SIMULATION OF RAINFALL OVER WEST NUSA TENGGARA PROVINCE BASED ON ECHAM5/MPI-OM AND GFDL CM2.1

SIMULASI CURAH HUJAN DI PROPINSI NUSA TENGGARA BARAT BERDASARKAN ECHAM5/MPI-OM DAN GFDL CM2.1

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ABSTRACT

Rainfall over the West Nusa Tenggara Province were simulated by a Regional Climate Model (RCM)—the CSIRO Conformal-Cubic Atmospheric Model (CCAM) driven by two host General Circulation Models (GCMs), ECHAM5/MPI-OM and GFDL CM2.1. Three periods considered for this study were 1980–1999, 2050–2069, and 2080–2099 for the IPCC SRES greenhouse gas emission scenario A2. Simulations for the 1980–1999 periods were evaluated against observational data. The finding shows that in general, ECHAM5/MPI-OM and GFDL CM2.1 do not show any significant behaviour in simulating annual mean rainfall patterns for the period of 2050 – 2069 and period of 2080 – 2099. Nevertheless, for current period (1980 – 1999) those both GCMs are markedly different in simulation of annual mean rainfall. There are also simulations of seasonal mean rainfalls, dry and wet season, and show that ECHAM5/MPI-OM and GFDL CM2.1 are nearly similar in simulating dry season but not for wet season.

Keywords*: ECHAM5/MPI-OM, GFDL CM2.1, GCM, RCM, Rainfall, Simulation of Rainfall, CCAM*

ABSTRAK

Simulasi curah hujan di Propinsi Nusa Tenggara Barat dipelajari dengan menggunakan Regional Climate Model (RCM)—the CSIRO Conformal-Cubic Atmospheric Model (CCAM) yang didukung oleh model global (General Circulation Models atau GCMs) yaitu ECHAM5/MPI-OM and GFDL CM2.1. Tiga periode yang dikaji dalam studi ini adalah 1980–1999, 2050–2069, dan 2080–2099 untuk. simulasi periode 1980–1999 dievaluasi terhadap observasional data. Secara umum, untuk simulasi pola curah hujan tahunan periode 2050–2069 dan 2080–2099, ECHAM5/MPI-OM and GFDL CM2.1menunjukkan pola simulasi yang hampir sama. Namun, simulasi kedua model global ini untuk curah hujan tahunan periode observasi (1980 – 1999) berbeda. Bila dilihat secara musiman, simulasi model untuk musim kemarau periode 2060 dan periode 2090, ECHAM5/MPI-OM and GFDL CM2.1jika dibandingkan tidak menunjukkan perbedaan yang signifikan, dan sebaliknya pada musim hujan.

Kata kunci: ECHAM5/MPI-OM, GFDL CM2.1, GCM, RCM, Hujan, Simulasi Curah Hujan, CCAM

1. Introduction

West Nusa Tenggara (NTB) Province has the monsoon type for its rainfall distribution in one calendar year and experiences a short wet season. In the wet season, monthly rainfall over this province ranges from 100 mm to more than 350 mm. In the dry season, monthly rainfall ranges from 0–150 mm per month. Sometimes, the effects of El Niño exacerbated the droughts that occurred in Lombok. The other big island in NTB, Sumbawa, is located to the east of Lombok. In the wet season, Sumbawa is mainly green, however in some areas it is dominated by dry throughout the year. Rainfall in Indonesia is coherent and correlated to ENSO variations in the Pacific basin and intimately linked to sea surface temperature (SST) anomalies over Indonesia and northern Australia [1,2]. Recent studies found that rainfall variability over some provinces in Indonesia is more dominantly controlled by ENSO than the Indian Dipole Mode (IOD) [3,4], that mostly drive the seasonal and inter-annual variability of rainfall and extreme events in Indonesia. Besides, it is unique and complex due to its location in the tropical convective areas known as the Maritime Continent. This was identified at 9 site stations in West Java [5] in

Sumbawa island [6] and in NTB province [7]. About 65% of Indonesia is affected by El Niño and its influence is very dominant in the dry season [8].

The unique island shape and topography of Indonesia, as well as its location in the Maritime Continent pose extra difficulties for simulating precipitation over this region [9]. Indonesia needs higher resolution climate projections in order to produce useful simulations of rainfall patterns and another local climate data. Additionally, a coarse model cannot capture the local circulation and convection effects produced by many islands [10]. Therefore, the information derived from the global coupled models simulation may not capture small events like tropical cyclones. It may be only sufficient for large-scale projections of mean climate [11]. Consequently, before the information derived from GCMs can be applied for local use, there is a need to obtain a finer resolution. A higher resolution better represents the topography, providing more realistic climate simulations than global climate simulations [10]. In order to get finer resolution climate information, the GCMs need to be downscaled. A variety of approaches to the downscaling of GCMs projections are available and include dynamical and statistical downscaling. Furthermore, there are also many different techniques in dynamical downscaling [10]. As this research is part of a Commonwealth Scientific and Industrial Research Organisation (CSIRO) project, the dynamical downscaling approach in this study uses the Conformal-Cubic Atmospheric Model (CCAM) developed at the CSIRO for over twenty years.

CCAM downscaling approach in this study not only produced current finer resolution information but also rainfall data projection over NTB. A number of complex General Circulation Models (GCMs) have been used to project the climate for different scales and periods [12]. GCMs are numerical models that represent physical processes in the atmosphere, ocean, and land surface [13]. GCMs are comprehensive models; however, to represent unresolved physical processes such as the formation of clouds and precipitation, parameterizations are still used. The different models produce different climate projections due to the uncertainty of those parameterizations [12].

Projected climate changes in Indonesia generally have the same trend as for the South-East Asian region [14]. In terms of rainfall, projections of precipitation over tropical land regions are more uncertain than at higher latitudes but some robust features emerge in climate models [12], such as precipitation that is also expected to increase in most part of Asia because of the increasing GHGs.

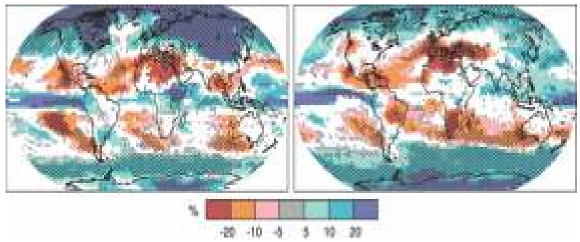

Figure1. Multi-model mean precipitation changes during the period 2090–2099 relative to 1980–1999 (% change) based on the SRES A1B scenario for December to February (left) and June to August (right). Stippling indicates areas where the magnitude of the multi-model ensemble mean exceeds the inter-model standard deviation[1]

The South-East Asian region is projected to be warmer and wetter in all seasons [14; 13]. With the same trend as Asia, the annual average precipitation is projected to increase over most of Indonesia [14].

Extending those efforts, this study aim to explore the behaviour of finer-resolution of ECHAM5/MPI-OM and GFDL CM2.1 in simulating annual mean rainfall and seasonal mean rainfall over NTB Province. The construction of this paper is organized as follows; Section 2 describes the study area, the data and methods, which are applied in this study. Next, the result and discussion will be discussed in Section 3. Furthermore, concluding remarks will be given in Section 4.

2. Methods

Study Area and Data. NTB province is located in the east of Bali Island. NTB is situated between 115o 46' – 119 o5' East Longitude and 8 o10' – 9 o5' South Latitude. This province has two major islands, Lombok and Sumbawa, which are bordered to the south by the Indian Ocean, to the north by the Flores Sea, to the west by the Lombok Straits, and to the east by the Sape Straits. The data used in this study were acquired using Climate observation data and climate model data.

Observational monthly average data for rainfall were obtained from 56 stations scattered in NTB province. BMKG manages most of the stations. Data periods vary from one station to another. Secondly, stations were chosen based on the length of the record (20 years or longer, mostly beginning in the 1980s) and the completeness of the data sets (i.e., amount of missing data). There are two models data used in this analysis; ECHAM5/MPI-OM and GFDL CM2.1.

ECHAM5/MPI-OM is the fifth-generation atmospheric general circulation model developed at the Max Planck Institute for Meteorology, Germany. There are two components of this model: ECHAM5 for the atmosphere and MPI-OM for the ocean [15]. ECHAM5 is run at a horizontal resolution, while MPI-OM is a primitive equation z coordinate model. The CSIRO ran a global Conformal Cubic Atmospheric Model (CCAM) climate simulation for this model with 14 km horizontal resolution in the region over NTB province using the A2 emission scenario. In this study, three periods of the long monthly average 14 km resolution data for rainfall are used; 1980–1999, 2050–2069, and 2080–2099.

GFDL CM2.1 is a coupled climate model that was developed in the Geophysical Fluid Dynamics Laboratory (GFDL) of the National Oceanic and Atmospheric Administration (NOAA), USA in 2004. Based on its reliability in simulating the seasonal and inter-annual variability [16], this model has been commonly used to investigate phenomenon in the atmosphere and the ocean, as well as for global anthropogenic climate change prediction (i.e., Meehl et al. [17]). Downscaled GFDL CM2.1 model simulation at 14 km resolution for A2 emission scenario over NTB province is also produced using the CSIRO CCAM, driven by the SSTs of the host GCM. The same periods and resolution were analysed with the ECHAM5/MPI-OM model. Three baseline periods of the long-term average precipitation and temperature data for precipitation and temperature are also employed: 1980–1999, 2050–2069, and 2080–2099.

Conformal-Cubic Atmospheric Model (CCAM) Downscaling Method. In order to get higher resolution climate information, the GCMs need to be downscaled. A variety of approaches to the downscaling of GCMs projections are available and include dynamical and statistical downscaling. Furthermore, there are also many different techniques in dynamical downscaling [10]. This study uses the Conformal-Cubic Atmospheric Model (CCAM) developed at the CSIRO for over twenty years. CCAM is a full atmospheric GCM and it is formulated using a conformal-cubic grid. This global conformal-cubic grid covers the sphere; it was derived by projecting the panels of a cube onto the surface of the Earth [18]. The CCAM can be stretched in regions of interest to produce a finer resolution [10]. CCAM is a model designed using semi-langrangian advection as well as semi-implicit step [10] and may efficiently run long downscaling simulations from many IPCC 4th Assessment report climate models [17].

CSIRO Marine and Atmospheric Research (CMAR) have developed downscaled climate projections for Indonesia at 60 km horizontal resolution [10]. Another advantage of CCAM as shown by Thatcher [19] is its ability to provide high flexibility for dynamical downscaling from GCMs using SST data and (optionally) some form of nudging from the host model. In CCAM, there is no singular point (e.g., North and South Pole) as well as any hard boundaries because this model is a global model. CMAR have recently downscaled CSIRO-CCAM to a 14 km horizontal resolution over NTB. The three periods considered for this study were 1980–1999, 2050–2069, and 2080–2089 for the IPCC SRES GHG emission scenario A2.

In brief, and Katzfey et al. [10] explained the several steps that should be conducted in the CCAM downscaling process. Initially, SST biases must be eliminated from the host GCM due to the coarse resolution and many unresolved physical and dynamical processes in the models. The SST biases should be removed because they produce air-sea fluxes that affect the atmospheric downscaling model and cause deficiencies in the simulation. Subsequently, correction of the biases is the next step. The SSTs simulated by the GCMs for the current period are compared to the extents of the National Oceanic and Atmospheric Administration (NOAA) for the same period. Following this, a quasi-uniform atmospheric climate simulation driven only by the bias-corrected, interpolated SSTs and sea ice concentrations from the GCMs is performed. Firstly, the 200 km resolution climate simulation was dynamically downscaled to 60 km resolution. Secondly, by running CCAM with a stretched grid over a target area, the 60 km CCAM simulation results in a 14 km resolution. The CCAM's 14 km resolution will then capture the main islands and topography of the region [10]. Digital filter forcing of surface pressure, wind, temperature and moisture above 850 hPa was used every 6 hours to conserve the large-scale patterns generated by the 200 km simulations in this process [18;19].

Rainfall Analysis Method. The next stage of the analysisi, the better resolution of the data such as the rainfall variability is then performed by mapping the monthly rainfall after applying the Inverse Distance Weighting (IDW) interpolation method. Moreover, due to its simplicity, this method has been broadly used. In addition, interpolation using this method remains stable regardless of the number of sample locations [20].

Two assumptions used in this method are 1) nearby control points are more influenced by the unidentified value of a point rather than the farther away points, and 2) the value of weight/the influence of point is proportional to the inverse of the distance between the points than it is raised to a power6. This method is represented by:

$$Z = \frac{\sum_{i=1}^{n} w_i Z_i}{\sum_{i=1}^{n} w_i} \quad (1)$$

Where,
Z = interpolated value
w_i = the weighting function. This determines the relative importance of each individual control point Z_i (where Z_i the closest observed value, and i=1,...,n)
n = total number of such points that are used in the interpolation.

To transfer information from raster system of climate model data into a spatial map, the ESRI ASCII raster format is employed. Nevertheless, to make it readable in ArcGIS software, this ASCII raster file should begin with header information that defines the properties of the region of interest. Furthermore, the 'cell statistic' function in the spatial analysis option in ArcGIS software is the main tool in the further calculation of the raster data in this study. This function offers some statistic analysis calculations for raster, namely mean, standard deviation, median, maximum and minimum value.

3. Results and Discussion

Seasonal Climatological Rainfall. NTB has a tropical climate like other Indonesian regions, with two distinct seasons: a dry season and a monsoonal wet season. The dry season that occurs from May to September is influenced by the Australian continental air masses that move over Asia. Aldrian [18] noted that dry wind from Australia begins blowing towards Indonesia in May and as a result, the Inter Tropical Convergence Zone (ITCZ) is subdued. NTB province is a dry area, especially during the dry season when average monthly rainfall only reaches 50 mm per month. Only a small region in western Lombok receives rainfall between 51 to 100 mm/month during the dry season, while other regions receive less rainfall. August is the peak of the dry season, and rainfall sometimes drops to 0 mm in this month. Aldrian [8] noted that during this month convection only occurs in western Sumatera and the northern parts of Indonesia.

The rainy or wet season in NTB usually takes place from November to March, while April is a transition month from wet to dry. The wet season is a time when air quality improves, freshwater quality improves, and vegetation grows significantly. In November, the influence of the Australian monsoon is weakening, while the wet air mass of the Asian monsoon is becoming stronger [8]. The ITCZ, close to the equator, plays a significant role in the Indonesian wet season, which occurs at the time the southern hemisphere (Australia) is experiencing summer (December–February) [21]. Warming in the Australian mainland leads to the development of low air pressure, which in turn draws air from the tropics toward Australia. Easterly trade winds, rich in moisture from the Pacific Ocean, move toward Australia, which are then called northwesterly winds. These northwesterly winds cause the rainy season in most areas of Indonesia. The wet season is augmented by humid winds from the Indian Ocean, producing significant amounts of rain throughout many parts of Indonesia. Nevertheless, this oscillating seasonal pattern of wind and rain is related to the geographical location of Indonesia, an archipelago between two large continents. Moreover, local wind can greatly modify the general wind patterns that cause rainfall variation. As a result, mean precipitation in NTB during the wet season is more heterogeneous than the dry season. In NTB province, the northwest part of East Lombok receives the most rainfall during the wet season and receives the highest total annual rainfall. Meanwhile, most of the province receives 200–250 mm/month of rainfall in the wet season. Only a small part of Bima district receives less than 150 mm/month. The eastern regions of NTB province receive less annual rainfall during the wet season.

In every wet season, rainfall varies depending on pressure differences that drive the movement of the easterly trade winds. The easterly trade winds that normally move to the west sometimes discontinue or even turn to the east [22]. The eastward change in direction of the trade winds leads to the replacement of large-scale rainfall regimes in the tropics. This produces global atmospheric circulation changes, which in turn force changes in weather over the tropical Pacific region. This condition is called the El Niño phenomenon [21]. El Niño is the warm phase of ENSO, occurring when above-average SSTs develop across the east-central tropical Pacific. The cold phase of ENSO is called La Niña. The Walker circulation, driven by the east-west SST contrast across the Pacific Ocean, controls this phenomenon [23]. Throughout the maritime continent, El Niño years are typically drier than normal years, and can lead to drought in Indonesia.

Seasonal rainfall during El Niño years. During El Niño years, mean precipitation in NTB is about 50–100 mm less per month than in normal years. Kirono et al. [22] identified the early onset of the dry season and the delayed onset of the wet season as a major feature of El Niño events in Indonesia. For example, in El Niño year 1997/1998, in eastern Indonesia (including NTB), the onset of the dry season occurred about 20 to 30 days earlier, while the wet season was delayed by 60 days [23] suggested that the westward-blowing trade winds collapsed. This delay was then followed by heavy convective rainfall. This heavy convective rainfall accompanied warm SSTs moving eastward. Climate variability strongly correlated with drought could lead to crop failure, particularly over rain-fed areas. Figures below indicate that even though El Niño years are typically drier than average in both the dry season and the wet season, the largest relative decrease in rainfall is seen in the wet season. During this time, rainfall is generally more than 50 mm/month below normal.

Simulation of Annual Mean Monthly Rainfall (Current Period). Annual mean monthly rainfall based on model data fluctuates more in the dry season than in the wet season. Meanwhile, the spatial patterns of annual mean monthly rainfall in both models are predominantly similar. ECHAM5/MPI-OM only has higher rainfall than GFDL CM2.1 by about 50 mm/month over a small northern coastal area of Lombok Island. Meanwhile, GFDL CM2.1 tends to overestimate ECHAM5/MPI-OM in the southern coastal region of Sumbawa Island. For example, the rainfall in the southern coastal region of Sumbawa, based on GFDL CM2.1, is about 50–150 mm/month higher than ECHAM5/MPI-OM.

Simulation of Seasonal Mean Rainfall. In general, the dry season simulation results show that the models reproduce the spatial distribution of precipitation in NTB fairly well, except in the southern coastal area of Sumbawa Island, along the eastern coast of Lombok Island, and in small parts of Bima and Dompu districts. In comparison to the seasonal spatial map based on BMKG observational data in Figure 6, models significantly overestimate the BMKG data, particularly in the southern coastal area of Sumbawa Island. The dry season that occurs from May to September is influenced by the Australian continental air masses that move over Asia. Aldrian[4] noted that dry wind from Australia begins blowing towards Indonesia in May and as a result, the Inter Tropical Convergence Zone (ITCZ) is subdued. Aldrian[4] also explained that in June, surface temperature in central Australia, a desert region, significantly drops in response to high pressure. This causes steady north westward winds off the continent. As the winds reach the equator, they change direction due to the rotation of the earth. This causes them to veer off their original course in a northeastward direction towards the Southeast Asian mainland.

Similar to the dry season, the wet season simulation indicates that the models agree, on average. However, models are likely to give more detail about variation within the regions. Models simulate high intensity rainfall over the north and west coastal regions in NTB, varying from 250 mm/month to more than 350 mm/month. In addition, both models show that rainfall intensity in the wet season lowers as you move further inland. The rainy or wet season in NTB usually takes place from November to March.The wet season is a time when air quality improves, freshwater quality improves, and vegetation grows significantly. In November, the influence of the Australian monsoon is weakening, while the wet air mass of the Asian monsoon is becoming stronger [4]. The ITCZ, close to the equator, plays a significant role in the Indonesian wet season, which occurs at the time the southern hemisphere (Australia) is experiencing summer (December–February)[21]. Warming in the Australian mainland leads to the development of low air pressure, which in turn draws air from the tropics toward Australia. Easterly trade winds, rich in moisture from the Pacific Ocean, move toward Australia, which are then called north westerly winds. These north westerly winds cause the rainy season in most areas of Indonesia. The wet season is augmented by humid winds from the Indian Ocean, producing significant amounts of rain throughout many parts of Indonesia. Nevertheless, this oscillating seasonal pattern of wind and rain is related to the geographical location of Indonesia. Moreover, local wind can greatly modify these general wind patterns that cause rainfall variation. As a result, mean precipitation in NTB during the wet season is more heterogeneous than the dry season.

Models show more detailed variations of rainfall within regions than the BMKG observational data because the RCMs provide high-resolution climate simulations. Therefore, RCMs are able to improve simulation at the regional scales, resolving complex regional topography in areas where forcing is due to complex orography and coastlines [24] and resolving land-sea contrast issues [25]. RCMs regulate the spatial distribution of climate variables [24]. For example, processes strongly forced by topography like orographic rainfall and monsoon circulations, will improve at increased resolution. Thus, high-resolution RCMs are important for impact assessment and resource management in NTB province, which consists of two large mountainous islands and several small islands.

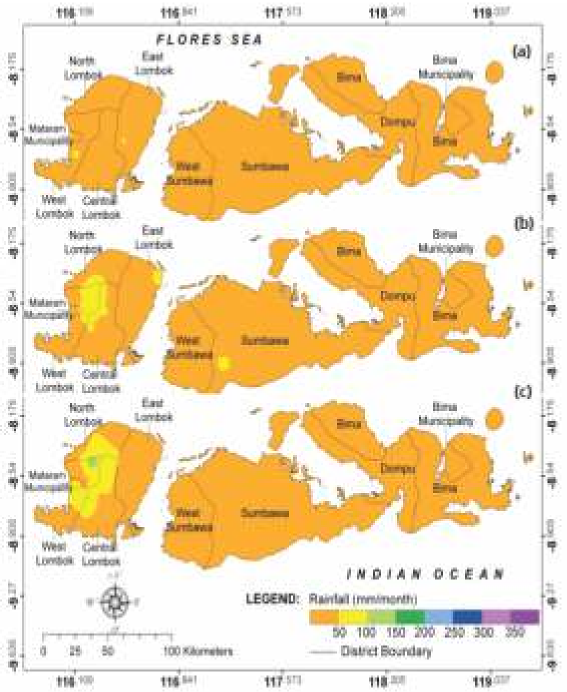

Figure 2. Dry season average monthly rainfall in El Niño years. The dry season average monthly rainfall (a-c) is the average rainfall of May–September (a) year 1982/1983 (b) year 1986/1987 and (c) year 1997/1998.

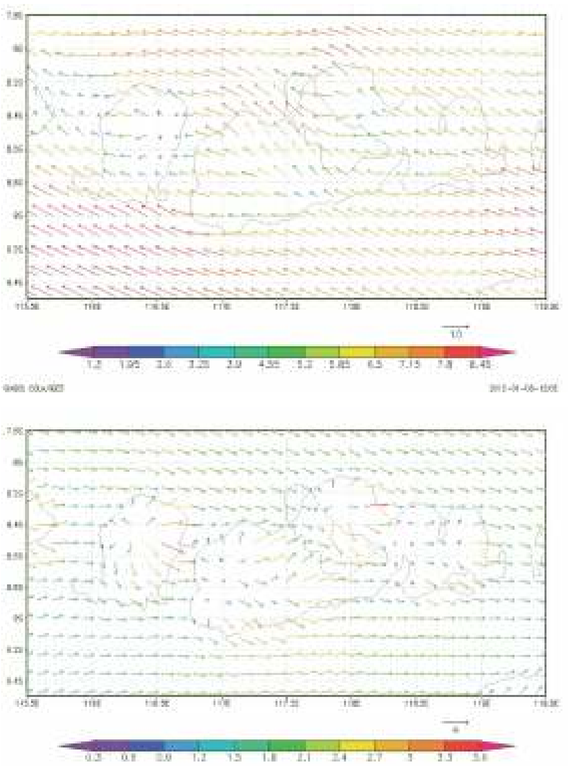

Figure 3. Annual pattern (1980 – 1999) of wind during dry season (top) and wet season (bottom) based on ECHAM5/MPI-OM.

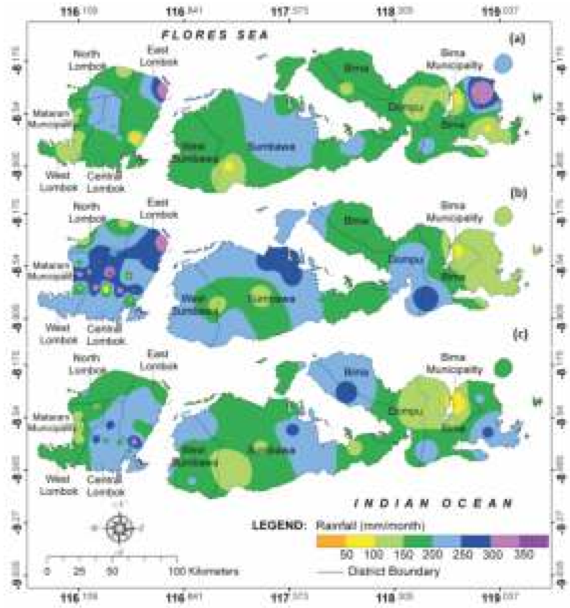

Figure 4. Wet season average monthly rainfall in El Niño years. The wet season average monthly rainfall (a-c) is the average rainfall of November–March (a) year 1982/1983 (b) year 1986/1987 and (c) year 1997/1998

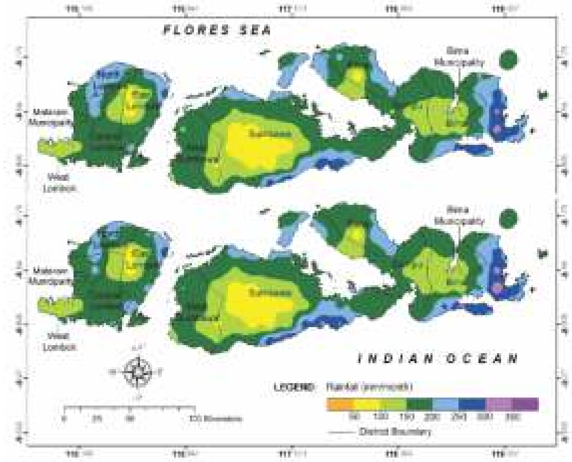

Figure 5. Annual mean monthly rainfall, 1980–1999, based on ECHAM5/MPI-OM (top) and GFDL CM2.1 (bottom).

Simulation of Annual Mean Monthly Rainfall (Future Periods). Rainfall Figure 8 and Figure 9 show spatial maps of rainfall projections for the periods 2050–2069 and 2080–2099, as simulated by ECHAM5/MPI-OM and GFDL CM2.1. Generally, both models resemble each other by showing similar patterns of future monthly rainfall projections in NTB province for those two periods.

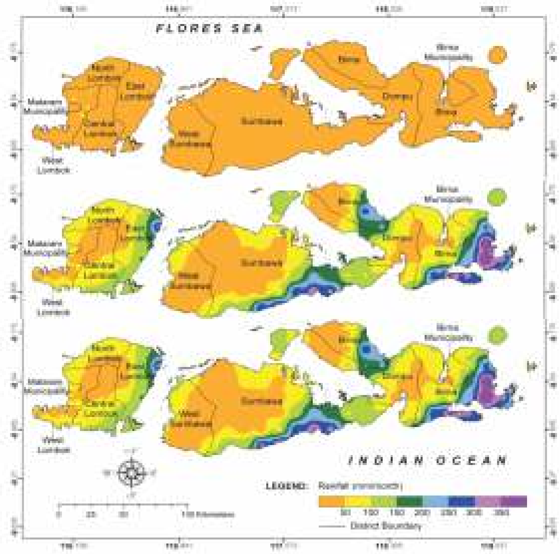

Figure 6. Average rainfall in the dry season, 1980–1999, based on Observation (top), ECHAM5/MPI-OM (middle) and GFDL CM2.1 (bottom)

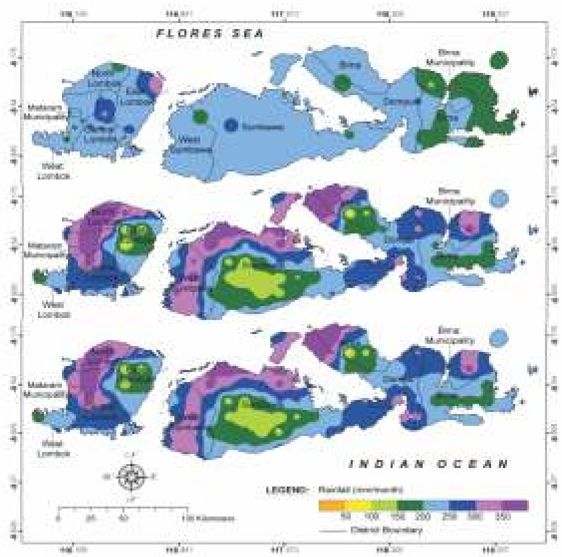

Figure 7. Average rainfall in the wet season, 1980–1999, based on Observation (top), ECHAM5/MPI-OM (middle) and GFDL CM2.1 (bottom)

To begin with, the annual mean projected monthly rainfall based on ECHAM5/MPI-OM for the period of 2050–2069 and 1980–1999 was compared. This comparison showed that the projected changes in Lombok Island are not as large as in Sumbawa Island. Only small regions in North Lombok and East Lombok are projected to receive 50 mm less per month in the middle of the century than in the current period, while other regions are projected to remain constant. On the other hand, rainfall in some regions in West Sumbawa, simulated to receive 100–150 mm/month in the 1990s, is projected to expand westward in the 2060s. Moreover, there is a small decreasing rainfall trend along the south coast of Sumbawa district, from 300–350 mm/month to 250–300 mm/month.

Based on the ECHAM5/MPI-OM simulation, low rainfall regions tend to shift northward and cover larger areas in the 2080–2099 period in comparison with 2050–2069. Looking in detail at the low level of rainfall for Lombok Island, the areas projected to have 50–150 mm per month in 2050–2069 will shift slightly to the north-west in 2080–2099. Some areas, including the North Lombok district, Mataram Municipality and the northern part of West Lombok are projected to receive rainfall of 50–150 mm per month by the end of the 21st century. In addition, low amounts of annual rainfall (50–100 mm/month) in Sumbawa Island will have a tendency to shift north westward. Additionally, in the 2080-2099, only a small part of West Sumbawa is projected to have 150–200 mm of rainfall every month, located in the south of the district. Meanwhile, most of the other areas of West Sumbawa, Bima, and Dompu districts are projected to have 100–150 mm/month.

Furthermore, as for ECHAM5/MPI-OM, the annual mean monthly rainfall simulated by GFDL CM2.1 for the 2060s was compared to the simulation for the 1990s. This comparison shows more varied changes occurring in Sumbawa Island than Lombok Island. The most westerly part of West Sumbawa district, simulated to receive about 150–200 mm/month in the 1990s, is projected to have 50 mm less per month in the 2060s. However, small regions in the south coast of the Sumbawa and Bima districts are projected to experience 300–350 mm/month in the 2060s, 50 mm/month higher than in the 1990s.

By contrast, unlike the ECHAM5/MPI-OM, Figure 10 shows the changes between the period of 2050–2069 and 2080–2099 based on GFDL CM2.1 are not significant. Instead, rainfall will have a tendency to shift northwestward. Despite this, some parts are likely to become somewhat wetter, increasing from 100–150 mm/month to 150–200 mm/month, such as in the south part of West Sumbawa district and in the small island above Bima district (Mojo Island). The GFDL CM2.1 model shows more variation in high rainfall than low rainfall. For example, rainfall higher than 300 mm per month is projected to arise during the end of the 21st century in only a small part of Bima district.

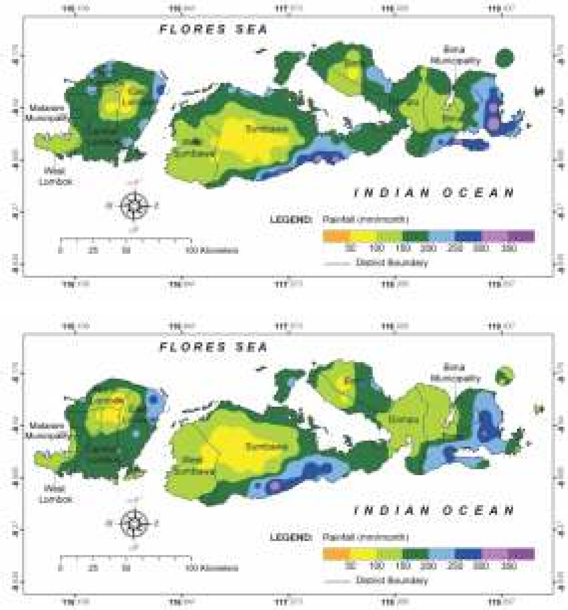

Figure 8. Annual mean monthly rainfall projection based on ECHAM5/MPI-OM for the periods 2050–2069 (top) and 2080-2099 (bottom)

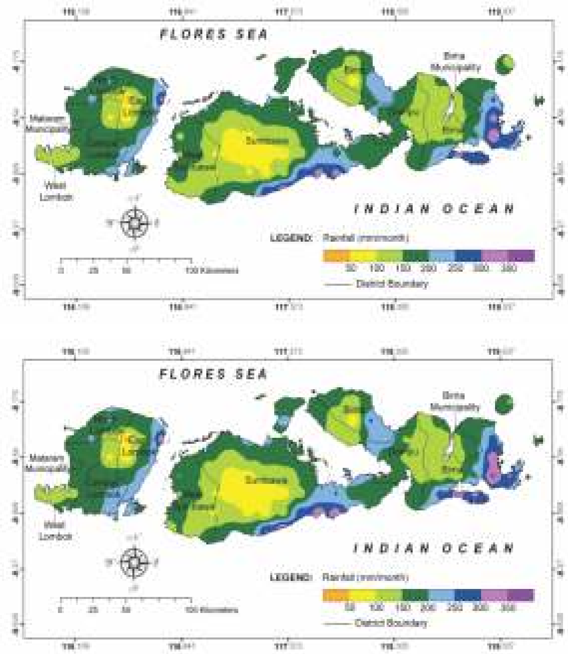

Figure 9. Annual mean monthly rainfall projection based on GFDL CM2.1 for the period 2050–2069 (top) and 2080–2099 (bottom)

Comparing Figure 8 and Figure 9, the ECHAM5/MPI-OM tends to simulate drier conditions than GFDL CM2.1. The GFDL CM2.1 predicts high rainfall (200–350 mm/month) to occur in a larger area than ECHAM5/MPI-OM. For example, high rainfall is predicted to occur in some parts of East and Central Lombok, both in the middle and at the end of the twentieth century projections. In this case, based on ECHAM5/MPI-OM model, Lombok Island does not have any areas covered by rainfall up to 350 mm/month. However, in Sumbawa Island particularly in the east part of Bima district, there is a small area projected to have 350 mm/month of rainfall simulated by GFDL CM2.1. This, however, is not projected by ECHAM5/MPI-OM.

Nevertheless, if we look at the future changes relative to the period 1980–1999, they are markedly different (Figure 10). The figure shows the annual rainfall changes during the period 2080–2099, relative to the period of 1980–1999. It clearly appears that NTB is projected to receive more rainfall based on GFDL CM2.1 than ECHAM5/MPI-OM. Based on the ECHAM5/MPI-OM, the trend of rainfall over NTB province at the end of the 21st century is projected to vary from increases of 10 mm/month to decreases of 50 mm/month. The biggest decreasing trend (-50 mm/month) is estimated to occur in the west of Lombok Island as well as in the western and northern parts of Sumbawa Island. However, an increasing rainfall trend is also estimated to occur in the west coastal region of West Lombok district (0–10 mm/month), in the east coastal region of East Lombok district (0–20 mm/month), and in the southern coastal and inland regions of Sumbawa Island (0–20 mm/month).

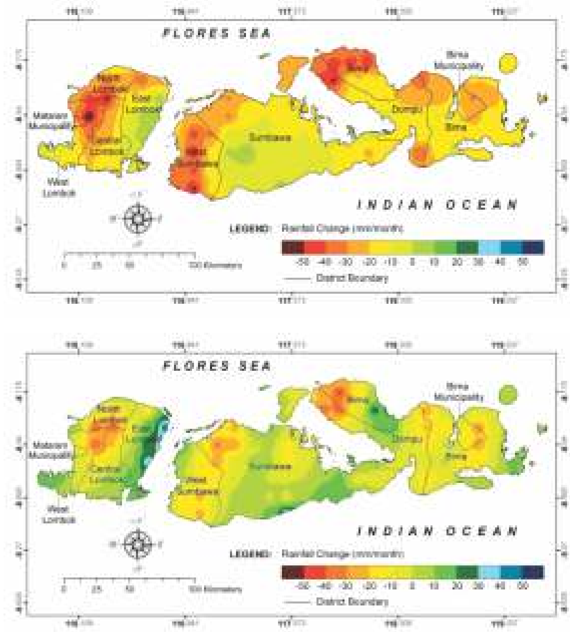

Figure 10. Annual rainfall changes (2080–2099 relative to 1980–1999) based on ECHAM5/MPI-OM (top) and GFDL CM2.1 (bottom)

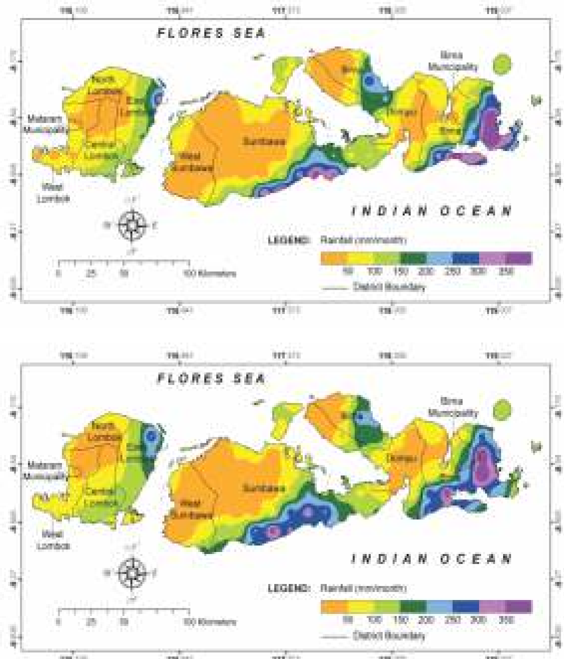

Figure 11. Monthly mean rainfall projection in the dry season based on ECHAM5/MPI-OM period of 2050–2069 (top) and 2080–2099 (bottom)

However, rainfall loss identified using GFDL CM2.1 is generally less severe than ECHAM5/MPI-OM. The only area where a projected decreasing trend of more than -40 mm/month was identified is in the northern part of Bima district. In addition, Lombok Island could be diagonally separated into two areas of changes: the rainfall in the north-west part is estimated to decrease by about 0–40 mm/month while rainfall in the south-east is estimated to increase by about 0–50 mm/month. At the same time, the southern coastal and inland areas of Sumbawa Island are estimated to experience an increasing trend of precipitation by about 0–40 mm/month.

Simulation of Seasonal Rainfall Period of 2050 – 2069 Relative to Period of 2080 - 2099. When comparing the dry season periods in 2050–2069 and 2080–2099, both periods show similar rainfall patterns. Most of the districts are projected to experience rainfall of about 150 mm/month to less than 50 mm/month. The ECHAM5/MPI-OM projections agree with GFDL CM2.1 in showing the wettest area during the dry season. These areas include the southern part of Sumbawa district and the eastern part of Bima District, where mean rainfall increases by up to 350 mm/month.

Overall, the differences between the dry seasons in 2050–2069 and 2080–2099 are not large. Some small changes are projected to occur in a small region in northwest Lombok Island. Rainfall in this region, which extends between 250–350 mm/month, is projected to shift slightly northward at the end of the 21st century. A slight decrease in rainfall, about 50 mm/month, is also projected to occur in the southern coastal region of Sumbawa Island. On the other hand, Figure 13 shows that the differences projected between the wet seasons of these two periods are larger than the dry season. In the wet season, rainfall is projected to decrease moderately in the northwestern coastal regions and in small regions inland. On the contrary, in the southern coastal region of Sumbawa, rainfall is projected to increase considerably. Figure 13 shows projected changes in rainfall at the end of the 21st century relative to the current period. In general, rainfall loss in future wet seasons is more severe than in future dry seasons, especially over the northwestern coast. However, rainfall in the 2090s, over some areas like the east coast of Lombok Island, and inland and south coast Sumbawa Island, is projected to increase moderately relative to the 1990s. A slight increasing trend in rainfall (10–20 mm/month) is also projected in the dry season in some areas, such as the western and eastern parts of Sumbawa Island.

ECHAM5/MPI-OM relative to GFDL CM2.1. GFDL CM2.1 agrees on average with ECHAM5/MPI-OM in projecting dry season precipitation for the 2060s and 2090s. The differences between the dry seasons of 2050–2069 and 2080–2099 are small (Figure 14). However, GFDL CM21 does not agree with ECHAM5/MPI-OM in simulating wet season precipitation for the 2060s and 2090s. Figure 15 shows only small differences in the projected rainfall in the wet seasons of 2050–2069 and 2080–2099, while ECHAM5/MPI-OM shows significant differences. This slight dissimilarity mostly arises inland. For example, the wet seasons in 2050–2069 in inland Sumbawa are projected to receive rainfall of about 150–200 mm/month, and by the end of the century are projected to experience small decreases in rainfall. Meanwhile, high rainfall (250 mm/month to more than 350 mm/month) projected to occur over the north western coastal region in the 2060s is likely to be the same in the 2090s.

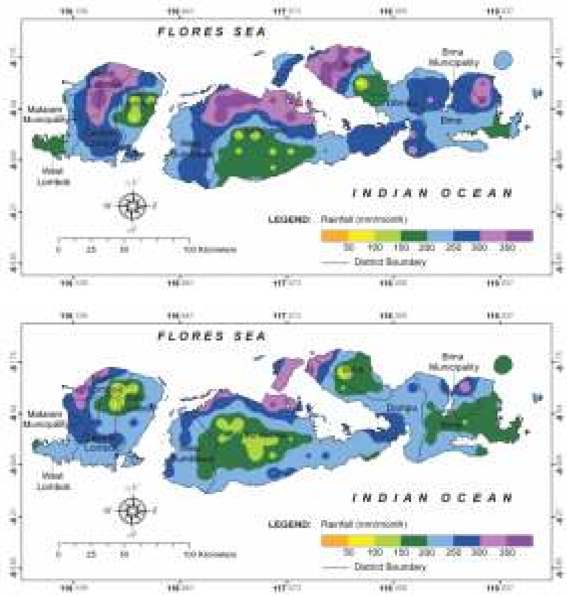

Figure 12. Monthly mean rainfall projection in the wet season based on ECHAM5/MPI-OM period of 2050–2069 (top) and 2080–2099 (bottom)

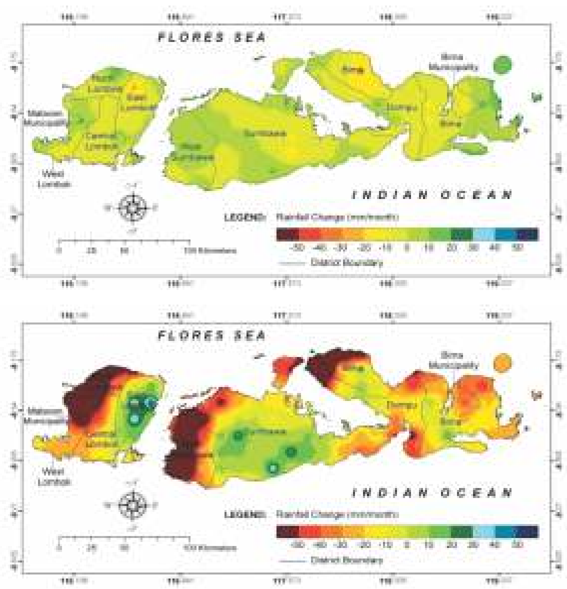

Figure 13. Monthly rainfall changes (2080–2099 relative to 1980–1999) in the dry season (top) and the wet season (bottom) based on ECHAM5/MPI-OM

Meehl et al. [18] explained that climate models tend to show poor agreement in projecting mean precipitation changes, particularly at a regional scale. The results of this study show there are some disagreements between ECHAM5/MPI-OM and GFDL CM2.1 in simulating the spatial distribution of mean precipitation changes during the 2090s relative to the 1990s. This is possibly caused by an imperfect simulation of rainfall distribution in climate models [34] and a simple underlying factor, where the thermodynamic element is supposed to be a good approximation for large scale averages (i.e., averages across convection and descent zones) [34]. However, Chou et al. [33] explained that dynamical feedback in the convergence zones could considerably augment or reduce rainfall anomalies.

Meehl et al. [18] described a common feature among climate models— rainfall at high latitudes is projected to increase, while rainfall in the subtropics is projected to decrease. Additionally, the deep tropics tend to show an increasing trend in annual average rainfall. For a small region like NTB, changes in moisture and changes in SST are generally likely to increase, and changes in wind patterns will influence the amount and location of rainfall changes. The moisture changes are not uniform, associated with mean circulation and thermodynamic components. In a warmer climate, mean circulation carries more moisture vertically as the increased moisture induced by global warming is concentrated in the lower troposphere [33]. Rainfall in NTB is variable and this feature is seen in GFDL CM2.1, which shows that the annual mean precipitation at the end of the 21st century in the southern parts of NTB is projected to increase by 0–40 mm/month, while a decreasing trend of 0–30 mm/month is evident in the north-western parts. It is predicted that the rainfall will increase moderately in the south.

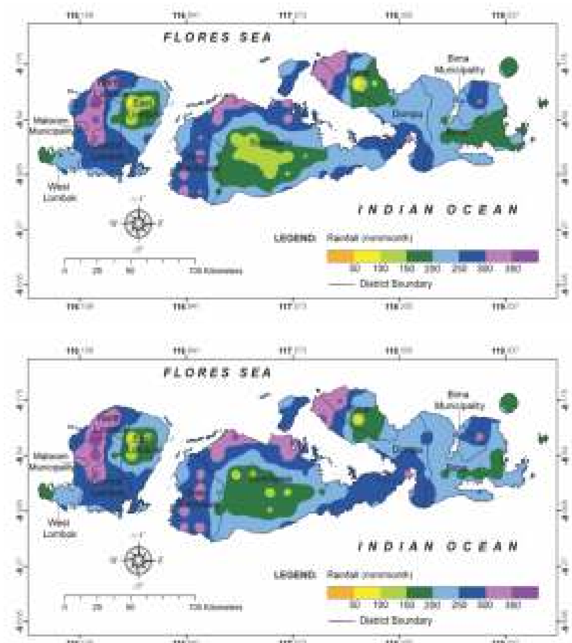

Figure 14. Monthly mean rainfall projections in the dry season based on GFDL CM2.1 for 2050–2069 (top) and 2080–2099 (bottom)

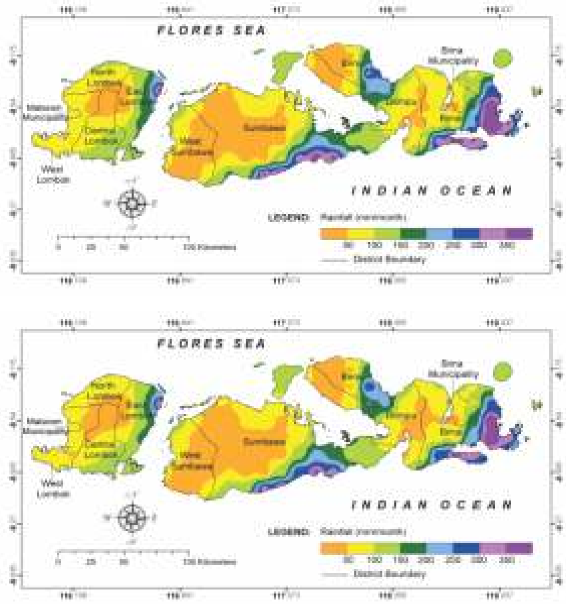

Figure 15. Monthly mean rainfall projections in the wet season based on GFDL CM2.1 for 2050–2069 (top) and 2080–2099 (bottom).

4. Conclusion

Models provide important insight into how the regional climate may respond to global climate change. This study has evaluated the performance of a RCM-CCAM (Conformal-cubic Atmospheric Model) in simulating climate and seasonal variability in NTB province. In this study, the RCM simulation for climate variability is driven by two General Circulation Models (GCMs): ECHAM5/MPI-OM and GFDL CM2.1 under A2 IPCC scenario. This study analysed present (1980–1999) and future periods (2050–2069 and 2080–2099).

Compared to the BMKG observational data, the CCAM climate model data with ECHAM5/MPI-OM and the GFDL CM2.1 climate model boundary conditions tend to overestimate the annual mean of precipitation for the present period, except over high elevation regions. In general, even though the rainfall projections based on ECHAM5/MPI-OM are slightly lower than GFDL CM.21, reasonable agreement of the seasonal precipitation patterns is found between those two models and the observational data. Meanwhile, the mean rainfall projections of the dry season for the two future periods based on the ECHAM5/MPI-OM model as well as for the two future periods based on the GFDL CM2.1 do not show significant differences. On the other hand, rainfall averages in the wet season projections for the two future periods show obvious differences between the ECHAM5/MPI-OM and GFDL CM2.1 simulations. The differences mostly appear in the western areas of the two large islands, Lombok and Sumbawa. Moreover, the changes in annual mean precipitation projected by the ECHAM5/MPI-OM model are likely to be 33% larger than GFDL CM2.1 in the 2080–2099 period relative to the 1980–1999 period.

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