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High-Resolution Simulations for Vietnam - Methodology and Evaluation of Current Climate

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Abstract: To assist the government of Vietnam in its efforts to better understand the impacts of climate change and prioritise its adaptation measures, dynamically downscaled climate change projections were produced across Vietnam. Two Regional Climate Models (RCMs) were used: CSIRO's variable-resolution Conformal-Cubic Atmospheric Model (CCAM) and the limited-area model Regional Climate Model system version 4.2 (RegCM4.2). First, global CCAM simulations were completed using bias- and variance-corrected sea surface temperatures as well as sea ice concentrations from six Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models. This approach is different from other downscaling approaches as it does not use any atmospheric fields from the GCMs. The global CCAM simulations were then further downscaled to 10 km using CCAM and to 20 km using RegCM4.2. Evaluations of temperature and precipitation for the current climate (1980-2000) were completed using station data as well as various gridded observational datasets. The RCMs were able to reproduce reasonably well most of the important characteristics of observed spatial patterns and annual cycles of temperature. Average and minimum temperatures were well simulated (biases generally less than 1°C), while maximum temperatures had biases of around 1°C. For precipitation, although the RCMs captured the annual cycle, RegCM4.2 was too dry in Oct.-Nov. (−60% bias), while CCAM was too wet in Dec.-Mar. (130% bias). Both models were too dry in summer and too wet in winter (especially in northern Vietnam). The ability of the ensemble simulations to capture current climate increases confidence in the simulations of future climate.

Key words: Regional climate, dynamical downscaling, evaluation

1. Introduction

Climate change has been recognized as one of the greatest challenges for our planet, not only for the environment, but also for economic development, with changes occurring in the physical, ecological and socio-economic systems. Climate change is likely to affect climate patterns and cause sea-level rise which will have impacts on ecosystems, water resources, agriculture, forests, fisheries, industries, urban and rural settlements, energy usage, tourism and health (IPCC, 2013).

Vietnam is located in South East Asia, with a tropical monsoon climate and a coastline of more than 3200 km. It is one of the most disaster-prone countries in the world, with most of the disasters related to weather and climate. Consequently, climate change and climate variability are likely to pose increasing threats to Vietnam and its inhabitants in the near and long-term future (MONRE, 2009 and MONRE, 2012).

Global climate models (GCMs) provide the best available tools for simulating large-scale future climates based on various greenhouse gas and aerosol emission scenarios, since they are able to couple atmosphere and ocean systems and incorporate their complex linked interactions over the entire Earth system. However, their resolution (approximately 100-200 km) is too coarse to capture regional impacts of climate change, especially in areas of complex topography and land use. For this reason, two RCMs have been used in this study to dynamically downscale simulations from six GCMs.

There have been many previous studies of impacts of climate change over South East Asia and possible changes to weather patterns over Vietnam. In an earlier study by the Asian Development Bank (1994), simulations from nine global climate models were used to project temperature and precipitation for northern and southern Vietnam. Subsequently, climate change projections have been used to assess the impacts of climate change for the tropics (Hulme and Viner, 1998). A number of studies have focused on climate change and its likely impact on various sectors of Vietnam (Waibel, 2008; Asian Disaster Preparedness Center, 2003; Eckert and Waibel, 2009). Most projections are derived from multiple model results, using simple averages or weighted values based on statistical measures of model reliability, such as correlations between observed and simulated climate patterns. The underlying assumption is that projections are likely to be more reliable

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from models that simulate the present climate well.

Regional climate models (RCMs) have become important tools for the prediction of climate variability and change in the regions of southern and eastern Asia. For instance, Afiesimama et al. (2006) used RegCM3 (Regional Climate Model system, version 3) to simulate the Indian summer monsoon and showed that the average precipitation over the region was well represented by the model, which demonstrated considerable skill in reproducing the extreme precipitation regimes. Francisco et al. (2006) applied the RegCM model to simulate monsoonal precipitation over the Philippines and found that the model could reproduce observed monsoonal precipitation patterns well. Phan et al. (2009) used RegCM3 to simulate the observed annual cycle, seasonal and inter-annual variability of precipitation and surface air temperature over Vietnam and adjacent areas, and showed that RegCM3 is able to reproduce the regional circulation patterns and the spatial and temporal distributions of surface air temperature, as well as precipitation, over the model domain. In a recent study (Oh et al., 2014), RegCM4 simulated rainfall over East Asia for the historical period 1986-2005 reasonably well over Vietnam relative to gridded observations. In a study using CCAM (Conformal Cubic Atmospheric Model) nested within NCEP re-analyses, Nguyen and McGregor (2009) demonstrated that the model could simulate the main features of the Asian monsoon, including seasonal shifts of the precipitation throughout the year. Ho et al. (2011) used RegCM3 to examine changes in extremes over Vietnam.

To assist the government of Vietnam in its efforts to better understand the impacts of climate change and prioritise its adaptation measures, detailed climate change projections at 10 km resolution across Vietnam were produced for the *High-resolution Climate Projections for Vietnam* (HCPV) project (Katzfey et al., 2014). A key priority identified by stakeholders was the need to better understand the likely effects of climate change at the local level, since most of the impacts in this vulnerable region occur at this scale. The project was funded by Australia's Department of Foreign Affairs and Trade (DFAT) and carried out by partners from the Institute of Meteorology, Hydrology and Climate Change (IMHEN) and the Hanoi University of Science - Vietnam National University (HUS) in Vietnam and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia.

To address the inherent uncertainty in future climate change projections, the HCPV project used a range of GCMs, RCMs and emission scenarios, as well as analysis techniques such as ensemble statistics to ensure that a broad range of plausible changes to the climate of Vietnam were evaluated. In the project, six of the latest available GCMs from the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor et al., 2012) were selected on the basis of their ability to realistically capture current climate and climate features such as El Niño-Southern Oscillation (ENSO). Two RCMs were then used to dynamically downscale the global data to produce high-resolution (10 km or 20 km) simulations for current and future climate. Simulations were performed for historical (1970-2005) and future (2006 to 2099) time periods using two representative concentration pathways: RCP 4.5 and RCP 8.5 (Meinshausen et al., 2011). Results were analyzed over Vietnam and its seven climatic sub-regions, although results for the sub-regions are not presented in this paper.

This paper focuses on the downscaling methodology and evaluation of the current climate ensemble simulations[1]. The results of the climate change projections and other aspects of the project will be presented in future papers. Section 2 of this paper details the methodology used to generate the new climate projections for the HCPV project, including a summary of the downscaling method and Sea Surface Temperature (SST) bias correction technique. Section 3 provides evaluation of the simulations for the current climate. A summary is presented in Section 4.

2. Methodology

This section describes the methods used in this study to provide high-resolution climate scenario information for Vietnam, and the techniques used to evaluate the simulations of current climate (1980-2000). A range of possible methodologies can be used to downscale global climate information (see for example McGregor (1997) and Katzfey (2013). The process employed here to generate the high-resolution simulations from GCM data is known as dynamical downscaling, since the model explicitly simulates atmospheric dynamical and thermodynamical processes. This is in contrast to other methods, such as statistical ones, that are based on statistical relationships between large-scale and small-scale variables.

The global and regional climate simulations used in this study were driven by observed changes in greenhouse gases and aerosols. Some GCM simulations included direct and indirect effects of aerosols, some included ozone depletion, and some included volcanic aerosols and solar forcing (IPCC, 2013).

a. Observational datasets

The selection of the six GCMs was partly guided by comparing their output against available observational datasets. The datasets were also required for evaluating the subsequent dynamically downscaled fine-resolution simulations for present-day conditions. This section describes the derivation and contents of the available data, from station datasets to gridded global and regional datasets.

Observed daily data of temperature, precipitation, wind speed, potential evapotranspiration and humidity are available from about 70 stations in Vietnam for the present climate. Only 58 stations had sufficient good quality average temperature,

[1]Project data and reports can be accessed at www.vnclimate.vn.

Table 1. Climate variables and details of a number of global and regional gridded datasets.

DATASET	CLIMATE VARIABLES	DESCRIPTION	SOURCES
Stations	Tave, Tmax, Tmin, precipitation	Station locations	
APHRODITE	Precipitation (v1101), temperature (v1204R1)	Station-based gridded analysis. Daily precipitation (1951-2007, 60°E-150°E, 15°S-52°N, 0.25° resolution) Daily temperature (1961 to present)	Yatagai et al. (2012)
Climate Research Unit, East Anglia (CRU 3.22)	Precipitation and wet-day frequency, mean, maximum and minimum temperature, vapour pressure and relative humidity; sunshine percentage and cloud cover; frost frequency, wind speed	Gridded station-based Average monthly (1961-1990, global, 0.5°)	Harris and Jones (2014)
NCEP/NCAR Re-analysis 1	Atmospheric variables at surface and upper levels and precipitation	Gridded re-analysis dataset Daily time scale (1948 to present)	Kalnay et al. (1996)

average daily maximum and minimum temperature, and precipitation data to be useful in this study (see Fig. 4 for locations of the stations, as well as topography used for the RCM simulations).

Several global gridded datasets are available for studying present climate and climate variability, and also for comparing with global climate simulations performed for the IPCC (2013). Some of the datasets include enough climate variables over an appropriate geographic area to make them useful for studies that focus on regional scales in the Asia-Pacific area. The global atmospheric component datasets include the re-analysis dataset from the National Center for Environmental Prediction (NCEP), USA. Sets of global precipitation data include the CRU datasets and the APHRODITE dataset, which covers most of Asia. Table 1 provides details of data available from each global and regional dataset.

b. GCM selection for downscaling

Downscaling the results of all available CMIP5 GCMs is computationally too expensive at present. However, to capture the plausible range of the climate projections, ensemble simulations of GCMs are needed. For this project, data from a subset of six different GCMs provide a compromise between computational costs and the provision of a range of different climate change signals that arise from model-to-model variations. To determine which of the 24 GCMs available from CMIP5 at the time of this study to downscale, their performance at simulating current climate was ranked, based on two criteria:

1. Ability to capture observed spatial patterns and trends of atmospheric variables such as mean sea level pressure, temperature and precipitation.
2. Ability to simulate oceanic features such as El Niño Southern Oscillation (ENSO), which have a large impact on climate variability in Vietnam.

Initially, a ranking of the models based on the first two criteria was prepared using studies that focused on CMIP5 simulations. At the time of this study, there were over 30 evaluation studies available, but most of them do not provide a ranking, or consider only a small subset of the CMIP5 models. For the first criterion, results of the analyses conducted in this project and results of three additional studies were incorporated. Based on the results of the validation of model simulations of current climate (see Katzfey et al., 2014), the GCMs were ranked according to the root mean square error (RMSE) values for annual temperature and rainfall as well as the pattern correlation of the annual rainfall. The ranking by Bhend (personal communication), which is based on the analyses of Bhend and Whetton (2013), was constructed using the agreement between observed and simulated temperature trends. Watterson et al. (2013a, b) ranked the models using a skill score that combined the agreement of the models with observations of temperature, rainfall and MSLP. Watterson et al. (2013a) ranked the models on global-scale performance, while Watterson et al. (2013b) provided a ranking focusing just on results for Asia.

For the second criterion, a review of three different studies that focused on SSTs was conducted. Grose et al. (2014) analysed the GCM SSTs in the Pacific Ocean with a special focus on the two El Niño regions (the Central and Eastern Pacific regions). They also investigated the observed and simulated frequency of extremes of the ENSO phenomenon, El Niño and La Niña events. Kim and Yu (2012) correlated the spatial patterns of the two types of El Niño with the observed patterns, while Kug et al. (2012) focused on the temporal correlation between both types. Results of these studies indicate how well the spatial and temporal patterns of the ENSO phenomenon are represented in the models.

The rankings of the individual studies were averaged to yield a final ranking of the models. If there was more than one ranking from a single study (e.g. for rainfall and temperature) these rankings were averaged in order to produce just one ranking per study. Not all studies considered had the same number of GCMs used in the rankings. Therefore, the rankings were normalized by the number of models analysed in the individual studies. Consequently, the possible range of the averaged score could vary between 0.15 (first place in the rankings of the 24 GCMs) to 1.0 (last place in all rankings). The final scores for the different models are listed in Table 2.

Table 2. Summary of CMIP5 model ranking. The numbers in the columns related to publications denote the rank of the model, while the final score is a combined measure that ranges from 0.15 (first place in all rankings) to 1.0 (last place in all rankings). Models chosen for this study are highlighted. Corr - correlation, PC - pattern correlation, N3.4 - Nino 3.4 index, N3 - Nino 3 index, N4 - Nino 4 index, CP - Central Pacific, EP - Eastern Pacific, EOF1 - first empirical orthogonal function.

	Bhend (pers. comm.)	Katzfey et al. (2014)			Watterson et al. (2013a)	Watterson et al. (2013b)	Grose et al. (2014)				Kim and Yu (2012)		Kug et al. (2012)	
GCMs	Z-score Temp trend	RMSE Temp	RMSE Prec	PC Prec	M-Score	M-Score	No. ENSO	RMSE N3.4	Corr N3.4	Std N3.4	Corr EP ENSO EOF1	Corr CP ENSO EOF1	Corr N3 N4	Final score
ACCESS1.0	4	8	19	20	3	2	7	1	2	7			12	0.39
ACCESS1.3	1	6	22	21	8	7	2	11	5	8				0.35
CanESM2	17	11	7	11	12	12	7	5	2	11	3	5	18	0.61
CCSM4	22	3	1	1	7	5	6	20	5	13	2	1	2	0.34
CNRM-CM5	21	17	2	2	2	1	8	8	2	9	3	2	1	0.31
CSIRO-Mk3-6-0	10	10	14	4	15	16	6	14	11	1	11	8	6	0.57
FGOALS-g2	12	23	9	10	14	13	2	4	3	4			13	0.57
FGOALS-s2	23	16	10	12	19	20	9	21	4	14				0.80
GFDL-CM3	9	22	6	6	5	9	9	19	5	12			4	0.42
GFDL-ESM2M	2	15	11	9	11	14	4	22	12	15	5	7	3	0.48
GISS-E2-H	20	12	24	24	20	17	9	7	4	10	9	1		0.70
HadCM3	15	13	23	19			3	1	1	3				0.53
HadGEM2-CC		9	15	18	6	6	2	13	9	4	7	3	7	0.44
HadGEM2-ES	14	4	18	16	4	4	6	10	6	2	6	7	15	0.54
Inmcm4	8	24	13	17	13	15	4	16	8	11	10	4	5	0.61
IPSL-CM5A-LR	16	21	17	15	22	22	1	6	3	4	4	4	16	0.71
IPSL-CM5A-MR	7	5	16	14	21	21	5	9	4	2	2	3	9	0.53
MIROC4h	18	2	8	13			2	3	5	5				0.46
MIROC5	5	7	3	7	16	10	8	23	5	15	6	5	10	0.47
MIROC-ESM	19	19	20	22	18	19	3	17	10	14				0.84
MIROC-ESM-CHEM	3	20	21	23	17	18	3	15	7	13			14	0.69
MPI-ESM-LR	11	1	5	5	1	3	7	18	7	6	1	4	17	0.41
MRI-CGCM3	13	14	12	3	10	11	9	12	3	11	6	6	11	0.51
NorESM1-M	6	18	4	8	9	8	5	2	4	6	8	1	8	0.35

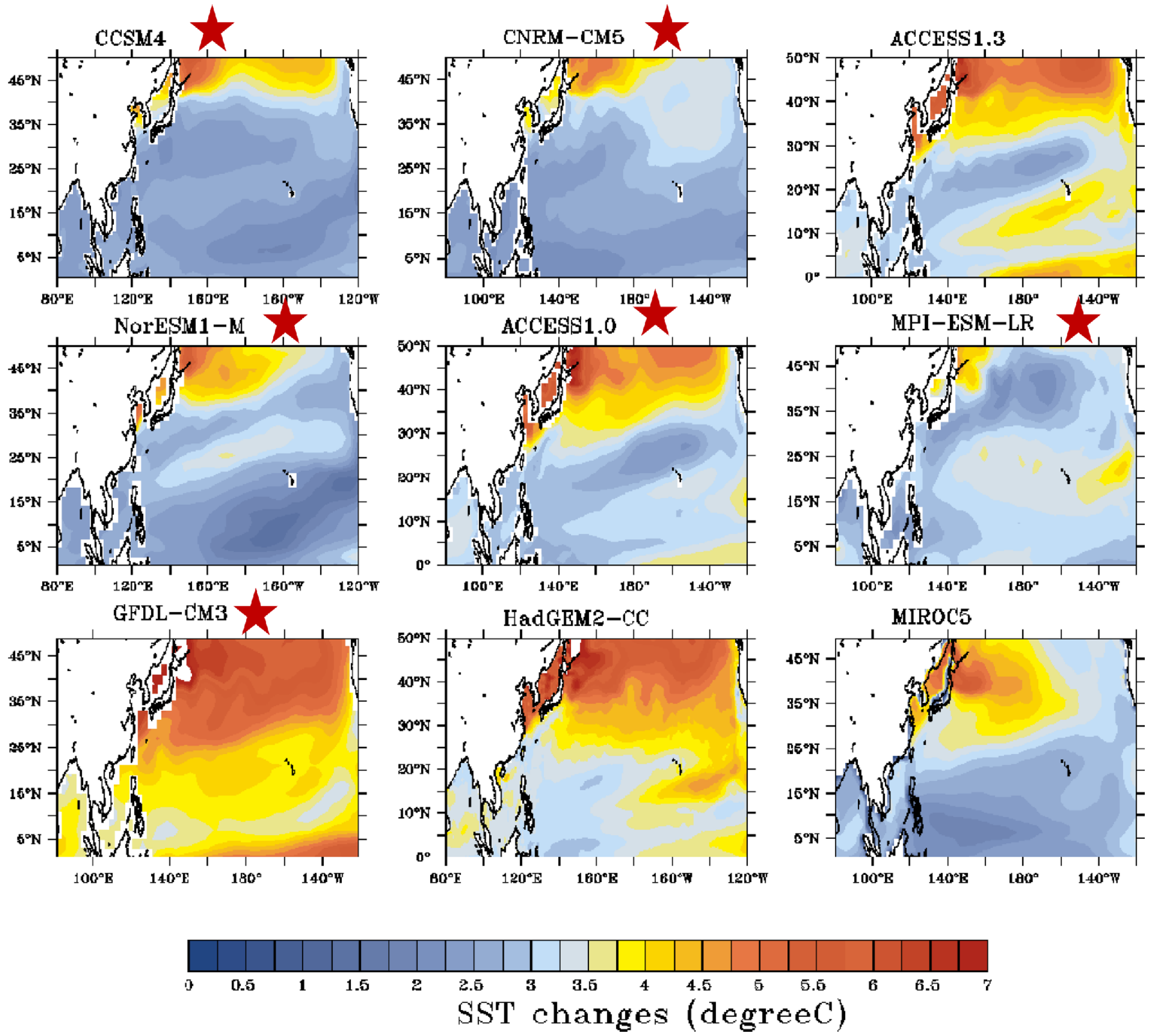

Fig. 1. SST changes in the tropical Pacific (°C) from the best-performing models for the months July-August by 2071-2100 compared with 1971-2000, based on the RCP 8.5 emission scenario. Starred GCMs are the ones chosen to downscale in this study.

Although in this study only SST and Sea Ice Concentrations (SICs) are used from the GCMs, it is expected that GCMs with more realistic atmospheric simulations will also have better representation of these fields. Similarly, although we correct the magnitude of the SST variability (see below), the GCMs with more realistic distributions and frequency of interannual variability in SSTs (the latter which is not altered in the bias-correction procedure) will provide more realistic forcings to the downscaling.

Although not relevant for this paper, an additional selection consideration was choosing GCMs with different amounts and patterns of warming in the SSTs. While this does not impact on the evaluation of the current climate, these simulations will also be used to project future climate and it is desirable to represent the full range of possible future changes in SSTs in order to address the uncertainty inherent in climate modelling and capture the most probable/realistic range of changes. The range of SST warming patterns projected by some of the higher ranking GCMs at the end of the century with RCP 8.5 are presented in Fig. 1. Note the similar SST warming patterns for both ACCESS1.0 and ACCESS1.3. Hence, although ACCESS1.3 ranked third, it was not chosen as one of the GCMs used in this study due to data availability problems and similarity of climate change signal. A summary of the strengths and weaknesses of the six GCMs chosen to be downscaled to fine resolution for this project (using the historical simulation r1i1p1 data) can be found in Table 3.

c. Correction of GCM SSTs

GCMs simulate the global climate reasonably well, but still have biases and some do not simulate inter-annual variability in the atmospheric and oceanic system (e.g. ENSO) very well (IPCC, 2013; Grose et al., 2014). One technique to address

Table 3. Strengths and limitations of the six GCMs selected for downscaling.

GCM, Institute, reference	Strengths	Limitations
CCSM4, National Center for Atmospheric Research (Gent et al., 2011)	- Good agreement with precipitation and temperature observations over South East Asia - ENSO pattern well reproduced	- Observed temperature trends poorly reproduced - Less realistic SST pattern in the tropical Pacific
CNRM-CM5, Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique (Voldoire et al., 2012)	- ENSO pattern well reproduced - Good agreement with precipitation observations over South East Asia - Good agreement with observations globally and over Asia	- Observed trends poorly reproduced over South East Asia - Too few ENSO events
NorESM1-M, Norwegian Climate Centre (Bentsen et al., 2013)	- ENSO pattern and tropical Pacific SSTs well reproduced	- Poor agreement with precipitation patterns over South East Asia
ACCESS1.0, Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BOM), Australia (Bi et al., 2013)	- SSTs in the Pacific well reproduced - Observed temperature trends well reproduced - Good agreement with observations globally	- Poor agreement with precipitation patterns over South East Asia
MPI-ESM-LR, Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology) (Giorgetta et al., 2013)	- ENSO pattern and SSTs in the Pacific well reproduced - Good agreement with temperature observations over South East Asia	- ENSO variability not well reproduced
GFDL-CM3, NOAA Geophysical Fluid Dynamics Laboratory (Griffies et al., 2011)	- Good agreement with precipitation observations over South East Asia	- Poor agreement with temperature patterns over South East Asia

these biases and potentially improve the dynamical downscaling results is to correct the SSTs from the GCMs before they are used by the RCMs. CCAM can be run with a globally uniform grid and therefore only requires an initial atmospheric analysis, SSTs, and SICs from the host GCM. Limited area models cannot easily use this approach since they require lateral boundary atmospheric data from GCMs. The deficiencies or biases of GCMs, due to differing model configurations and physics, if not corrected before downscaling can cause unrealistic behaviour of the RCM simulations and thereby affect the reliability of the climate projections. In previous downscaling simulations with CCAM, a simple correction of the climatological monthly means was applied to GCM SSTs (Katzfey et al., 2009; Nguyen et al., 2012, Ngo-Duc et al., 2014). This method preserved the inter-annual (year-to-year) variation of GCM SSTs, and therefore any errors in variability of SSTs from GCMs, such as those related to ENSO, were also imposed upon the downscaled simulations. Therefore a method was developed that corrects both the monthly climatological bias, as well as the monthly variance, of the SSTs. Consequently, while the climate change signals of the GCMs are preserved in the downscaled simulations, the location of the ENSO variability, particularly over the tropical Pacific, is more realistic. However, it should be noted that the frequency of the ENSO variability simulated by the GCMs was not adjusted.

The GCM SSTs are corrected to match the Optimum Interpolation SST dataset Version 2 (OISSTv2, Reynolds et al., 2007), which contains daily SST and SIC data on a 0.25° longitude by 0.25° latitude grid for the period 1982 (September) to 2011. The dataset is based on measurements conducted by NOAA's polar orbiting Advanced Very High Resolution Radiometer (AVHRR) meteorological satellites[2] in combination with buoy data and ship measurements. Since only monthly averaged GCM data is used, the OISSTv2 SST and SIC data were averaged monthly as well. Additionally, the model SSTs and SICs are interpolated to match the observation grid prior to correction.

In the bias correction method, the following steps were conducted (see Katzfey et al. (2009, 2013) and Hoffmann et al. (2016) for more details of the bias correction procedure).

For each month and year:

1. SST data were de-trended at each grid point using the 30-year backward running trends.
2. The standard deviation (SD), which is a measure of the year-to-year variability of the de-trended 30-year period, was calculated for the period 1982-2011 (the timespan of OISSTv2).
3. The monthly anomalies of SD were corrected using the ratio of the observed SD to the model SD.
4. Monthly biases of the resulting SSTs were then calculated for the period 1982-2011 and subtracted from the results of step 3, giving the bias- and variance-corrected SSTs.

The correction is linearly reduced from the equator to 50°N and 50°S. This means that the full variance correction is applied at the equator, but no variance correction is applied north of 50°N or south of 50°S. This step is necessary to avoid

[2]See http://noaasis.noaa.gov/NOAASIS/ml/avhrr.html for more information on AVHRR satellites.

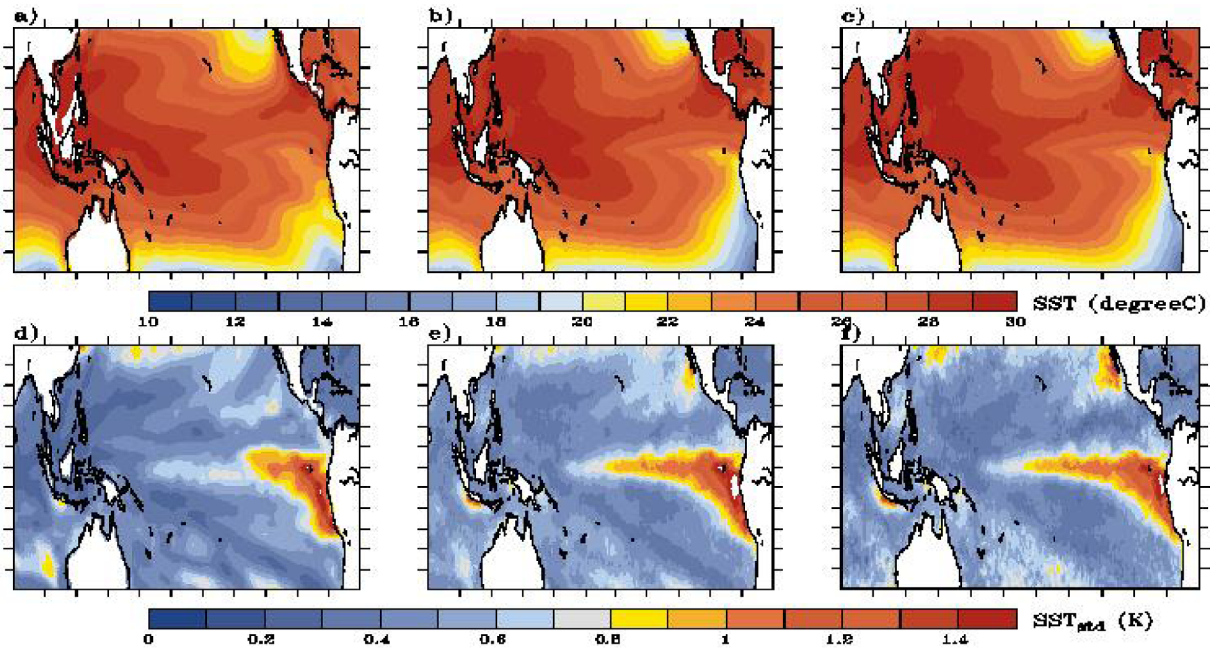

Fig. 2. Long-term mean (top panel) and standard deviation (bottom panel) of July SSTs for the period 1982-2011 from (a, d; left) uncorrected ACCESS1.0 results, (b, e; middle) corrected ACCESS1.0 results and (c, f; right) observed data from OISSTv2.

problems arising from applying a bias correction to regions where in a future climate spatial shifts of strong ocean currents, such as the Gulf Stream, are possible. Problems due to differences between SIC distribution in the GCMs and in the observations were avoided by reducing the SST bias correction near the ice edges. This was accomplished by weighting the correction by one minus the sea ice concentration, resulting in no correction where the sea ice concentration was one and full correction when sea ice concentration was zero. Note that all the adjustments prevented any significant changes to the climate change signal in the corrected SSTs compared to the uncorrected SSTs.

As an example, Fig. 2 shows the uncorrected and corrected July SSTs from the ACCESS1.0 GCM as well as the observed SSTs in the tropical Pacific for the period 1982-2011. As intended, the GCM SSTs are very close to the observed SSTs after the correction. Also, the standard deviation is very similar to the observations, especially close to the equator.

d. Dynamical downscaling methodology

In this study, two regional models were used to dynamically downscale global climate model information over Vietnam. The following section describes the methods used to produce the simulations. The process had two steps:

1. Global simulations with initial input from the six selected CMIP5 GCMs (see Section 2.3) were completed using CCAM with a uniform grid.
2. These global simulations were dynamically downscaled to fine resolutions, using two RCMs, the variable-resolution CCAM and the limited-area RegCM4.2 model, in order to produce simulations of the current climate or future climate at regional scale.

CCAM, a global model, requires only SST and SIC data from the GCMs as inputs to drive the model. RegCM4.2, a limited area model, requires input of more detailed initial and boundary condition data, including atmospheric variables such as MSLP, temperature and wind.

The resolutions of the GCM and RCM grids and time periods for the various simulations varied due to technical and computer resource constraints. For details of the set-up of the two types of downscaled simulations, see the following sections and Table 4.

(1) Conformal Cubic Atmospheric Model (CCAM)

CCAM is a variable-resolution, non-hydrostatic global atmospheric model that has been developed at CSIRO (McGregor, 2005; McGregor and Dix, 2001, 2008). The updated Geophysical Fluid Dynamics Laboratory (GFDL) parameterisations for long-wave and short-wave radiation (Schwarzkopf and Ramaswamy, 1999; Freidenreich and Ramaswamy, 1999) are employed, with interactive cloud distributions (Rotstayn, 1997). The simulations also include the scheme of Rotstayn and Lohmann (2002) for the direct and indirect effects of sulphate aerosols. The model employs a stability-dependent boundary-layer scheme based on Monin-Obukhov similarity theory (McGregor, 1993). The CABLE biosphere-atmosphere exchange model is included, as described by Kowalczyk et al. (2006). The cumulus convection scheme uses mass-flux closure as described by McGregor (2003). CCAM also includes a simple parameterisation to enhance SSTs under conditions of low wind speed and large downward solar radiation, affecting

Table 4. List of RCMs used in this project, with their resolution, number of levels, and some details of the simulations.

Model	Resolution/ vertical levels	GCM data used	Input data (IC: Initial condition)	Years simulated	Emission scenarios
CCAM50	50 km/L27	CNRM-CM5 CCSM4 ACCESS1.0 NorESM1-M MPI-ESM-LR GFDL-CM3	Sea ice and variance and bias-corrected SSTs IC: 01 Jan 1970 NCEP R1	1970-2099	Historical for 1970-2005 RCP 4.5 and 8.5 for 2006-2099
CCAM10	10 km/L27	CNRM-CM5 CCSM4 ACCESS1.0 NorESM1-M MPI-ESM-LR GFDL-CM3	CCAM 50 km	1970-2099	Historical for 1970-2005 RCP 4.5 and 8.5 for 2006-2099
CCAM100	100 km/L18	ACCESS1.0 NorESM1-M	Sea ice and variance and bias-corrected SSTs IC: 01 Jan 1970 NCEP R1	1970-2099	Historical for 1970-2005 RCP 4.5 and 8.5 for 2006-2099
RegCM4.2	20 km/L18	ACCESS1.0 NorESM1-M	CCAM 100 km	1979-2000 2045-2065 2080-2099	Historical for 1979-2000 RCP 4.5 and 8.5 for other periods

the calculation of surface fluxes. Further details of the model dynamical formulation are provided by McGregor (2005). CCAM may be employed in quasi-uniform mode or in stretched mode by utilising the Schmidt (1977) transformation. The quasi-uniform mode allows one to apply the bias-corrected SSTs, while the stretched mode focuses the computational resources on the region of interest, but with lateral boundary conditions (a scale-selective digital filter is used to force the large-scale atmospheric fields of the host model onto the stretched-grid simulation).

(a) Step 1: CCAM at 50-km resolution

For these simulations, CCAM was first set up on a C192 grid (with six panels each of 192×192 grid points) having a quasi-uniform horizontal resolution of about 50 km over the whole globe (Fig. 3, top) and 27 vertical levels. It was run for 130 model years (1970-2099) forced by SSTs and SICs from each of the six selected CMIP5 GCMs. From 1970 to 2005, historical values of greenhouse gases and aerosols were used. As described above in Section 2c, the biases and variances of the GCM SSTs were corrected before they were used to force CCAM.

(b) Step 2: CCAM at 10-km resolution

All CCAM quasi-uniform global simulations were further downscaled using CCAM to 10-km resolution over Vietnam with 27 vertical levels, utilizing the C96 grid shown in Fig. 3 (lower plot). To provide a further degree of consistency with the host CCAM simulation, a scale-selective digital filter (Thatcher and McGregor, 2009) was applied every six hours to replace selected broad-scale (with length-scale about the width of the Vietnam domain) fields of the high-resolution CCAM simulation with the corresponding fields of the 50-km CCAM simulation. The filter was applied to the MSLP, moisture, temperature, and wind components above pressure-sigma level 0.9 (about 1 km above the surface). The terrain used for the simulations is shown in Fig. 4.

The full model output was saved four times per day at 0000, 0600, 1200 and 1800 GMT. These data have been post-processed by interpolating them onto a 0.5^{o} grid for the 50-km simulations, and a 0.1^{o} grid for the 10-km simulations for easier interpretation. Many prognostic and diagnostic fields are available for impact assessment studies at local to regional scales.

(2) RegCM4.2

The Regional Climate Model Version 4.2 (RegCM4.2) developed at the Abdus Salam International Centre for Theoretical Physics (ICTP) in Trieste, Italy (Giorgi et al., 2011; Elguindi et al., 2011), was also used in the project. RegCM4.2 is a primitive equations, hydrostatic, compressible, limited-area model with sigma-pressure (σ) vertical coordinates. The model was run with 18 vertical σ-levels, the standard resolution for the model at the time, due to limited computer resources available. The experiments conducted in this project use the Grell scheme with a simplified form of the Arakawa-Schubert closure assumption for convective parameterisation (Grell, 1993; Arakawa and Schubert, 1974). Exchanges of energy, moisture, and momentum between the land surface and the atmosphere are computed using the Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al., 1993).

(a) Step 1: CCAM at 100-km resolution

For the RegCM4.2 simulations, due to restricted computer resources, CCAM was first set up on a quasi-uniform C96 grid (with $6 \times 96 \times 96$ grid points) having a resolution of about 100 km over the whole globe and 18 vertical levels. CCAM C96 was run for the period 1979-2000, forced by the bias-corrected SSTs of two of the global models used in the CCAM

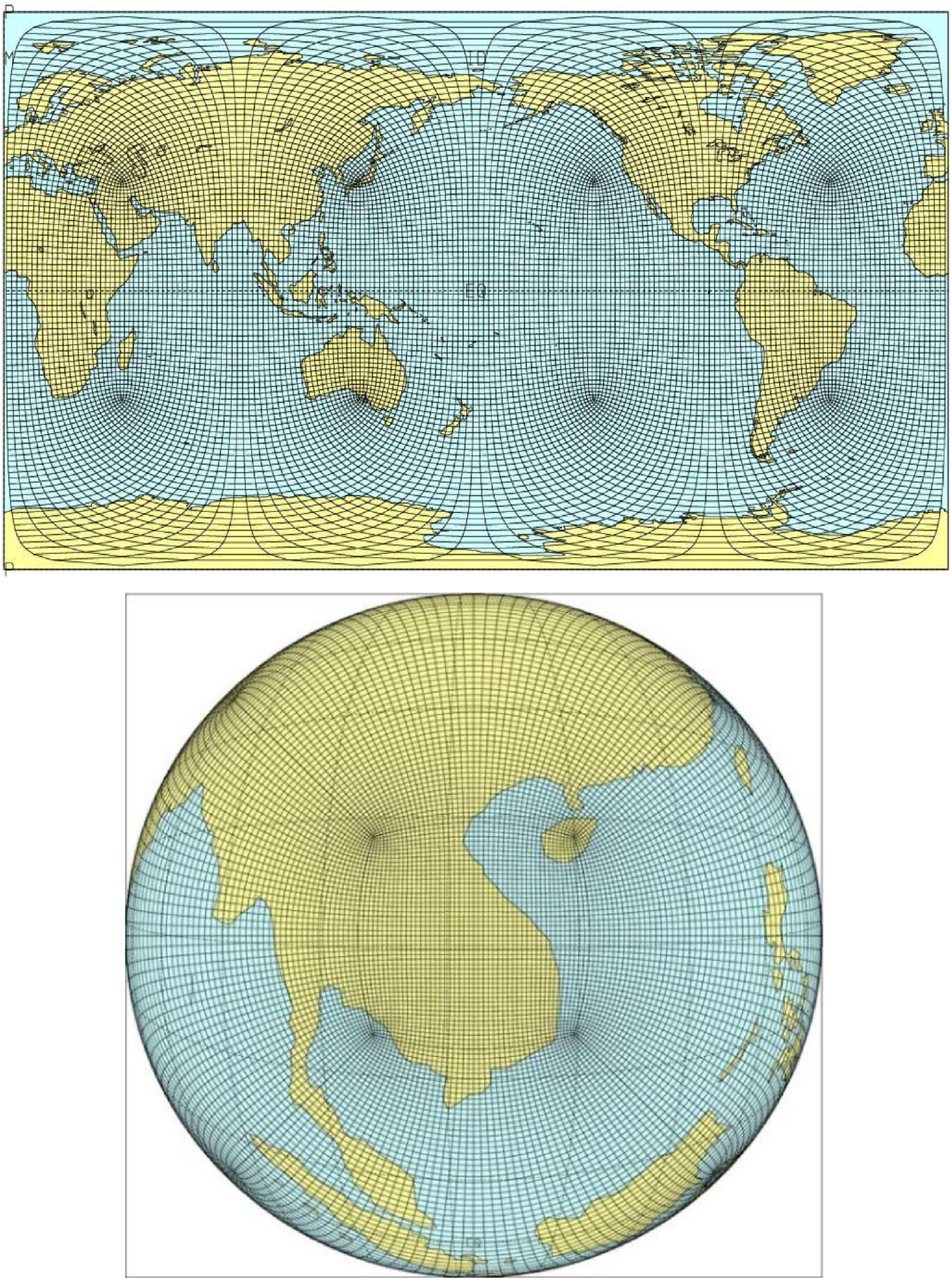

Fig. 3. CCAM grids used for the 50 km global (C192 grid; top) and 10 km (C96 grid; bottom) downscaled simulations over Vietnam (plotting every 2nd grid point).

downscaling process, ACCESS 1.0 and NorESM1-M.

(b) Step 2: RegCM4.2 at 20-km resolution

The CCAM 100-km outputs were used to create the initial and boundary conditions, updated every six hours, for the limited-area RegCM4.2 simulations. The model output was saved four times per day at 0000, 0600, 1200 and 1800 GMT. These data cover the domain from 100°E to 120°E and from 6°N to 25.5°N (Vietnam plus part of the East Sea), with horizontal resolution of 20 km for both east-west and north-south directions. The terrain used for the simulations is shown in Fig. 4. Many prognostic and diagnostic fields were saved from these experiments.

3. Model performance for current climate

This section assesses the performance of the two RCMs (CCAM and RegCM4.2) driven by GCM data in simulating

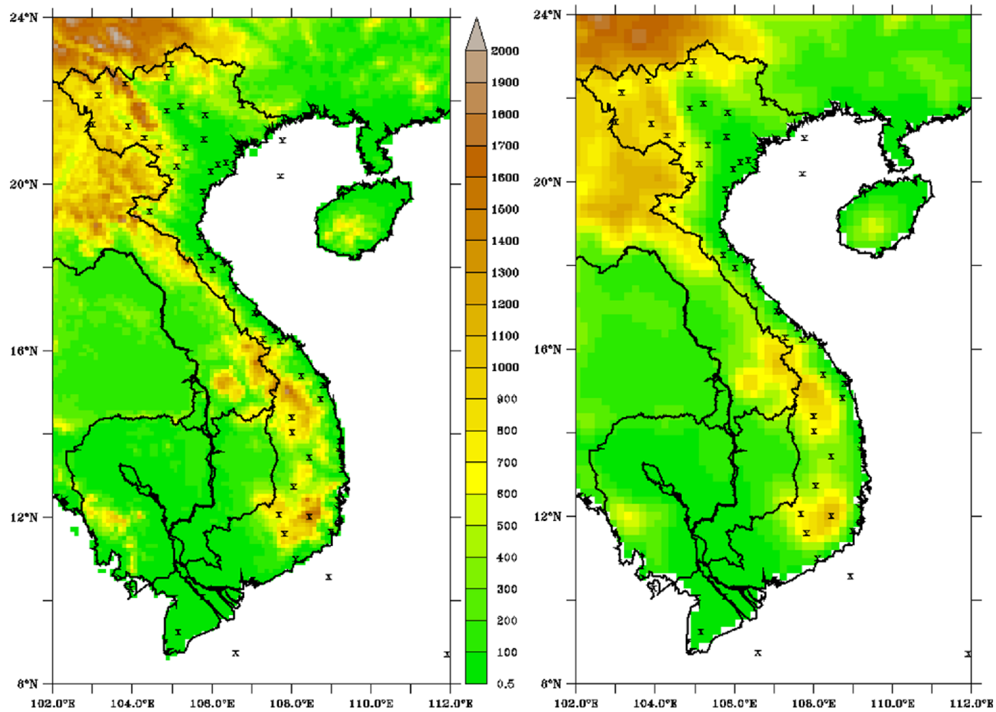

Fig. 4. Topography used for the a) CCAM 10 km and b) RegCM4.2 20 km simulations. Locations of the 58 stations for which observations were available are indicated by x.

Table 5. Definitions of monsoonal-based seasons used for evaluation.

FIMS	First Inter-Monsoon Season	AM: April-May
SWMS	South West Monsoon Season	JJAS: June, July, August, September
SIMS	Second Inter-Monsoon Season	ON: October-November
NEMS	North East Monsoon Season	DJFM: December, January, February, March

characteristics of the observed climate (1980-2000) over the area that covers Vietnam. Evaluating and comparing these model simulations with observed data allows us to assess the skill of the models in reproducing current climate. Note that when RCMs are run with the boundary forcing from GCM data, the downscaled simulations can inherit deficiencies from the GCMs. Here, biases from the CCAM-50 and CCAM-100 simulations will also affect the high-resolution downscaling results.

Biases, RMSE and spatial pattern correlations (PC) were used to compare model simulations against station observations. The reference period of 1980 to 2000 was used for evaluation of all RCM simulations. We note that a one-year spin-up period was removed before evaluation so that the model's land surface properties (particularly the soil temperature and moisture) can adjust to the model's atmospheric conditions. For regional analysis, see the HPCV project website (www.vnclimate.vn).

Seasons are monsoonal based, and are defined as in Table 5.

(1) Evaluation of temperature for Vietnam

The spatial distribution of the APHRODITE surface air temperature (Tave) and the ensemble-mean model biases for CCAM and RegCM4.2 simulations for both NEMS and SWMS are shown in Fig. 5, with seasonal and annual statistics presented in Table 6a. Generally the agreement is very good for both models, with biases less than 1°C and RMSE less than 2°C. The PCs are also quite high, greater than 0.8, indicating that the models are capturing the spatial pattern of temperature well. CCAM generally follows the observations more closely than RegCM4.2, with smaller biases and RMSE and higher PCs. RegCM4.2 has a slight warm bias during the beginning and end of the year (SIMS and NEMS) and a cool bias in mid-year (SWMS).

Comparison of the annual cycle of average surface air temperature (Tave) with the station observations (Fig. 6) shows the close correspondence of the models and the observations. It can be seen that the CRU dataset is warmer than the other datasets for the second half of the year, while the APHRODITE dataset is cooler during the first half of the year. The small biases for CCAM are similar to those noted in Ngo-Duc et al. (2014). It is interesting to note that the results for RegCM4.2 are significantly better than in previous studies (Phan et al., 2009; Ho et al., 2011; Ngo-Duc et al., 2014), where a cold bias

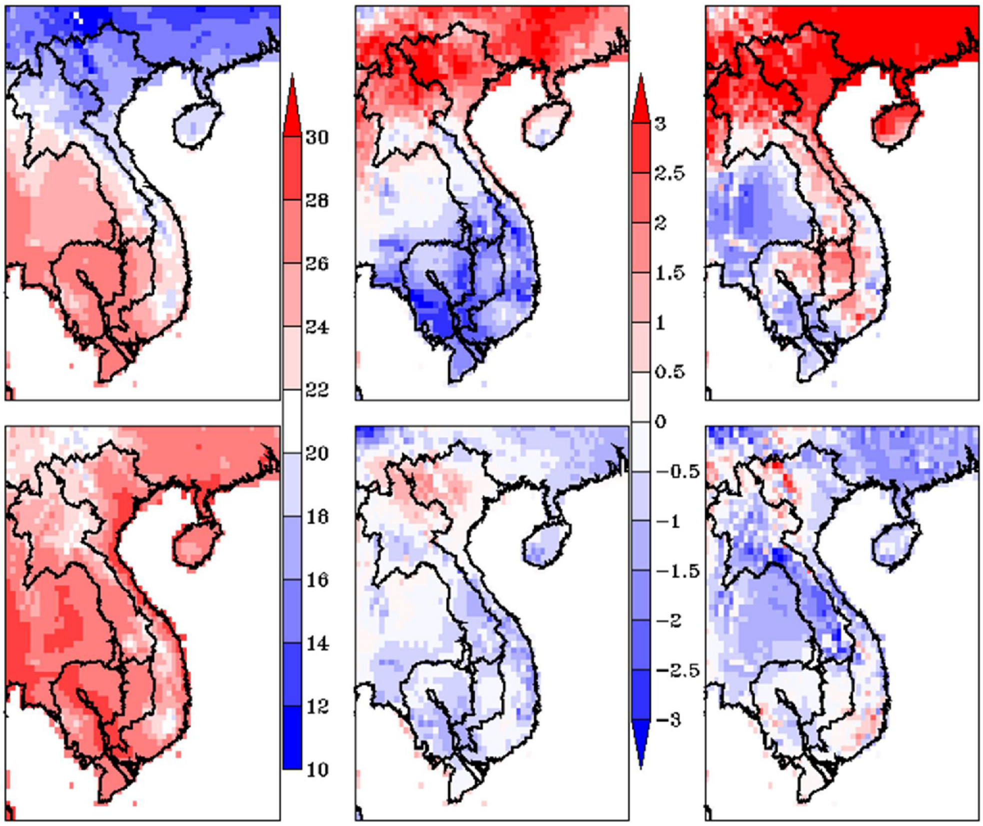

Fig. 5. Seasonal mean surface air temperature (°C) for APHRODITE dataset (left column) and biases for CCAM-OBS (middle column) and RegCM4.2-OBS (right column) for two seasons (NEMS, top row and SWMS, bottom row) over Vietnam for the 1980-2000 period.

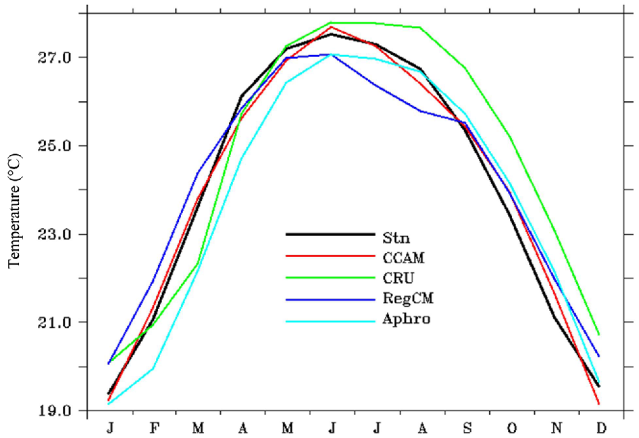

Fig. 6. The annual cycle of the temperature (°C, monthly averages) over the whole of Vietnam for station observations (black), CRU dataset (green) and the APHRODITE dataset (cyan) compared with ensemble means for CCAM (red) and RegCM4.2 (blue) for the period 1980-2000.

of about 1-2°C was noted for most seasons. For the simulations in Phan et al. (2009) and Ho et al. (2011) this was partly explained by the height difference of the model terrain and the station heights. In Ngo-Duc et al., the cold bias was partly explained as due to cold SSTs coming from the GCM forcing.

In addition to the ensemble mean statistics, the ranges of statistics from the individual ensemble members are also presented in Table 6a. Due to bias correction of the forcing SSTs used in the global 50/100-km simulations for the period 1982-2011, the monthly mean SSTs for all runs will be the same for this period, but not necessarily for the evaluation period 1980-2000. In addition, the interannual variability is different for each simulation, and the land surface temperatures will evolve differently. As a result, the atmosphere fields will be slightly different for each simulation, resulting in non-identical climatologies for each of the members of the ensemble, as shown by the range of the evaluation statistics in Table 6a. However, the range of the statistics is relatively small, indicating the controlling influence of the SSTs in this region. Of course, with only two members for the RegCM4.2 ensemble, versus six for CCAM, the range tends to be less for RegCM4.2.

Seasonal and annual statistics for Tmax and Tmin are presented in Table 6b and Table 6c, respectively. In general, the statistics show that the simulations are still quite realistic, with biases generally less than 1°C. While the statistics for Tmin are similar to those for Tave, the values are not as good for Tmax. The Tmax RMSE is generally slightly above 2°C, with pattern correlations generally less than 0.80. For Tmax, CCAM has a cold bias of more than 1°C in FIMS and SWMS,

Table 6. Evaluation of a) Tave, b) Tmax and c) Tmin from the RCM simulations for the current climate period, 1980-2000. The mean Tave, Tmax, and Tmin are based on station observations, while Bias, RMSE and Pattern Correlation are for the 6-member CCAM ensemble means and the 2-member RegCM4.2 ensemble means relative to the station observations. The range of values for the individual ensemble members are given only for Tave.

a) Tave							
Season	Mean (°C)	Bias (°C)		RMSE (°C)		Pattern Correlation	
		CCAM	RegCM4	CCAM	RegCM4	CCAM	RegCM4
FIMS	26.7	−0.4 −0.6 to −0.2	−0.2 −0.2 to −0.2	1.0 1.0 to 1.0	1.4 1.4 to 1.4	0.91 0.88 to 0.93	0.77 0.76 to 0.78
SWMS	26.7	0.0 −0.1 to 0.2	−0.5 −0.6 to −0.5	0.7 0.7 to 0.8	1.5 1.5 to 1.5	0.95 0.95 to 0.95	0.82 0.82 to 0.82
SIMS	22.3	0.5 0.4 to 0.9	0.7 0.6 to 0.7	1.1 1.0 to 1.4	1.7 1.7 to 1.7	0.94 0.92 to 0.95	0.86 0.85 to 0.86
NEMS	20.9	0.0 −0.3 to 0.3	0.8 0.7 to 0.8	1.4 1.4 to 1.6	2.0 1.9 to 2.0	0.91 0.88 to 0.93	0.85 0.85 to 0.86
Annual	24.0	0.0 −0.1 to 0.3	0.1 0.1 to 0.2	1.1 1.0 to 1.2	1.7 1.7 to 1.7	0.93 0.91 to 0.94	0.83 0.82 to 0.83
b) Tmax							
Season	Mean (°C)	Bias (°C)		RMSE (°C)		Pattern Correlation	
		CCAM	RegCM4	CCAM	RegCM4	CCAM	RegCM4
FIMS	31.5	−1.2	−0.1	2.5	2.4	0.62	0.51
SWMS	31.1	−1.0	−0.6	1.9	2.3	0.84	0.62
SIMS	26.3	−0.1	0.7	1.8	2.2	0.72	0.60
NEMS	25.3	−0.6	0.7	3.1	2.8	0.64	0.74
Annual	28.5	−0.8	0.1	2.4	2.4	0.72	0.64
c) Tmin							
Season	Mean (°C)	Bias (°C)		RMSE (°C)		Pattern Correlation	
		CCAM	RegCM4	CCAM	RegCM4	CCAM	RegCM4
FIMS	31.5	−1.2	−0.1	2.5	2.4	0.62	0.51
SWMS	31.1	−1.0	−0.6	1.9	2.3	0.84	0.62
SIMS	26.3	−0.1	0.7	1.8	2.2	0.72	0.60
NEMS	25.3	−0.6	0.7	3.1	2.8	0.64	0.74
Annual	28.5	−0.8	0.1	2.4	2.4	0.72	0.64

while RegCM4.2 has a warm bias of 0.7°C during SIMS and NEMS. Note that these results are different than those of Ngu-Duc et al. (2014) where Tmax was slightly warm and Tmin slightly cold in the CCAM simulations. For RegCM3, they found a cold bias for both Tmax and Tmin, possibly related to the cold bias in the GCM forcing.

(2) Evaluation of precipitation for Vietnam

The APHRODITE dataset is used to evaluate the spatial distribution of the simulated multi-year mean of seasonal precipitation for Vietnam. Biases of the simulated precipitation relative to the APHRODITE dataset (Fig. 7) indicate that both models tend to significantly overestimate the precipitation in southern and central Vietnam during NEMS, the dry season. In SWMS, the wet season, both models have generally small biases. Note this pattern of bias is similar to the results of Nguyen et al. (2013). Some caution is needed in interpreting the results using the APHRODITE dataset in mountainous regions as it is generated from observational stations which are not densely distributed in central and southern Vietnam (see Fig. 4).

The annual cycles of precipitation from the station data and the gridded APHRODITE and CRU datasets, along with those from the two RCMs, are shown in Fig. 8. Both models capture the annual cycle reasonably well, except in October, when RegCM4.2 is very dry. As indicated above, both models also tend to overestimate the precipitation during the dry months (NEMS), with CCAM generally worse. CCAM also tends to be drier than the observations during the wet season (SWMS).

Seasonal and annual evaluation statistics for the simulated precipitation, compared with the observational stations across Vietnam, are presented in Table 7. Based on the relative bias, both models perform reasonably, except for the dry (NEMS) season, where both models are too wet (CCAM: +129.5%, RegCM4.2: +48.9% relative bias). However, while the relative biases are large, the RMSE numbers are similar to the other seasons. As indicated in Fig. 8, RegCM4.2 is too dry in SIMS (−61.8% relative bias, 8 mm d^{-1} RMSE). It appears the main cause for this dry bias is the weaker northeast onshore flow (wind speed about half) in RegCM4.2 than in the re-analyses

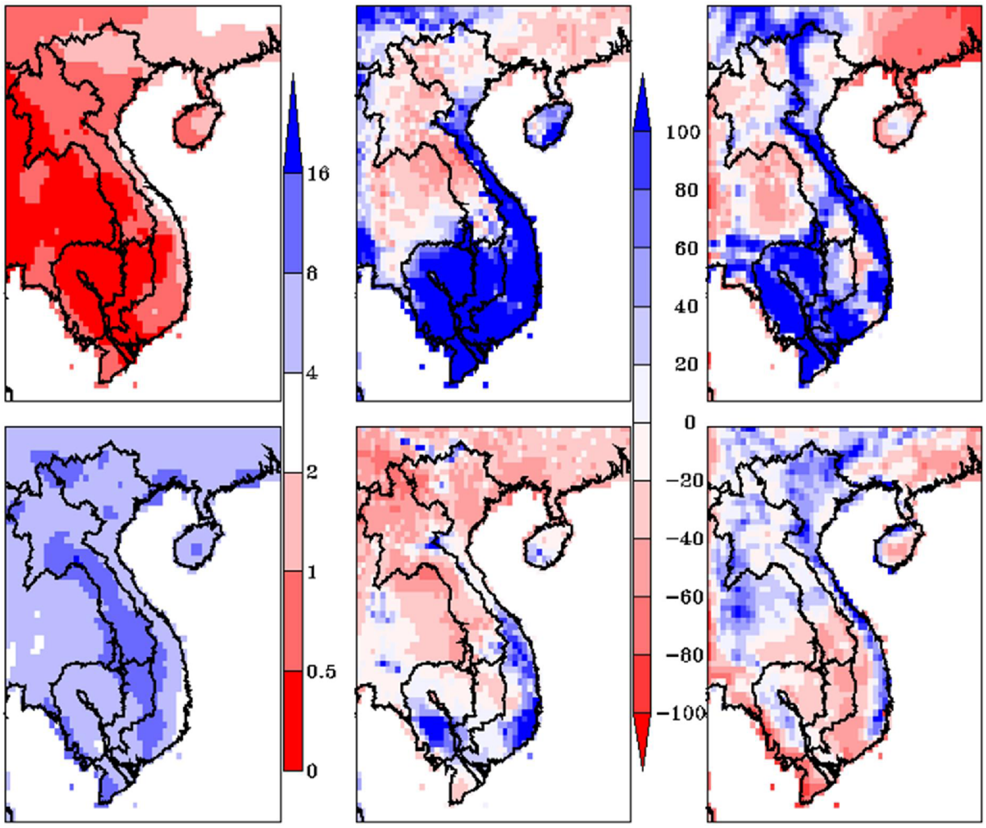

Fig. 7. Seasonal mean precipitation average (mm d^{-1}) for APHRODITE dataset (left column) and percent biases for CCAM-OBS (middle column) and RegCM4.2-OBS (right column) for two seasons (NEMS, top row and SWMS, bottom row) over Vietnam for the 1980-2000 period.

Table 7. Evaluation of seasonal and annual precipitation from the RCM simulations for the current climate period, 1980-2000. The mean precipitation is based on station observations. Bias, RMSE and Pattern Correlation are given for the 6-member CCAM ensemble means and the 2-member RegCM4.2 ensemble means relative to the station observations. The ranges for the individual ensemble members are given as well.

Season	Mean (mm d^{-1})	Relative Bias (%)		RMSE (mm d^{-1})		Pattern Correlation	
		CCAM	RegCM4	CCAM	RegCM4	CCAM	RegCM4
FIMS	5.7	−27.5 −39.0 to −21.6	−1.9 −1.4 to −2.4	3.3 3.1 to 3.5	3.4 3.4 to 3.4	0.46 0.40 to 0.48	0.36 0.35 to 0.36
SWMS	9.0	−27.1 −40.0 to −22.0	−14.2 −16.4 to −12.0	5.0 4.9 to 5.5	5.8 5.6 to 6.0	0.46 0.38 to 0.50	0.22 0.20 to 0.23
SIMS	7.5	13.2 −6.0 to 27.1	−61.8 −65.3 to −58.4	4.2 3.9 to 5.1	8.0 7.7 to 8.2	0.92 0.91 to 0.92	0.63 0.61 to 0.64
NEMS	1.6	129.5 82.6 to 148.9	48.9 43.7 to 54.2	4.0 3.4 to 4.3	2.2 2.1 to 2.4	0.37 0.32 to 0.40	0.60 0.58 to 0.62
Annual	5.7	−4.3 −21.1 to 1.4	−16.8 −16.8 to −16.8	4.3 4.2 to 4.5	4.6 4.5 to 4.6	0.51 0.48 to 0.52	0.44 0.44 to 0.44

or CCAM. This weak flow causes less uplift as it impinges upon the central Vietnam mountain range, resulting in less rain in this region. Elsewhere, the precipitation in RegCM4.2 is reasonable (not shown). The cause of the weak flow needs to be determined.

Phan et al. (2009) found a winter wet and summer dry bias of similar magnitude in CCAM. In Nguyen et al. (2014), the winter wet bias was not obvious, but the summer dry bias was evident. In Ngo-Duc et al. (2014), there was a similar dry bias annually as well.

Similar to Tave in Table 6a, the range of statistics from the individual ensemble members for precipitation are also indicated (Table 7). Here the range among individual members is much larger than for Tave, which is expected since precipitation

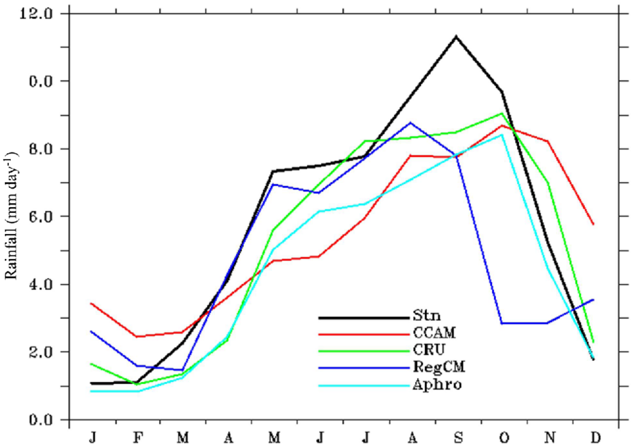

Fig. 8. The annual cycle of precipitation (mm d^{-1}, monthly average) over the whole of Vietnam for station observations (black), CRU dataset (green) and the APHRODITE dataset (cyan) compared with ensemble means for CCAM (red) and RegCM4.2 (blue) for the period 1980-2000.

is more sensitive to a range of processes than temperature, with less constraint (such as solar radiation and land surface specification for temperature). However, for most of the relative bias statistics, the sign of the bias is similar for all members (except for the annual CCAM bias, where the ensemble mean bias is near zero, while both positive and negative biases among ensemble members are apparent). This indicates that the biases are systematic for the models and are not related to the forcing.

4. Conclusions

While global climate models are the best available tools for simulating future climates, they are computationally expensive and have a relatively coarse resolution. At their low resolution, it is not possible to take into account regional effects such as topography or land use. For this reason, regional climate models are used to dynamically downscale the GCM results and provide more detailed climate change projections. This paper presents an evaluation of the ability of two high-resolution RCMs to simulate seasonal current climate for the area encompassing Vietnam, assuming that future projections are more reliable if the present climate is simulated well. Simulations are compared against station data as well as gridded observational datasets for both temperature and precipitation.

The downscaling methodology used in this study is different than those typically used by other downscaling groups in that no atmospheric information from the GCMs was used. Instead, only the SSTs and SICs were used from the GCMs. The SSTs were corrected so that the monthly mean SSTs match the observed SSTs. In addition, the interannual variance of SSTs in the GCMs was corrected to match the observed variance. These corrected SSTs and the GCM SICs were then used to force CCAM globally with an even resolution at both 50 km and 100 km resolutions. The 50 km global CCAM simulation data was then used to spectrally nudge the atmosphere of a stretched-grid version of CCAM at 10-km horizontal resolution centered on Vietnam. Due to computational resource constraints, the 100-km CCAM global data were used to provide the lateral boundary conditions for the RegCM4.2 simulations at 20-km horizontal resolution over Vietnam.

The RCM simulations of current climate successfully reproduced most of the important characteristics of observed spatial patterns and annual cycles of precipitation and temperature, especially for the two main seasons, NEMS (winter) and SWMS (summer). The simulated temperatures agree rather well with the station data, with a slight warm bias in northern Vietnam in winter. Overall, CCAM simulations of the mean annual cycle of temperature were closer to observations than those of RegCM4.2. It is important to note that there is observational uncertainty, since the CRU temperature is warmer than the other datasets for the second half of the year, while the APHRODITE temperature is cooler during the first half of the year. This indicates that care must be taken when using various datasets to evaluate the simulations. Evaluation showed that the skill at simulating minimum temperatures was similar to the skill for average temperatures, while the maximum temperatures were simulated slightly less successfully.

The simulations of the annual cycle of precipitation by both models capture the wet and dry seasons as well as the range of precipitation amounts, but CCAM tends to underestimate precipitation amounts in summer and overestimate precipitation in the dry season. RegCM4.2 tends to underestimate rain for most seasons, especially in SIMS, overestimating it only for NEMS.

Evaluation of the trends and inter-annual variability was not undertaken in this paper. Previous work indicated CCAM can capture the precipitation variability related to ENSO (Nguyen et al., 2014). The ability of the models to capture this variability for the climate of Vietnam needs to be explored further. The ability of the simulations to capture extremes should also be investigated.

The results of this study provide some information about the reliability of the simulations and their suitability for use in assessing possible future climate changes in Vietnam and for use of model output to provide inputs into impact assessment models such as hydrological or crop models. However, it is always advisable that users make a more detailed assessment before using climate model data for their application. Potentially, some sort of 'bias-correction' of the regional output prior to use in an impact model may be required. In future papers, assessment of the ability of the simulations to capture extremes and their projected changes in the future will be presented.

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