d , q95 and q99 increase respectively by +4%, +2% and +2% in RCP4.5 and +7%, +4%, +4% in RCP8.5 (Fig. 5.d). For the other boxes, the relative changes for the whole year are weaker and vary from -1% (B5) to +4% (B2, B3) for std_d , from -2% (B5) to 2% (B2,3) for q95 and from -2% (B2) to 3% (B3) for q99 (Fig. 5.a,b,d,e).

Changes are more negative and much stronger for RegCM, locally 3 to 5 times larger than for CNRM-CM5 (e.g. std_d varies from -11% (B1) to -1% (B2) for boxes B1,2,3,5 in RegCM, vs. -1% to +4% in CNRM-CM5, Fig. 5. a,b,d,e), and quite similar in both RCPs. On average over the SEA, RegCM produces for every season an average decrease equal for the whole year to -4% for std_d , -3% for q95 and -5% for q99 (Tab. 3), and varying seasonally from -11% to -1%, with weakest decreases obtained for DJF. Regionally, changes are highly contrasted (Fig. 11, 13 and Fig. ESM4) : they locally reach +/- 30% for std_d and +/-25% for q95 and q99, and vary for boxes B1-B5 from -11% (B1) to +3% (B4) for std_d , -8% (B1) to +1% (B4) for q95 and -13% (B3) to -1% (B4) for q99 (Fig. 5). The first most significant change is a strong 30% decrease of std_d , and 25% decrease of q95 and q99 in the northern SCS and northwestern PAC for all seasons except DJF, especially in JJA and SON (Fig. 11.a,c-e.ii-iii, 13.a,c-e.ii-iii, ESM4.a,c-e.ii-iii). This decrease is spatially wider and more intense in JJA in RCP8.5 and in SON in RCP4.5. It occurs for periods and regions of initially very high values (up to 4.5 m.s⁻¹ for std_d , 16 m.s⁻¹ for q95 and 25 m.s⁻¹ for q99 over the XX period, Fig. 11.a,c-e.i, 13.a,c-e.i, ESM4.a,c-e.i), that actually correspond to the areas and periods of TC. RegCM also produces a strong 20% to 30% decrease in the southern IO region in MAM, again for a region and season of initially high values (~3 m.s⁻¹ for std_d ; ~10 m.s⁻¹ for q95; and ~17 m.s⁻¹ for q99; Fig. 11.c, 13.c and ESM4.c). Second, RegCM produces a weaker but non negligible decrease of ~5-10% for std_d and 10-15% for q95 and q99 for SON

in the south-equatorial IO and INDO (Fig. 11.e.ii-iii, 13.e.ii-iii, ESM4.e.ii-iii), where initial values are much weaker than in the northern part (lower than 3 m.s^{-1} for std_d , 8 m.s^{-1} for q95 and 10 m.s^{-1} for q99, Fig. 11.e.i, 13.e.i, ESM4.a.e.i). Third, RegCM produces a strong increase (up to 25%) of std_d , q95 and q99 in the eastern/central PAC for all the seasons except DJF, for regions and periods of initially weak values (not exceeding 2.5 m.s^{-1} for std_d , 8 m.s^{-1} for q95 and 10 m.s^{-1} for q99, Fig. 11.a,c-e, 13.a,c-e, ESM4.a,c-e). Present-future changes of std_d , q95 and q99 computed over the whole year mainly reflect the seasonal decreases observed in MAM for the south-equatorial IO and INDO and from MAM to SON in the northern SCS/northwestern PAC, with a decrease for the year reaching 10%-15% for those areas (e.g. B1 and B3, Fig. 5a,c).

For both RCPs, the absolute and relative changes produced in RegCM are stronger for intense to extreme values (i.e. q95 to q99) than for the rest of the spectrum. For B1 and B3, located in the southwestern IO and northern SCS, i.e. regions of strongest decrease of wind speed average, daily variability and intense/extreme values, QQplots in Fig. 5.a,c deviate more from the identity line for high percentiles (B1 : -8% for q95 and -12% for q99 vs. -6%-7% for the average wind; B3 : -4%-5% and -12%-13% vs. -5-6%).

4.4. Spatial variability

To examine how climate change affects the spatial variability of sea surface wind speed in SEA, we compute the ratio of the standard deviation and the correlation between the spatial 2D fields of the average, CV_y , std_d , q95 and q99 of daily sea surface wind speed over the XX and XXI periods (see Taylor Diagrams in Fig. 14). First, for both models, the correlation between future and present spatial fields is always significant at more than 99% (p-value < 0.01) for all the metrics, seasons and simulations, indicating that the main spatial patterns of sea surface wind speed remain similar between the XX and XXI periods at all time scales. For CNRM-CM5, the XXI-XX difference of standard deviation for the climatological average and the daily metrics (std_d , q95 and q99) is generally less than 10%, and the correlation higher than 0.90 (Fig. 14.f,h,i,j): changes of spatial patterns for those metrics are very weak, consistently with the weakness of the changes observed in Section 4.1 to 4.2. For CV_y , stronger changes are observed: correlations vary between 0.52 and 0.91 and changes of spatial standard deviation between -21% and +36% depending on the seasons and simulations (Fig. 14.g). The main change is the increase of CV_y spatial variability for the whole year (+9% in RCP4.5 and +36% in RCP8.5) that results from the spatially contrasted CV_y changes over this period (increase in the PAC, decrease in the SCS see section 4.2 and Fig. 8.a.ii-iii, with a very weak initial spatial variability, Fig. 8.a.i); and the decrease of CV_y spatial variability for MAM (-21% in RCP4.5, -13% in RCP8.5), that results from the negative, respectively null to positive change of CV_y in area of initially strong values (regions of boxes 1 and 5, Fig. 8.c.i-iii), respectively weak values (region of box 4).

For RegCM, the spatial variability weakly decreases for the climatological average and daily metrics for all the seasons except DJF : the change of standard deviation remains generally weaker than -20%, and correlations higher than 0.78 (Fig. 14.a,c,d,e). This weak decrease is related to the general weakening of those metrics observed for those seasons (see Section 4.1 and 4.3 and Table 3 and Figures 7,11,13). For DJF, the spatial variability increases for those

metrics by ~10%, due to the contrasted changes for those metrics during this season (increase in the Northern PAC vs. decrease in the IO and southern PAC, Figures 7,11,13.b.ii-iii). As observed for CNRM-CM5, stronger changes are observed for CV_y (Fig. 14.b) : the correlation varies between 0.39 and 0.87, and the change of standard deviation between -46% and +21%. In general, however, the spatial standard deviation decreases, related to the general weakening of CV_y over SEA (Table 2, Section 4.2) in RegCM.

4.5. Tropical cyclones

Results described above for RegCM suggest in particular a decrease from the XX to the XXI periods of the strength of intense and extreme wind speed events for the regions and seasons of TC. To examine if this decrease is related to a change of TC frequency, we computed the number of TC over the area for each year and season using the algorithm developed by Phan-Van et al. (2015), which is a modified version of the vortex tracking algorithm proposed by Walsh (1997). The model outputs were first interpolated to 4 standard isobaric levels at 850, 700, 500 and 300 hPa. Then TC centers were identified based on the TC predefined criteria for relative vorticity, minimum sea level pressure, core temperature anomaly and outer core wind strength (OCS). In contrast to the original Walsh (1997) algorithm, Phan-Van et al. (2015) gave more weight on OCS and imposed empirical thresholds on the vorticity criterion, allowing a more realistic simulation of TC near the coastal zone.

Fig. 15a shows the time series of the yearly number of TC and the 30-year moving average in the RegCM HIST, RCP4.5 and RCP8.5 simulations, and the times series over the HIST period from Digital Typhoons database (see 2.3). Fig. 16 shows for the whole year and for each season the average number of TC in the XX period in RegCM and the observations, and the relative changes between XX and XXI for both RCPs in RegCM.

First, over the XX period RegCM represents realistically the TC frequency and slightly overestimates its interannual variability (Fig. 15a,16a) : the yearly average number of TC and its standard deviation are respectively equal to 29.8 TC.year⁻¹ and 26% in RCM-HIST vs. 27.8 TC.year⁻¹ and 18% in the observations. The seasonal distribution of the number of TC in RegCM qualitatively agrees with the observations : most of the TC occur from June to November, with maximum values in JJA and SON, and minimum in DJF and MAM (Fig. 16a). However quantitatively, RegCM underestimates the proportion of TC occurring during the JJA+SON seasons (64% vs. 85% in observations), whereas it overestimates it for DJF+MMA (36% vs. 15% in observations).

Second, consistently with the decrease of intense/extreme values of sea surface wind speed observed above for periods and regions of TC, RegCM produces a strong decrease of the yearly number of TC between the XX and the XXI periods, of respectively 41% and 48% for RCP4.5 and RCP8.5 (Fig. 16b). The seasonal distribution of TC however does not change significantly : the JJA+SON season still produces 66% and 69% of the TC respectively in RCP4.5 and RCP8.5 .

5. Discussion

5.1 Physical explanation of predicted changes in sea surface wind speed over SEA

The changes of sea surface wind speed described above can be linked to the change of sea level pressure SLP over the area, as suggested by Hanafusa et al. (2013). Fig. 17.a,b shows for DJF and JJA the difference of mean SLP between the XXI and XX periods, and Fig. 18 shows the zonally averaged mean meridional SLP gradient for the XX and XXI periods (Fig. 18.a,b) and the variation between the XX and XXI periods of the mean of the meridional SLP gradient (Fig. 18.c,d) and of its interannual (Fig. 18.e,f) and daily (Fig. 18.g,h) variances. For both models, the DJF wind is globally southward (Fig. 7.b.i and 8.b.i), resulting from a positive SLP gradient (Fig. 17.a and 18.a), and the JJA wind is globally northward (Fig. 7.d.i and 8.d.i), resulting from a negative SLP gradient (Fig. 17.a and 18.b). Fig. 17.a,b reveals an overall increase of SLP in the SEA domain by the end of the 21st century for both models. This increase is stronger in the northern part of the domain in JJA and DJF, corresponding to a positive variation of the south to north SLP gradient, both in DJF (in average over the SEA, 0.009 hPa/deg for RCP4.5 and 0.027 hPa/deg for RCP8.5 for CNRM-CM5; 0.009 hPa/deg for RCP4.5, 0.022 hPa/deg and for RCP8.5 for RegCM; Fig. 18c) and in JJA (CNRM-CM5 : 0.019 hPa/deg for RCP4.5, 0.015 hPa/deg for RCP8.5 ; RegCM: 0.008 hPa/deg for RCP4.5, 0.005 hPa/deg for RCP8.5; Fig. 18d). This increase of mean SLP gradient explains the intensification of winter northeast monsoon in DJF over the SCS and northern PAC for both models (Fig. 6.b.ii-iii and Fig. 7.b.ii-iii), and the weakening of summer southwest monsoon in JJA over the whole SEA (Fig. 6.d.ii-iii and Fig. 7.d.ii-iii, Tab. 3). Moreover, for DJF the SLP gradient increase is much stronger in the north ($> 10^{\circ}\text{N}$) for CNRM-CM5 for RCP8.5 (Fig. 18c), explaining the strong winter monsoon increase for this simulation (Fig. 6.b.iii and Tab. 3).

RegCM produces a decrease of the daily variance of SLP gradient for both seasons, ~ 3 times stronger for JJA (RCP4.5: $-0.028 \text{ hPa}^2/\text{deg}^2$, RCP8.5: $-0.020 \text{ hPa}^2/\text{deg}^2$ in average over the SEA, Fig. 18.h) than for DJF (RCP4.5: $-0.009 \text{ hPa}^2/\text{deg}^2$, RCP8.5: $-0.007 \text{ hPa}^2/\text{deg}^2$, Fig. 18.g). This decrease explains the decrease of daily variability of sea surface wind speed observed for RegCM for both seasons, stronger for JJA (-6% to -9% for std_d , q95 and q99 for both RCP4.5 and RCP8.5 in average over the SEA, Tab. 3) than for DJF (-1 to -4% for both RCP4.5 and RCP8.5, Tab. 3). It is particularly strong between 5°N and 10°N for DJF (Fig. 18.g) and north of 10°N for JJA (Fig. 18h), explaining the strong decrease of wind speed daily variability in those range of latitude (Fig. 11.b,d 13.b,d ESM4.b,d). For CNRM-CM5, the average change of daily variance of SLP gradient is weaker than for RegCM, about 2.5 to 5 times less for DJF ($+0.002 \text{ hPa}^2/\text{deg}^2$ for RCP4.5 and $-0.003 \text{ hPa}^2/\text{deg}^2$ for RCP8.5 in average over the SEA, Fig. 18.g), and one order of magnitude less for JJA ($-0.005 \text{ hPa}^2/\text{deg}^2$ for RCP4.5 and $-0.002 \text{ hPa}^2/\text{deg}^2$ for RCP8.5, Fig. 18.h). This explains the much weaker changes of wind speed daily variability, with a weak decrease for JJA (-1% to 0% for std_d , q95 and q99 for both RCP4.5 and RCP8.5, Tab. 3) and null to positive changes for DJF (0% to $+2\%$ for std_d , q95 and q99 for both RCP4.5 and RCP8.5, Tab. 3).

Changes of CV_y produced by RegCM and CNRM-CM5 are weak over the SEA (between 0 and 1% for DJF and JJA for CNRM-CM5, and between -1% and -2% for RegCM, Tab. 3),

and are spatially more contrasted (Fig. 8,9.b,d and Fig. 14.b,g), especially for RegCM. Similarly, both RegCM and CNRM-CM5 produces weak changes of yearly variance of SLP gradient, one order of magnitude smaller than the changes of daily variance observed in RegCM (between -0.005 and $+0.001$ $\text{hPa}^2/\text{deg}^2$ in average over the SEA in RegCM, and between -0.001 $\text{hPa}^2/\text{deg}^2$ 0.003 $\text{hPa}^2/\text{deg}^2$ in CNRM-CM5, Fig. 18.e,f). These results therefore suggest that we do not obtain a clear trend of interannual variability of SLP gradient and sea surface speed in average over the SEA, for both models and simulations. This will be further confirmed below (Section 5.2) when examining the choice of the period of reference.

This analysis of the evolution of SLP meridional gradient confirms that the changes of climatological mean and daily variability of sea surface wind speed described above can be linked to the change of sea level pressure SLP. We obtain an overall increase of SLP in the SEA domain by the end of the 21st century for both models, in particular in the norther part, with an associated increase of meridional SLP gradient and a decrease of the daily variability of this gradient. This higher SLP in the west side of the Pacific ocean could be associated to the weakening of the Walker circulation in a warmer climate (as suggested by Held and Soden 2006; Vecchi and Soden 2007) where a change in the west-east pressure gradient would result in lower surface easterlies with a weaker daily variability. Finally, the amplification of SLP increase in the RegCM for JJA compared to CNRM-CM5 (Fig. 17) could be related to the lack of air-sea coupling in the downscaling experiments. Previous studies indeed showed that in atmosphere only simulations the atmospheric responses are stronger because no damping effect from the ocean exists (Zhu and Shukla 2013; Zou and Zhou 2013; Juneng et al. 2016). Further studies based on a RCM air-sea coupling system would be of great interest to fully investigate this hypothesis in details.

5.2 Choice of the period of reference

To assess the impact of climate change on sea surface wind speed over SEA, we compared the 30-years periods 1961-90 (XX) and 2070-99 (XXI). Fig. 15b shows for RegCM the time series of yearly sea surface wind speed over SEA in HIST, RCP4.5 and RCP8.5. Yearly values differs by the average value by more than 2 standard deviations for 3 exceptional years : 1980 and 1981, which show exceptionally high numbers of TC (Fig. 15a), and 1982, which shows very weak wind over the whole year. To assess the influence of the occurrence of those exceptional years on results obtained above, we examine the same metrics as in section 4 but using a slightly different 30-year reference period for the 20th century, named XXnoext hereafter : 1960-92 excluding 1980, 1981 and 1982.

SEA average values of the mean, CV_y , std_d , q95 and q99 of the daily sea surface wind over XXnoext and of their relative change between XXnoext and XXI are given in Tab. 3. For most of the indicators (except for CV_y in JJA which becomes positive, +1%), trends remain of the same sign, though numbers vary. For the average, the SEA future decrease only weakly differs in XXnoext compared to XX for the whole year and for all the seasons (by no more than 2%), and significance levels remain similar. Similarly, for indicators of daily variability (std_d , q95 and q99), trends are similar with XXnoext, the future decrease is mainly attenuated for JJA (3% to 5%) and SON (1% to 4%), and much less for the other seasons (0% to 2%).

For CV_y , the decrease attenuation does not exceed 1% for DJF and MAM (Tab. 3), but exceeds +2% for JJA (from -1% to 1%) and SON.

Spatially, this attenuation for XXnoext compared to XX of the future decrease of wind speed mostly occurs in the SCS and PAC regions. B3 is the box for which QQplots show the strongest differences between XX and XXnoext (Fig. 5), and these differences increase for higher percentiles : the future decrease respectively weakens with XXnoext compared to XX by 6% for q99, 1% for q95, 2% for CV_y and 1% for the average. However the trends for B3 are qualitatively similar for XX and XXnoext. For the other boxes, the attenuation does not exceed 1% to 2% for all scales. The attenuation between XX and XXnoext of the future SEA decrease is mainly related for all the scales to an attenuation over the SCS and PAC in JJA, i.e. a region and period of initially strong average winds at all scales (Fig. 19). For this region and period, the average -10-20% decrease obtained with XX weakens by ~3-4% with XXnoext, the ~10% CV_y decrease strongly decreases by ~8%, and the -15-25% q95 decrease by ~4-8% (Fig. 19). This is consistent with the removal of years with exceptionally high winds and TC numbers in XXnoext compared to XX, which reduces the interannual to daily variability over the present reference period.

Over the XXnoext period, RCM-HIST produces 29.1 TC.year⁻¹ (29.8 for XX), with a yearly standard deviation of 19% (26% for XX), in better agreement with the observations (28.1 TC.year⁻¹ with a standard deviation of 17% over XXnoext). Between XXnoext and XXI, the yearly TC number decreases by 40% in RCP4.5 and 47% in RCP8.5 (vs. respectively 41% and 49% with XX).

Overall, removing exceptional years from our periods of reference does not significantly change our results concerning the impact of climate change on sea surface wind speed and TC frequency over the SEA for the average and daily indicators. Spatial and seasonal patterns of present-future variations are similar for XX and XXnoext at the first order, though differences can be observed at the second order. In particular the future decrease at all scales could be slightly attenuated for the summer TC season in the SCS and western PAC. Our sensitivity analysis moreover shows that the choice of period of reference affect the results regarding CV_y , confirming that there is no clear trend of the relative interannual variability in average over the SEA.

6. Summary and conclusion

We performed a dynamical downscaling to study the regional impact of climate change on daily sea surface wind speed in the SEA : RegCM4 was used to downscale global simulations performed in the framework of CMIP5 with CNRM-CM5 under the hypothesis of IPCC medium (RCP4.5) and high (RCP8.5) scenarios.

The added value of this downscaling in terms of representation of daily sea surface wind was first assessed by comparing the initial coarse resolution CNRM-CM5 outputs and the associated downscaled high resolution RegCM outputs with QuikSCAT satellite dataset. The downscaled simulations reproduce generally better the spatial and temporal variability of sea surface wind speed at all scales, from the climatological average to the extreme events. The downscaling improves the representation of average wind values over ~66% of the SEA (though it does not improve the representation of its spatial variability). The representation of

daily variability and intense/extreme values is improved over ~90% of the SEA, and RegCM downscaling also slightly improves the representation of their spatial variability in terms of spatial patterns, though it overestimates their range of variability. Both for average and daily variability, the improvement mainly consists in reducing the underestimation observed in CNRM-CM5, in particular in the regions and periods of strong winds. The downscaling also improves the representation of seasonal variability in regions of strong wind, in particular the northern and Indonesian sea regions of our domain. Similar conclusions were found by Tangang et al. (2019), who analysed the 850-hPa ensemble mean winds and compared them with the ERA-Interim data for the 1976-2005 period. They concluded that the ensemble mean winds at 850-hPa from 7 CORDEX-SEA RCM experiments, including the RegCM one of this study, well reproduced the patterns of winter and summer monsoon circulations, and over-estimated the strength of the monsoon given by the ERA-Interim reanalysis (Simmons et al., 2007). The ability of the RegCM downscaling in reducing the underestimation of CNRM-CM5 average sea surface wind found in this study, sometime leading to an overestimation, suggests that this monsoon strength overestimation found in Tangang et al. (2019) could be partly attributed to the downscaling effects.

Models outputs over the 20th and 21st centuries were then compared to assess the impact of climate change on sea surface wind speed in SEA, taking respectively 1961-90 and 2070-99 as reference periods. A sensitivity study showed that our results are quite robust to the choice of those reference periods. Changes of indicators of climatological average, interannual variability, daily variability and intense/extreme events were examined here.

CNRM-CM5 produces weak but regionally and seasonally contrasted changes. In average over the SEA, CNRM-CM5 produces weak and non significant changes at all time scales, except for an increase of the climatological average (+2% for RCP4.5 and +4% for RCP8.5) of DJF wind. This increase is spatially related to a significant increase in the SCS and northern PAC of the climatological average (+5-10%) and intense values (+5-10%) of the northeast winter monsoon. CNRM-CM5 moreover produces weaker but significant decreases of wind climatological average and variability in some regions, in particular in the southwestern IO in MAM. For most of the other seasons and regions, CNRM-CM5 produces weak and non significant changes.

RegCM produces much stronger (up to ~5 times) and more negative changes than CNRM-CM5, and also shows strong seasonal and regional contrasts. In average over the SEA, RegCM produces for all the seasons except for DJF a significant decrease of sea surface wind speed from the climatological (-4% in average over the year) to daily time scales (-4-3%), with a weaker decrease of relative interannual variability (-1%-2% for RCP8.5). This decrease is mainly associated with significant decreases from March to November in the northern SCS and from March to May in the IO, in regions of initially strong values of wind indicators. These local decreases reach 20% for the climatological average, 15% for the relative interannual variability, and 30% for daily variability and extreme events. Sensitivity tests to the period of averaging suggest that our results concerning the climatological and daily time scales are robust, but that for the relative interannual variability, there is no clear trend in average over the domain, but spatially strongly contrasted changes.

Analysis of the variability of spatial fields suggests that both models do not produce significant changes of spatial patterns for the climatological average and daily variability of

sea surface wind speed. For the relative interannual variability however, changes of spatial patterns are stronger, regionally and spatially more contrasted, consistently with the conclusion that no clear trend can be obtained at the scale of the average domain.

The decrease of daily variability and extreme speeds of sea surface wind in RegCM is associated with a 41% (in RCP4.5) to 48% (in RCP8.5) decrease of TC frequency. DJF change is not significant at the SEA scale in RegCM, though RCP8.5 produces a significant ~5% increase of winter monsoon wind in the northern PAC and southern SCS. For future projections, the overall decrease of the RegCM sea surface wind speed in the SEA is also in agreement with previous studies (Tangang et al., 2019; Siew et al., 2014; Kitoh, 2017) where both projected winter and summer circulations were shown to weaken. Previous RCMs studies also pointed out a weakening of the large scale monsoonal circulation in the South Asia and SEA regions by the end of the 21st century (Ashfaq et al. 2009; Ho et al. 2011; Manomaiphiboon et al. 2013; Loh et al. 2016).

Finally, CNRM-CM5 produces weak and non significant decreases, and significant increases only for some precise regions and seasons. Oppositely, RegCM produces at all scales a stronger and significant decrease at the yearly and SEA averages, associated with significant negative trends for large regions of the SEA from March to November. The values of present-future variations are thus quite different in CNRM-CM5 and in RegCM. However, the general qualitative patterns in terms of sign of changes are roughly similar, both spatially and seasonally and for both RCPs (Fig. 6 to 13). In particular, both models produce in DJF an increase of wind speed indicators in the SCS and northern PAC and a general decrease from March to November, though decreases are much stronger and more significant in RegCM than in CNRM-CM5, and conversely for increases (see Tab. 3). Moreover, for a given model, both RCPs produce similar changes, however areas and values of significant changes (both positive and negative) are generally stronger in RCP8.5 than in RCP4.5.

For both CNRM-CM5 and RegCM, those changes of climatological average and daily variability of sea surface wind speed over SEA and the differences between both models and both RCPs are associated with the change of sea level pressure. Both models show an overall increase of sea level pressure in the future, especially in the northern part of the domain. For DJF, this induces an intensification of pressure gradient especially in CNRM-CM5 and RCP8.5, explaining the strengthening of northeast winter monsoon wind. For JJA, this induces a weakening of the pressure gradient especially for RegCM and RCP8.5, explaining the weakening of summer southwest monsoon wind. The stronger decrease of daily variability of SLP gradient also explain the stronger decrease of daily variability of sea surface wind speed in RegCM for both seasons.

This work and the highlighted differences between the global and downscaled simulations confirm the relevance to use dynamical downscaling to study climate at regional scales. Our results indeed show that RegCM higher resolution improves the representation of wind at all time scales compared to CNRM-CM5, and can hence be used to better assess the effect of climate change on sea surface wind. Similarly, most of recently published regional climate studies are based on 25 to 12 km resolution RCMs developed over the last decade (see Giorgi, 2019, for a review). However, some improvements would help to further increase the quality and realism of our downscaled simulations, though those developments still require substantial developments and represents a huge computational cost. Giorgi (2019) indeed

underlined that the present effort now focuses on the development of fully coupled nonhydrostatic convection permitting RCMs usable for resolutions of a few kilometers, as done for example by Ito et al. (2015) for typhoons with a 5 km resolution nonhydrostatic coupled model. Figure ESM2 indeed shows, despite the satellite measurements errors, that real wind exhibits a stronger fine scale spatial variability than simulated wind, especially for strong wind events. Moreover air-sea interactions are very important in the studied area, in particular for processes like typhoons however our forced atmospheric RCM RegCM only sees the sea surface temperature from the coupled GCM CNRM-CM5, the ocean and atmosphere interactions can therefore not be represented, which could partly explain the amplification of sea level pressure increase in RegCM compared to CNRM-CM5 in JJA. Finally this study focus on one given RCM and one given GCM. Previous studies (e.g. Ngo-Duc et al. 2014; Raghavan et al. 2018) showed that the representation of atmospheric dynamics differs strongly depending on the choices of the RCM and GCM. Analysis of ensemble of simulations with different RCM and GCM would be useful and will now be possible in the frame of CORDEX-SEA. In particular for robust future projections, the projected changes should be based on ensemble mean where information on uncertainty must be provided, as done by Tangang et al. (2019) for precipitations projections.

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CNRM-CM5 outputs can be downloaded from the ESGS website (<https://esgf-node.llnl.gov/projects/esgf-llnl/>), informations about output files are available on CNRM-GAME website (<http://www.umr-cnrm.fr/cmip5/spip.php?article9>). This work is a part of LOTUS international joint laboratory (lotus.usth.edu.vn) and CORDEX-SEA activities. Thanh Ngo-Duc is supported by the Vietnam National Foundation for Science and Technology Development (NAFOSTED) under Grant 105.06-2018.05.

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