Evaluation of Climate Simulations at High Resolution over Sumatra Employing the WRF Model

Tomi Afrizal

A Thesis Submitted in Fulfillment of the Requirements for the Degree of Master of Science in Earth System Science
Prince of Songkla University
2018

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Major Program Earth System Science

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I hereby certify that this work has not been accepted in substance for any degree, and is not being currently submitted in candidature for any degree.

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ABSTRACT

Dynamical downscaling of global climate model at high-resolution (10-km) has been completed for 20 years period (1980-1999) over Sumatra Island. Models downscaled using the Weather Research and Forecasting (WRF) model driven by the global climate model Community Earth System Model version 1 and ERA-Interim reanalysis dataset. This paper focuses on climatological precipitation and temperature simulations over Sumatra. The results of CESM/WRF were evaluated by comparison using observation datasets of the University of East Anglia Climatic Research Unit, the University of Delaware Air Temperature and Precipitation, and the Global Precipitation Climate Center, ERA-Interim reanalysis, and ERA-Interim/WRF. The WRF model simulations driven by CESM performs much better than original CESM simulations. CESM/WRF simulated precipitation and temperature agree well with observation datasets and reanalysis dataset. CESM/WRF simulations shows perfectly agreement with ERA/WRF simulations. The WRF model was provide detail information of climate simulation at high resolution and enhances local spatial distribution. The regional climate model reproduces the spatial distribution of precipitation and temperature well; precipitation is higher in the high mountains and lower in around coastline. Temperature shown the same skill with precipitation. This study shows that WRF can be useful for generating high resolution climate information for precipitation and temperature of Sumatra.

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Tomi Afrizal

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CHAPTER 1
INTRODUCTION

1.1 Background and Motivation

Climate change is one of very important topics in the international level. Indonesia has often been affected by weather-related natural disasters, e.g., floods, intense storms, and landslides. Studies about how the climate change will impact Indonesia are hence important.

The increasing Earth's temperature is caused by the interaction between the Earth's atmosphere and solar radiation (Bradford, 2014). The latest report of Intergovernmental Panel on Climate Change (IPCC AR5) shows evidences of global warming. Many changes which are unprecedented in decades to thousands of years have been observed since the 1950s. The atmosphere and ocean have warmed; snow and ice have diminished; the sea level is risen; and the concentration of greenhouse has also increased. Since the 1850, Earth's surface has been warmer in the last three decades than previous decades. Besides, in the period of 1983-2012 Northern Hemisphere was likely the warmest, a 30-year period of the last 1400 years (IPCC, 2013). The phenomenon occurring radiation from the sun is called the greenhouse effect (Lallanila, 2015). The fact is that human life on the earth is required greenhouse effects. Otherwise, the Earth's surface would be below the freezing point of water (IPCC, 2007). The geological record of climate change shows that climate change has occurred in a large scale in the past, such as seven cycles of glacial advance and retreats over the last 650,000 years. Most of these climate changes are caused by small variations in Earth's orbit that results in changes to the amount of solar energy that goes into the Earth. Although climate change is natural variability from the Earth, but their differences on climate change from the mid to late 20th century are due to human activities through greenhouse gas emission in the atmosphere. It will continue at a higher level for another time in the past 1,300 years and will increase significantly in the 21st century (NASA, 2015; Smith *et al*., 2003). According to Bradford (2014), climate change caused by humans was due to an increasing amount of multiple gases into atmosphere. These gases are called greenhouse gases (GHGs) and mostly affect the greenhouse effect. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3) (Bradford 2014; IPCC, 2007: 875). Anthropogenic gas emissions have been increasing significantly since the pre-industrial era due to economic and population growth and now are at its peak (IPCC, 2014: 4).

The effect of global climate change is in the form of increasing temperatures, sea level rise, changes in precipitation, climate variability, and frequent events such as storms, floods, and cyclones. Furthermore, the agriculture, such as food, water, health and shelter, is threatened by global warming (EPA, 2013). Some areas have a major impact on climate change, such as in South and Southeast Asia and Africa. Severe countries in the world that have a large impact on climate change such as Cambodia, Vietnam and Bangladesh (Standard and Poor, 2014; Kreft and Eckstein, 2013). Indonesia is also one of countries that will have a major impact on climate change because it is an archipelago which is very sensitive to hazard of climate change impact, such as sea level rise. Besides, Indonesia is a developing country, so it does not have a strong capacity to adapt to the hazard. The fact that gross domestic product (GDP), which depends heavily on agriculture (14.2%), also increase sensitivity to the hazard of climate change. In Indonesia, the greatest impacts of climate change are in sea level rise, change in intensity and pattern of rainfall, and increases in surface and sea surface temperatures. These would have disastrous effects such as floods, droughts and the loss of (marine) biodiversity (loss of biodiversity because of frequent forest fires and loss of marine biodiversity because of the warming of sea temperature) (Measey, 2010).

The researchers have done an extensive research to changes in temperature and have understood various temporal and spatial scale. Base on the IPCC Working Group, there has been an increase in the globally average land surface air temperature since the 19^{th} century due to an average increase of 0.72 degree Celsius from 1951 to 2012 with the number of the greatest warming occurred since the 1970's. However, changes in precipitation both globally and regionally is less clear. The tropical precipitation has increased and decreased since the 1970's, the increased precipitation has occurred in the last decade (2000's), reserving the trend observation drought from the 1970's to the late 1990's (IPCC, 2013).

According to Brekke *et al*. (2009), changes of precipitation patterns cause concern to the management of water resource as an extreme event, such as floods, droughts allowing more frequent and more severe in the future. Nevertheless, the difference between local and regional trends is a very important consideration when performing various types of climate studies, as a condition of the average of a vast territory that became the local anomalies, both the magnitude and direction of climate change (Pielke *et al*., 2002).

Overall, climate change can be described as a changing global energy balance to changes in atmospheric concentrations of greenhouse and aerosol, natural variations in solar radiation and modification of the surface albedo. These factors do not contribute to the radiation source in the same direction, but everything replacing the radiation balance of the positive values that come up, causing to global warming. However, the information about climate change is not complete if the impact on the ecosystem and the population was not examined. Therefore, this should be viewed from a regional standpoint, whether to global warming varies from one region to another.

The diversity of Earth's climate is very unusual, it could also indicate that climate change varies greatly around the world. One of example is that the change of general circulation in the region may increase precipitation in the area, and instead will be a reduction of precipitation for the other regions (Figure 1.1), as in the predicted occurred in Europe, where strengthening the positive phase of the North Atlantic Oscillation (NAO) has occurred thus causing a poleward movement tracks of the storm. In addition, the forces of orographic, latitude and distance to the oceans are very dominant factors in the determining the climate and its evolution under conditions of climate change because it can increase and reduce the effects of global warming. For example, the thermal inertia of the oceans caused by the interior of the continent is warmer than the coastal areas. More than that, many of the characteristics of climate change are local and distributed unevenly, such as the incidence of extreme events that occur on the regional scale. Therefore, it is vital for the estimated projections of climate change on a regional scale to be used as a repercussion to the environment and human life.

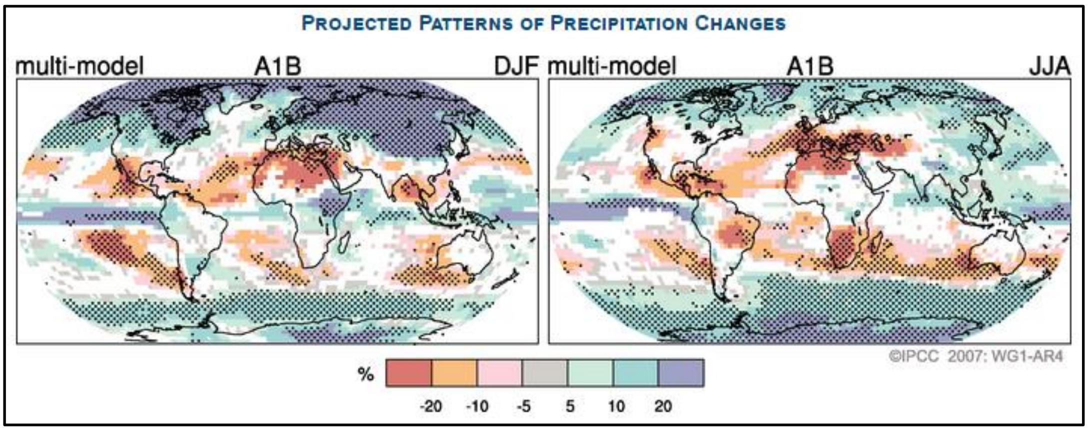

Figure 1.1 Projection of precipitation changes in 2090-2099 period (%) respect to 1980-1999 and used the SRES A1B scenario. The left side is mean of December to February period and the right side is mean of June to August period (IPCC, 2014)

General Circulation Models (GCMs) are the primary source of information for projecting future climate and they can provide a comprehensive knowledge of the large-scale climate and general circulation. However, GCMs still could not show the local climate and provide information that is more detailed to the impacts of climate change in the regional scale. It is because of their resolution is still large (~1.0^0 by 1.0^0) and models of physics have not been adequate to produce the phenomena at small scale (although recent GCMs are ran at finer resolutions and employing improved parameterizations). In addition, GCMs grid points cannot interpret the location where they are located (von Storch *et al*., 1993) because the grid boxes are often very different from local climate within the area (Good and Lowe, 2006) and therefore, it is not sufficient to conclude those good results from those of the large areas (Christensen *et al*., 2007a). As a result, some of aspects that determine climate change such as extreme events are very difficult to determine with current GCMs. Therefore, the climate projections at high spatial resolution are important for climate adaptation and impact mitigation. An increase GCMs resolution requires large computational costs, but the climate modelling has become one of the research fields that consume more computing resources and more powerful machines in the world which are dedicated to climate simulations. Therefore, the computational costs are very expensive to increase the resolution of CGMs, then the term downscaling is used as one of alternative approach.

1.2 Downscaling

Since the General Circulation cannot describe the local climate precisely, the downscaling can be used to overcome the problem of the increase in resolution at reasonable computational costs. In recent decades, there are several types of downscaling used and they can be classified in the statistical (experimental) and dynamical downscale. Basically, the statistic downscaling (von Storch *et al*., 1993; Wilby *et al*., 1999) has a strong empirical relationship between the large scale and the local variable. These relationships are determined by using the observational record and projected in the future, taking local scale information of GCMs. This technique has been widely used with extraordinary results (Boé *et al*., 2007; Huth, 1999; von Storch *et al*., 1993; Wilby and Wigley, 1997) and with low computational costs. However, because the relationship refers to a particular location, no information could be obtained outside of available observations. Besides, it is not easy to find the proper relationship and sometimes the statistic downscaling cannot determine that a solid connection between local variables and large scale. On the other hand, dynamic downscaling was found in the approximate resolution to the equations of the atmosphere using a physics models at a higher resolution than GCMs, but to impose some restrictions. Difference methods with dynamical downscaling techniques can be mentioned, those are still using GCMs but increasing the resolution in a particular region by stretching the grid (Déqué and Piedelievre, 1995), or reorienting the grid pole (Wang *et al*., 1999), or for a particular short time period (or time slice technique) (Cubasch *et al*., 1995) and those that use Regional Climate Models (Giorgi and Mearns, 1999; McGregor, 1997).

Regional Climate Models (RCMs) works by increasing the resolution of GCMs to a desired specific region, numerically solving the equations simplification over grid finer by adjusting the parameterization to a new spatial scale. This resulted in a more detailed explanation about the orography, and thus the process on a regional scale tended to be captured by the model. Since RCMs were restricted to a particular region, they touched to know what was going on outside, and therefore they required the boundary conditions to be specified, commonly derived from GCMs output or observational analysis. In addition, GCMs using a single configuration for the entire globe are not always appropriate to every region, while RCMs also allow them to adapt the configuration of the area under studies, which represents a considerable improvement over the GCMs.

Generally, it is believed that dynamical downscaling has the consistent physical and can be used to project future climate, while the statistical downscaling is based on the empirical relationship that it may not take place in the future. However, this statement does not claim that the parameterizations also supports the physical models, the semi-empirical approach to reality, and, therefore, vulnerable to changes in the future. Statistical and dynamical method have their own advantages and disadvantages, and researcher use them depending on the research to be conducted. Statistical downscaling is not only can be applied to the meteorological variables, but also the other variables, such as river flow and the annual crops. However, the statistical downscaling results are constrained to predictions and locations with available measurements, while dynamical downscaling is able to provide a number of climatic variables throughout the domain, but it requires high computational costs. The positive consequences have a various variable and have their potential use as input data to local model, such as the hydrological, which is an additional benefit for climate studies.

Dynamical downscaling using regional climate has been selected to create a climate change project with the high-resolution change over the Sumatera Island of Indonesia. Sumatra, Indonesia is located in tropics, where the equator line passes through the island. It is one of the areas with the highest annual precipitation on Earth. It has often been affected by weather-related natural disasters, e.g., floods, intense storms, and landslides. Precipitation over Sumatra varies from place to place. Clouds are mostly driven by convection. Researchers have made a lot of efforts to project global climate until the year of 2100. The CMIP5 project has evaluated performances of several global climate models for climate projections. However, the global climate models produce results which are low resolutions and hence, cannot provide useful high-detailed information about precipitation data for the region where precipitation is very variable from place to place. The high-resolution climate projections for Sumatra are hence important for adaptation and mitigating losses. On the other hand, to be able to project climate in the future, this thesis develops a high-resolution climate simulation model for Sumatra. The outputs from the global climate model CESM are used to drive the Weather Research and Forecasting (WRF) model to simulate climate at 10-km resolution for a 20-years period (1980-1999). Results will be compared with those simulated using the WRF model driven by the state of the art global ERA-Interim reanalysis data. Besides, no studies have done for the simulation of climate change at high-resolution for Sumatra.

1.3 Objectives

This thesis aims to develop a climate simulation system that can provide useful precipitation and temperature simulations at a high-resolution over Sumatra.

1.4 Scope

This thesis will develop a climate simulation system that can provide precipitation and temperature simulations at high resolution for Sumatra, Indonesia. The next-generation mesoscale numerical weather prediction model WRF will be employed. The WRF model driven by outputs from the global climate model CESM version 3.7.1 (WRFV3.7.1) will be used to simulate temperature and precipitation for Sumatra at 10-km resolution for a 20-year period (1980-1999). The CESM/WRF simulated temperature and precipitation for the 20-year period will be compared with those simulated using WRF driven by the state-of-the-art global reanalysis data, i.e., ERA-Interim. The ERA-Interim is considered as "perfect boundary conditions".

1.5 Expected outcome

This thesis will develop a climate simulation system that can provide precipitation and temperature simulations at high resolution for Sumatra, Indonesia.

CHAPTER 2
LITERATURE REVIEW

2.1 Climate Change

Any visible changes in climatic conditions that occur continuously in a specified period of time (over 10-years) can be regarded as climate changes (IPCC, 2012). The either natural (such as change in solar intensities) or artificial (such as greenhouse gas emissions, land use changes) sources can affect the climate system changes in observation. However, anthropogenic is a very significant factor which influences on climate change in comparison with other sources (Huber and Knutti, 2011; IPCC, 2007).

Carbon dioxide is a GHGs that since the day of the industrial revolution has significantly increased caused by the increasing use of fossil fuels and changes in land use. In 2005 the CO_2 concentrations in atmosphere was higher than it had been in 650,000-year ago and continuously increased for each year. It also occurs in other GHGs such as CH_4 and N_2O. Due to the chemical elements changes in the environment, mean changes, standard deviation and extreme variables are the key of climate change being observed. In the last 25 years it has also been an increase in the global average temperatures (Figure 2.1). In addition, changes in precipitation have also been seen throughout the world. In Figure 2.2 it is shown how directly observed of precipitation changes by using a Palmer Drought Severity Index (PDSI) by analyzing past and current evaporation and precipitation (calculated from average temperature) at a site. The global temperature shows in Figure 2.2a, the drier areas are shown in orange and red areas while the wetter areas are shown in green and blue where its than normal the positive (or negative) values of PDSI in Figure 2.2b. A difference post in 1975 on the PDSI is shown on Figure 2.2b addressing further changes to the spatial pattern of PDSI in worldwide. Aside from precipitation and temperature changes, another climate variable had also been preached (IPCC, 2007).

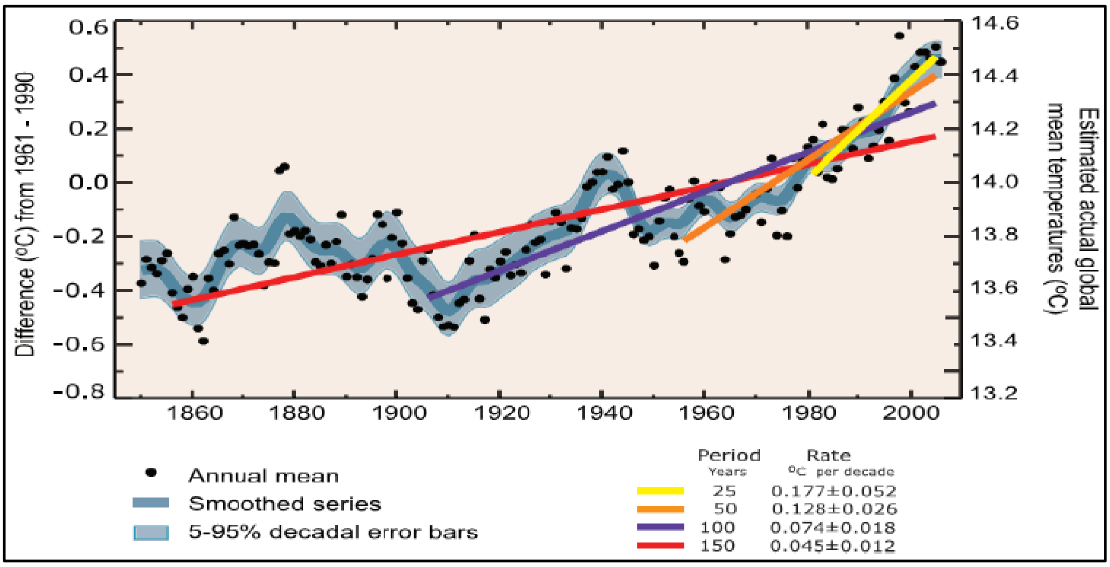

Figure 2.1 Annual average temperatures in global for 1856-2005 period (black dots). Left axis is anomalies of temperature with mean temperatures for 1961-1990 period while right axis is absolute temperature (°C). The red, purple, orange, and yellow line are linear line of time-periods 1856-2005, 1906-2005, 1956-2005, and 1981-2005, respectively (IPCC, 2007)

According to Labat, Godd, Probst, and Guyot (2004), there has been an increase of global runoff more than 4% with increase global temperatures every 1 ^{0}C over the last century by reconstructed monthly discharge of the largest rivers in the world. Furthermore, IPCC (2007) projected global average temperature change with a range about 1.8 °C (low emission scenario) to 4 °C (high emission scenario) in the 21st century. This is to be anticipated that changes in global temperature would produce unprecedented changes in hydrology worldwide.

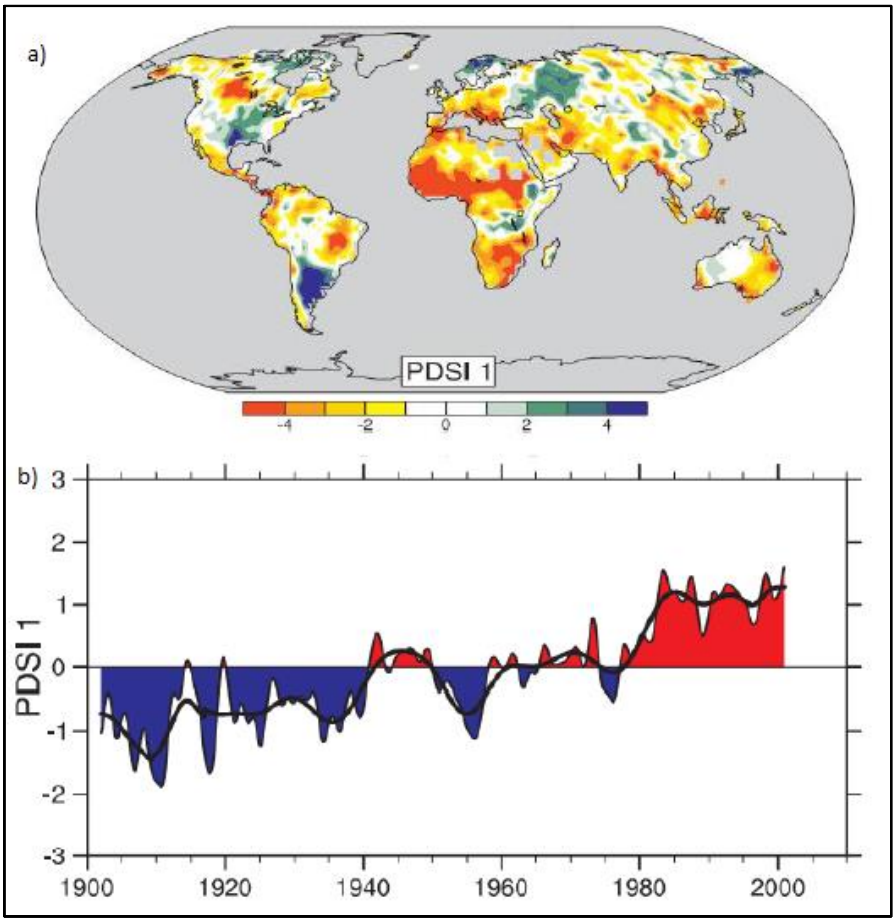

Figure 2.2 (a) Monthly Palmer Drought Severity Index (PDSI) Spatial distributions in period of 1900-2002. (b) temporal variability (IPCC, 2007)

The climate change impacts have been seen in the extreme events such as temperature and precipitation. Moreover, IPCC (2012) explains that since 1950 there has been a decline cold days and nights numbers, while hot days and nights numbers increased globally. This change is caused by the increase of anthropogenic emissions. Furthermore, it has been projected following SRES A2 and A1B scenarios that by the end of the 21st century, a 1 in 20 years return period annual hottest day event may become 1 in 2 years return period event (except for high latitudes of Northern America where it will become a 1 in 5 years event). Extreme precipitation changes have also been detected around the world, consistently increasing in the sub-continental North American. Besides, it is also projected that towards the end of the 21st century, within 20 years the maximum annual return period of 24 hours precipitation rates event will change to 1 in the 5 to 1 in the 15 years return period event.

Changes to floods and drought have also been shown, in which since 1950 there has been frequent droughts in Southern Europe and Western Africa, but less in the central North America and northwestern Australia (IPCC, 2012). In the flooding cases, changes in historical flooding trends and their attribution have not made proper identification of climate change possible. However, the evidence suggests shift in the time of spring peak flows. This is caused by overheating and subsequent melting of accumulated snow in the winter. Spring peak flows occur during the winter or early spring. Furthermore, the progressive global (Hirabayashi, *et al*., 2009) and continental scale (Dankers and Feyen, 2009) project increase in flood hazard worldwide, except for the central to the western Eurasia and the northern parts of North America where a decrease in flood hazard is projected.

2.1.1 Aspect of Climate Change

So far, the awareness of climate change that could affect the state of the environment, social, and economic is increasing. Climate change in the long term has been seen in the continental, regional, and ocean basin scales caused by increasing concentrations of greenhouse such as carbon dioxide. These changes include the amount and timing of precipitation, arctic temperatures, and aspects of extreme weather such as heavy precipitation, droughts, and heat waves (IPCC, 2007).

The precipitation patterns are not evenly distributed across the world, it is influenced by the pattern of atmospheric circulation and moisture availability. These factors can be influenced by temperature so that changes in precipitation patterns due to changes in temperature. The changes include the types of precipitation, the amount, intensity and frequency. According to Trenberth, K.E *et al*. (2007), there has been increased precipitation in the eastern North America, southern South America and northern Europe, but there is a decrease in the Mediterranean, most of Africa and South Asia.

According to IPCC (2007), the increase in global average air and ocean temperatures can change the type of precipitation during the winter season. The precipitation pattern has changed from snow to rain in the Northern regions and mountainous area so that large precipitation events have increased in the areas where the total amount of precipitation is low (Barnett, T.P., *et al*., 2008). All of these changes were associated with increased global temperatures because warmer air can hold and carry more moisture (Santer, B.D., *et al*., 2008; Willett, K.M *et al*., 2007; and Santer, B.D., *et al*., 2007).

2.2 Climate of Indonesia

Indonesia is one country that is large consisting of several large islands stretching along the equator from 6^0N to 11^0S and 95^0E to 141^0E. This condition indicates that the temperature remained high throughout the year with little variation of every month. The main variables of the climate in Indonesia are not the temperature and air pressure, but in the form of precipitation. Winds can generally be predicted by a monsoon that always blows from the south and east on gathering June to September and from the northwest in December through March (Met Office, 2011; Frederick and Worden, 2011). Extreme variations of precipitation are associated with the monsoons. Indonesia has two seasons of the year, the dry season (June to September) is influenced by continental Australia air masses and the rainy season (December through March), which is influenced by air masses from the mainland Asia and the Pacific Ocean. The local conditions of Indonesia can change this pattern, especially in the central islands of Maluku groups. According to Frederick and Worden (2011), oscillated seasonal patterns of wind and rain associated with the geographical conditions of Indonesia where an archipelago is flanked by two continents and supine on the equator. Winds patterns that interact with local topography can cause variations in precipitation and they are very significant in the entire archipelago. In general, the western and northern Indonesia experienced most precipitation due to the movement to northward and westward of monsoon clouds which were heavy with moisture by the time they reach the more distant regions. The annual average precipitation Indonesian is around 3,175 mm. Western Sumatra, Java, Bali, and the interiors of Kalimantan, Sulawesi, and Papua are the most consistently damp regions of Indonesia, with precipitation more than 2,000 mm per year.

2.2.1 Rainfall Regions

According to Aldrian and Susanto (2003), Indonesia is divided into three regions rainfalls which are dominated by different characteristic that are depended on annual rainfall cycles or an annual average variability by using double correlation method (DCM) as shown in Figure 2.3 and Figure 2.4

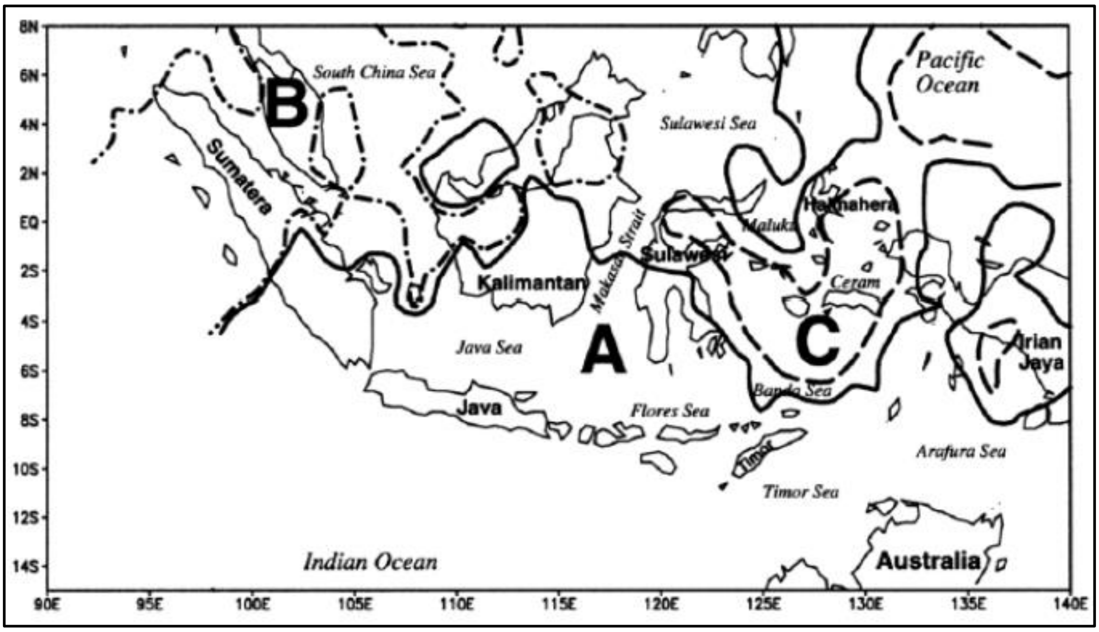

Figure 2.3 Region climates of Indonesia corresponds to type of rainfall based on DCM. (Aldrian and Susanto, 2003)

From the Figure shows that the southern Indonesia from south Sumatera to Timor Island, southern Kalimantan, Sulawesi and part of Irian Jaya is located in region A. The northwest Indonesia from northern Sumatra to northwestern Kalimantan is located in region B. Besides, region C encompasses Maluku and the northern Sulawesi (Aldrian and Susanto, 2003).

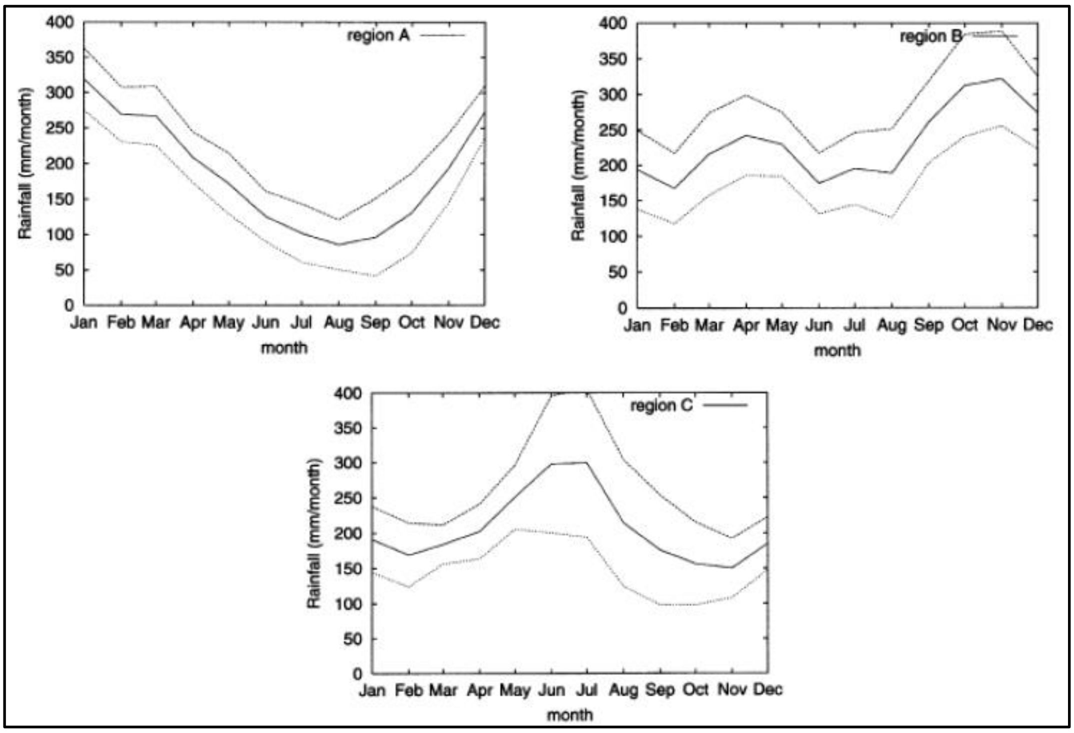

Figure 2.4 The annual rainfall cycles of three regions (solid line) based on DCM. Dashed line is a standard deviation below and above average (Aldiran and Susanto, 2003)

Region A has one peak and one trough and a strong influence on two monsoons, they are wet northwest (NW) monsoon in November until March and the dry southeast (SE) monsoon in May until September. The region B has two peaks associated with the movement of inter-tropical convergence zone (ITCZ) to the southward or the northward which occurs in October to November and March to May. Furthermore, the region C has one peak in June to July and one trough in December until February. The peaks in region C is approximately 300mm/month, while the peak for the region A is 320mm/month and for the region B is 310mm/month (Aldrian and Susanto, 2003). The region A has a low minimum value and achieve an average below 100mm/month. Therefore, the region A is a region that is very dry in dry season in July until September, it will be wettest region in December. Region C has one peak in mid-year (June until July) that is likely influenced by the influence of the ocean, while two other regions have one peak at the end or beginning of the year. Region C, or Maluku is a region which is located along the eastern route of Indonesia Through Flow (Aldrian and Susanto, 2003).

2.2.2 Rainfall Process and Cloud Formation

The occurrence of rainfall is through a cycle where the air is experiencing moisture, forming into clouds and eventually producing the rainfall. According to Barret and Martin (1981), cloud air movement and aerosol properties are the factors that determine rainfall. They can determine the concentration, initial size distribution and cloud properties.

The process of rainfall can determine the characteristic of the rainfall itself. This case illustrates the mechanism of cooling and condensation process that starts from humid air turn into cloud droplets. In principle, the cloud will be formed from the removal of air humidity. Petterssen (1958) explains that the rainfall starts from humid air rising and cooling by expansion, and then the relative humidity will increase. As the process continues, the air becomes saturated and form cloud droplets.

The droplets will not freeze until the temperature is well below freezing point (less than -28 ^{0}C). In this step, the clouds had formed, after some elements of the cloud has exceeded the other, that of the upper most likely to fall through the clouds and the subsequent collision will occur among themselves. The cloud droplets are large enough that they would fall to the Earth as rain droplets caused by gravity.

The probability of rainfall is a function of the thickness of the cloud, base and top temperature (Barrett and Martin, 1981). In the tropics, clouds will not produce rain until they reach a thickness of more than 6000 feet. Usually they produce rain when they reach a thickness of more than 12000 feet (Petterssen, 1958).

2.3 Dynamical Downscaling using a Mesoscale Model

Dynamical downscaling by way of RCM is one of the way used to produce high resolution climate change information over the Sumatra Islands, Indonesia. In particular, the WRF model is one model that can be used to perfume climate runs.

Mesoscale models are a numerical system that given an approximate solution to the primitive equations that are simplified. The estimates of the models are limited to a region defined by the domain and thus the lateral boundary conditions (LBCs) should be set at its borders because otherwise the equation is not solved. This procedure is referred to as nesting and is the starting point of a dynamical downscaling by mean of a regional model. Dynamical downscaling using mesoscale model is not a new idea. The problems of weather prediction have been discussed by solving the equations of atmospheric setting with excellent results. However, the use of mesoscale models to simulate the long-term need related to some concepts of issues should be checked for adequate climate design experiments and therefore it can produce the expected climate change projections.

2.3.1 Conceptual Issues

In principle, if the model can yield great results for short term forecasting should also be able to produce accurate results for a longer period. However, the problem is not simple because the strategy of nesting a RCMs with large scale data is not mathematically well posed. Where, there is no unique solution for conditions that cannot be determined precisely. Ideally, we should have our disposal for a continuous and perfect set of boundary data for solving equations, so the problem will be closed and pose properly. Unfortunately, equations and boundary conditions are discretized in regional modelling framework, so that the information that is used to drive the regional model is not complete then the problem is not necessary. In order to get full information, this approach provides a large number of variables that make the problem are being over specified. Excessive specifications will not be a major obstacle when the boundary data free of errors, since all the conditions will be heading to the same unique solution. But the boundary condition of data set is subject to errors and therefore they do not really consistent.

According to Staniforth (1997), the over specification might be the source of error in from of spurious wave that propagate to domain. If the LBCs are over specified and impose in a hard manner, there may be a difference in reflected domain border back and interfere with the dynamic models. For long term simulations, this noise may swamp the entire domain and is becoming increasingly important. According to Davies (1976), a buffer zone on the border of the domain where the model results are relaxed toward the driving fields, so the differences are damped. This technique is able to deal with problem on a small scale, but it cannot handle a large scale properly and long wave do reflect and changed the circulation.

A more efficient solution that has been proposed to manage the spurious long wave of and involves adjustment of the model results all over domain, but it is only at large scale more than 1000 km. It is referred to as spectral nudging (von Storch *et al*., 2000; Waldron *et al*., 1996) which can reduce the nesting errors and also make regional climate modelling a real downscaling procedure rather than a boundary value problem (Rummukainen, 2010). In addition, spectral nudging also provides interesting consistency between large scale by GCMs (or the observation reanalysis) and regional scale produced by mesoscale model.

The other element of dynamical downscaling that must be considered well is domain design because the size and location of domains have an important effect on the model results that cannot be ignored at all (Jones *et al*., 1995; Leduc and Laprise, 2009; Liang *et al*., 2001; Seth and Giorgi, 1998). The observation analysis and GCMs performances does not have the same quality all over the world, thus highly dependent on the placement of the domain and the boundary data is accurate. In addition, the borders of domain cannot be placed over major topographical features such as the mountain ranges because they would describe at different level of detail by the RCMs and the GCMs, and can cause unwanted artifacts. The domain size is an issue that should be discussed which should be large enough to provide the model to develop its own internal variability but not too deviate from the boundary data because it can produce imbalance. The size of domain is also much related to the cost of computing and it should be accommodated to the available resources.

The domain design implies some objections such as the locations of the borders over the area of homogeneous, spectral nudging also can help to reduce dependence on the size, location and geometry domains of the models (Míguez-Macho *et al*., 2004). It is still assumed that the nudged RCMs has not been able to develop its own dynamics and should be excessively forced by non-perfect boundary data. Although the use of spectral nudging is still controversial, and the decision often depends on the particular application and the criteria modelers, the application of a weak nudging is a good approach to take advantage of technique and retain RCMs internal variability.

The boundary data should also be attention because it represents the response of the climate system to forcing a large scale and then provide a framework for RCMs. If the main feature of general circulation is not adequately described by the data driven, so it cannot be expected that the regional model corrects these errors, although some correction might be completely achieved. In this case, the potential shortage of boundary conditions is a primer driver of dynamical downscaling biases. Therefore, not only determines the quality of the LBCs but also the update frequency of LBCs and the different between GCMs and RCMs resolutions play an important role.

The boundary conditions required at every time step of formulation nesting, but GCMs or observational analysis are only available at certain frequency. Interpolates of the LBCs is a common practice that is done to give the regional model. Therefore, the updating frequency should be high enough to produce the daily cycle and also capture the large scales systems that RCMs domain. Denis *et al*. (2002) addressed the frequency and resolution difference issues. They have shown that a 6 hours frequency suffices to drive the model correctly and there is no significant benefit gained from a higher frequency. Regarding the resolution 'jump', they conclude that the resolution difference ratio should not be more 10 or other spatially inconsistent may arises at the border. Multiples nesting technique is recommended for large ratios. There is consistence in using two or more domains arranged in a short of cascade with increasing spatial resolution.

For the resolution of the model always processes that occur at sub grid scale and have to be include in the formulation. They have been solved using semi empirical approach called parameterizations which can be considered models themselves. The consistency in parameterizations have been used to be a matter dispute between GCMs and RCMs. The difference schemes used cause an imbalance at the borders because the sub grid phenomena are represented dissimilarly. However, it can also be argued that the performance same parameterizations are differently at varying resolution such as happens to convective schemes. One of the advantages of the RCMs is possibility to allow use physics packages that are optimized for a specific area and resolution. In any case, the parameterization compatibility issue has been declared to be lees crucial than it was thought (Déqué *et al.*, 2007).

The model climatology evolution is the result of a dynamical equilibrium between the boundary conditions and the model dynamics. In addition, the regional climate modelling aimed at studying climate signal regardless of the initial conditions. The climate system is essentially chaotic and thus the little disruption in the original position may cause a different final state, long term simulations have proven to be sensitive to those perturbations after about fifteen days (Giorgi and Bi, 2000). The model takes time to achieve balance and forget the initial conditions are known to spin-up. The selection spins up the appropriate length depending on the application model to use because of differences in the variables have very different inertias (i.e., atmospheric fields reach a balance after few days whereas soil variables usually needs up to months to attain an equilibrium). If computational resource permits to an extended and conservative spin-up period is preferable, when the GCMs are employed as boundary conditions because many of them do not provide enough soil variables and the model has to be initialized with external datasets.

2.3.2 Dynamical downscaling uncertainties

The climate change research is influenced by a number of uncertainties restriction because there is no way to tell which projection is more probable. In global models, the main sources of uncertainty are related to the emission scenarios, formulations of the model, and climate natural variabilities. There are few other resources that can also be defined, but hard to define such as climate system that is non-linearity, the unexplored feedbacks, the long-term responses or unpredictable phenomena (e.g., volcanos). The downscaling of GCMs information using a RCMs introduces an additional source related to the technique itself. They are difference of formulation models, parameterizations or nesting methodologies that might produce different results. Regional climate models are afflicted by their own uncertainties and those inherited from GCMs, but they cannot be considered separately because the uncertainties overlap rather than simply add up.

The initial source of uncertainties is GHGs such as anthropogenic emission. The evolution of the emission is caused by the population growth, the society and economy development, and the technological advances. The anthropogenic emission can cause variations in atmospheric GHGs concentrations, which can produce a radiative forcing that changes the radiative balance in the Earth. All of these factors can be regarded as important and highly unpredictable climate drivers. Nakicenovic *et al*. (2000) states that climate change research has overcome their unpredictability by contemplating various plausible future evolutions of those factors (e.g., population, economic policies, energy sources) embodied in the emissions scenarios.

The formulations of GCMs are different and they do not provide better results under any circumstances, because there are no models which are more reliable than others. They have their own strengths and weaknesses. To reduce the uncertainty associated with the GCMs formulation is approximately to use different GCMs to constraint the regional models to cover a wider range of possible projections. The third uncertainty relates to the number of years simulations. Climate change projections span over a finite sample year. As it is known that the atmosphere is essentially chaotic and has high variables, an uncertainty is added due to sampling limitations.

Finally, the downscaling technique showed another source of uncertainty, the formulation of RCMs affects the accuracy output just as for GCMs. The experimental design (spatial setup, model configuration, time coverage) also has a significant impact on results. To further reduce sources of uncertainty, a new simulation should be performed by using various configurations over regions with different characteristics. The difference simulation aimed at the inclusion of the possibility of uncertainty that is known as ensemble. They might include different scenarios, GCMs, RCMs or various configurations of the same regional model (physical ensemble). The combinations of border range are explored, the better the uncertainties can be identified and eventually reduced. However, the costs of computing preclude the examination of complete matrix of possible combinations, so a representative selection must be made. The number of uncertainty source in climate change research is a great incentive to produce further simulations that are most important sources and then would help to provide new and more reliable insights into the issue of climate change at regional scales.

2.3.3 Downscaling ability of RCMs

Although the RCMs is a visible imperfection, it has been declared to be a very useful tool to provide climate information at scale that is very important for nature and human life. They can provide additional values of information with respect to the boundary data (Antic *et al*., 2006; Laprise, 2008) and improve climate simulations at the regional scale (Caldwell *et al*., 2009; Wang *et al*., 2004), evidencing RCMs downscaling ability. For example, Denis *et al*. (2002) have been designed the experimental RCMs that employed high resolutions boundary conditions that were filtered to remove the small-scale feature and showed that the RCMs was able to create those features even if they were not present in the boundary data anymore.

The regional model has been able to describe in detail the fine scale regional characteristics that are known to influence the climate such as the land use or vegetation (Ge *et al*., 2007; Hong *et al*., 2009; Sánchez *et al*., 2007), but topographical features also that might change local circulation (e.g., intricate coastlines, steep mountain ranges, inland waters). The affordable computational requirements of RCMs and the fact that the results are not restricted to places with available observations have made RCMs very widespread. As a result, the large number of institutions involved in climate modeling has contributed to a rapid development of the models. In spite of the large modeling community, the model evaluations are still necessary to assess their capabilities, particularly under troublesome conditions such as regions affected by very local processes caused by complex topography. Several studies have been called for further simulations to produce regional climate change information (Christensen *et al*., 2007a; Giorgi, 2005; Rummukainen, 2010) because the RCMs can be used as a supplementary tool to address the climate change problem.

2.4 Previous Studies of High-resolution Climate Projection

RCMs with a high-resolution is the model that can be used to look at climate change clearly in an area, so that it can easily be anticipated to the natural disaster. Nowadays, many researchers have conducted climate simulation at high-resolution. In the tropics region, Nguyen Kim C., *et al* (2012) have conducted the climate simulation by dynamical downscaling using the CSIRO Conformal Cubic Atmospheric Model (CCAM) at 60 km resolution for 1961-2100-time periods. In their study, the CCAM at 60-km resolution shows a good performance than GCMs at 200-km in the climate simulations. The CCAM shows the anomaly of warm temperature in the mid to upper-troposphere which is caused by excessive convective heating. The CCAM at 60-km also provides a good rainfall peaks averaged in 30^0S-30^0N and rainfall distributions across the Pacific. Besides, the CCAM also shows a good agreement with the observations compared to the GCMs, the pattern correlation of CCAM is between 0.7 and 0.9.

The climate projection over Southeast Asia also had been conducted by some researchers at high resolution. For example, Chotamonsak *et al.*, (2011) had conducted an experiment by using a WRF RCMs to project climate change from 1990-1999 to 2045-2055 at 60-km resolutions. In this study, they used ECHAM5 data GCMs and CRU observation data. Their results show a good agreement with observation by the high correlations, the temperature increase in the range 0.1-3^0 C in the future depending on the areas and season. In the future precipitation increased in average but decreased during the rainy season. The other study over Southeast Asia also had been conducted by Sentian J., and Kong S.S.K (2013) to project climate changes during summer and winter monsoons from 1961-1990 to 2071-2100 by using PRECIS RCM to downscale HadAM3H GCM at 0.22^0x0.22^0 resolutions. The correlation performances of their results are between 0.5 and 0.8 with the observation (CRU). The temperature increased over land during DJF and JJA in future. There was an average surface warming of 3^0C during DJF and 3.1^0C during JJA. The increase temperature was consistent with the lower precipitation where the precipitation decreased during DJF.

Over Indonesia, Katzfey *et al.*, (2010) have conducted the climate simulation by using CCAM to project climate change from 1971-2000 to 2041-2060 and 2081-2100. In their study the 200-km climate simulation was dynamical downscaled to 60-km resolution over Indonesia. The higher resolution simulation shows a more realistic topography and other features, improving current climate simulation and provide better projections of future climate. For future annual precipitation decreased over most of Indonesia and the temperature is increase. For the specifics area in Indonesia also has been conducted the climate simulation by McGregor *et al*., (2015) by using the CSIRO CCAM to project climate change for island of Lombok from 1971-2000 to 2021-2040 and 2051-2070. They downscaled GCMs at 200-km to 14-km resolutions. The fine 14-km scale providing projections with improved detail. For the current climate, CCAM provide the good precipitation on the southeast of Lombok and Sumbawa especially during the dry season and the temperature were a good agreement with CRU observations dataset. The future climatology in 2060s year, the precipitation changes from zero up to 5-10%, with some decrease in MAM and increase in DJF. For 2030s year also show the similar change to 2060s but have smaller magnitude. The high-resolution climate simulation generally indicates decreases in precipitation over eastern Indonesia in DJF and MAM, but some areas show increases in the DJF.

In the other region, Skamarock *et al*. (2008) have completed three 30-year climate runs at 10-km resolution over the IP to evaluate its capacity to simulate Spanish precipitation and to determine its adequacy for future climate simulations over Spain. In addition, Argüeso, D *et al*. (2012) also have done climate simulation by using WRF over Spain for present climate (1970-1999) to evaluate the models and climate simulations. They used two GCMs, the NCAR Community Climate System Model version 3 (CCSM3) and the Max Planck Institute ECHAM5 model (ECHAM5/MPI) to downscale by using WRF at 10-km resolution. The result performances of their study are a good agreement to the observation (Spain02) with 0.80 and 0.83 of the correlation coefficient. Besides, they also have done project climate for future climate change. In the northern of Thailand, Masud, M. B. *et al*. (2016) have projected change in extreme climate over 1960-2099. They used the observe data for daily maximum and minimum temperatures and total daily rainfall for the 1960-2010 period, and HadCM3 GCMs and PRECIS RCM data simulation for the 1960-2100. They are downscaled GCM at 280-km resolution to 25-km resolution. The extreme temperature indices about their studies which shows a significant increasing trend during the observed period and are expected to increase significantly with an increase in summer days and tropical nights in the future. The annual total rainfall and moderate rainfall (R10) indices were decreased which is supported by the negative trend of consecutive wet days (CDD).

In another region of Southeast Asia, Ngo-Duc, T. *et al*., (2014) have conducted the climate projection for Vietnam. They were simulated the baseline period from 1989-1999 and future period from 2000-2050. They used 3 RCMs which are the CCAM at 25-km, the RegCM3 at 36-km, and the REMO at 36-km driven by GCMs of CCAM, CCSM3, and ECHAM5, respectively. The RCMs simulation have evaluated using daily temperature and precipitation observation from 61 local meteorological stations in Vietnam. The future climate change of all RCMs shows that the average temperature significantly increases in the near-future (2001-2030) and mid-future (2031-2050) periods which is compared to the baseline period. The average precipitation changes vary substantially, depending on region and season. Generally, the model shown inconsistencies in representing precipitation changes, except for south and central region in the mid-future period. Chotamonsak, C. *et al*. (2012) have evaluated of precipitation simulation over Thailand using a WRF RCM in 2005 year. They have downscaled NCEP/NCAR Reanalysis data at 2.5^{o}x2.5^{o} resolution to 60-km and 20-km resolution. In this study, they used four different cumulus parameterizations schemes. The result evaluated by using two observational datasets which are CRU (0.5x0.5 degree) and observed data at 69 stations of the Thai Meteorological Department. Their result shown that difference in cumulus parameterizations and application of nudging can have substantial impact on simulated convection and precipitation. Deficiencies in simulated precipitation can result directly from the regional model, the convective parameterization used, or from the large-scale boundary conditions. The WRF simulations have shown realistic monsoon flow over Thailand and capture well the monsoon onset.

The evaluation of WRF modeling system on surface temperature and precipitation over Malaysia region have conducted by Kong, S. S. K, *et al* (2015). The NCEP FNL (1x1 degree resolution) is used in this as drive RCMs in two nested domains which are covered the SE Asia at 45-km resolution and Malaysia region (East and West Malaysia) at 15-km resolution. The CRU observation dataset was used to evaluate the model performance in the year of 2010 in this study. Generally, the model agrees well with CRU in simulating temperature by producing good value of statistical analysis formula. However, the precipitation did not perform as well as the surface temperature. Large biases were found over interior and mountainous regions. Besides, Kong, S. S.

K., and Sentian, J (2015) have also done climate simulation from 1961-1990 to 2071-2100 by using PRECIS RCM over Malaysia. They have downscaled HadAM3H at 150-km resolution to 50-km resolution. Model performance have evaluated using CRU observed data and ERA-40 reanalysis data. Overall, the result of PRECIS RCM simulation agree well with CRU and ERA40 data. It is a small cold bias across the region throughout all season. However, the precipitation did not perform as well as temperature especially in DJF. At the end of this century, the Malaysia domain is expected to experience a warming with the surface temperature increase between 2 and 3 degrees Celsius. The seasonal precipitations were decreased by 24% during DJF and 8% during JJA. The comparison between Malaysia sub-regions shows that the Malaysia peninsula region was projected to have a large increase in surface temperature compared to Malaysia Borneo. Both regions projected precipitation to receive a large annual decrement of rainfall with large magnitude in Malaysia Borneo. Seasonal precipitations of Malaysia Borneo also have experienced a larger decrement compared with the Malaysia Peninsula.

Singh, J. *et al* (2015) have conducted to evaluate about WRF model seasonal forecasts for tropical region of Singapore in 2014 year. The model is configured with four nested domains of 27-9-3-1 km resolution. The initial and boundary conditions are derived from NCEP GFS data with $0.5^{o}x0.5^{o}$ resolution. The WRF model performance is evaluated against near surface observations for temperature, relative humidity, and wind field. The observations are available from a dense network of monitoring stations across Singapore operated by the National Environment Agency Singapore. The model accuracy is significantly enhanced (approximately by 10%) by the high-resolution land use and sea surface temperature data. Their result suggests that the WRF model performs better for the monsoon seasons. Vaid, B. H (2013) has done to simulate and analysis of June 16, 2010 heavy rainfall event over Singapore using the WRFV3 Model. The NCEP FNL data with 1x1 degree has been used. He conducted multi-nested experiments of 3 model domains of 27, 9, and 3 km resolution to simulate a heavy rainfall case over Singapore on June 16, 2010. The model produced maximum precipitation of 5 cm over Changi airport which is very near to observation.

CHAPTER 3
MODEL AND METHODOLOGY

3.1 The Domain Position

The domain is the determination of the area simulation which is first determined by the region under survey. A large resolution difference between GCMs (the driving data) and RCMs have an important impact on the results (Denis *et al*., 2003). Therefore, the conventional approach is to use an intermediate coarse domain where to nest the finer domain to reduce the disparities. For WRF, usually the grid distance ratio of difference between the parent and nested domain is 3/1. Where, for the 10-km resolution domain typically is nested in 30-km resolution domain. If the scale of disparity between the coarse domain and the boundary conditions data is still large, the other domains can be added. Some researchers claim that a climate which is run at 10-km that is a high-resolution climate simulation (Caldwell *et al*., 2009; Evans and McCabe, 2010; Rummukainen, 2010).

In addition to a number of domains, the communication between them must also be considered. There are two techniques of communication between domain, namely one-way and two-way nesting distinguished by their feedback. In one-way nesting, the boundary conditions have been set at the border of the coarser domain that passed this information to the finer domains, while the two-way nesting have feedback between the two domains where the information is derived in the finer domain also passed to the coarser domains. The two-way nesting is very useful in simulating the short term but in the long-term simulation might cause instability. Indeed, the WRFV3.7.1 is unstable in the long-term simulation using tow-way nesting, this is caused by a very large vertical velocity occurs in the relaxation zone where the information is shared. However, some researchers have proven that the technical ability if one-way nesting to produce fine scale atmospheric features (Denis *et al*., 2002; Dimitrijevic and Laprise, 2005; Harris and Durran, 2010). In this scenario, this is the most comprehensive approach in climate simulations (Antic *et al*., 2006; Borge *et al*., 2008; Bukovsky and Karoly, 2011; Frei *et al*., 2006; Moberg and Jones, 2004; Salathé Jr *et al*., 2008), the procedure that has been selected in one-way nesting.

Besides what has been mentioned above, the location of the domain borders adequately should also be carefully consider. The aforementioned resolution disparity between the driving data and model itself shows that the orographic in homogeneities should be placed away from the domain borders to avoid the generation of artifacts. However, it is not possible to design a domain with the borders located in the area that is completely homogeneous and mountain areas are sometime unavoidable. If this happens, differences in position of the border should be checked to reject the configurations that might cause the error is too large. In addition, when deciding the location of domain, the atmosphere dynamical features of the region should also be taken in account.

All of the above factors, I determine two domains using one-way nesting with a resolution of 30-km and 10-km respectively, as in shown in the Figure 3.1 below. The interest area of this study is over Sumatra Island of Indonesia. The coarser domain (13^0S-13^0N, 87^0E-114^0E) consists of 100 by 100 grid points, equivalent to 3000 km (W-E) by 3000 km (S-N), and the nested one (8.5^0S-8.5^0N, 92.5^0E-110^0E) comprises 190 by 190 grid points, which amounts to 1900 km (W-S) by 1900 km (S-N). The simulation domain in this study is defined on Mercator projection as a map projection and the map center at $0\ ^0$N, 101^0E.

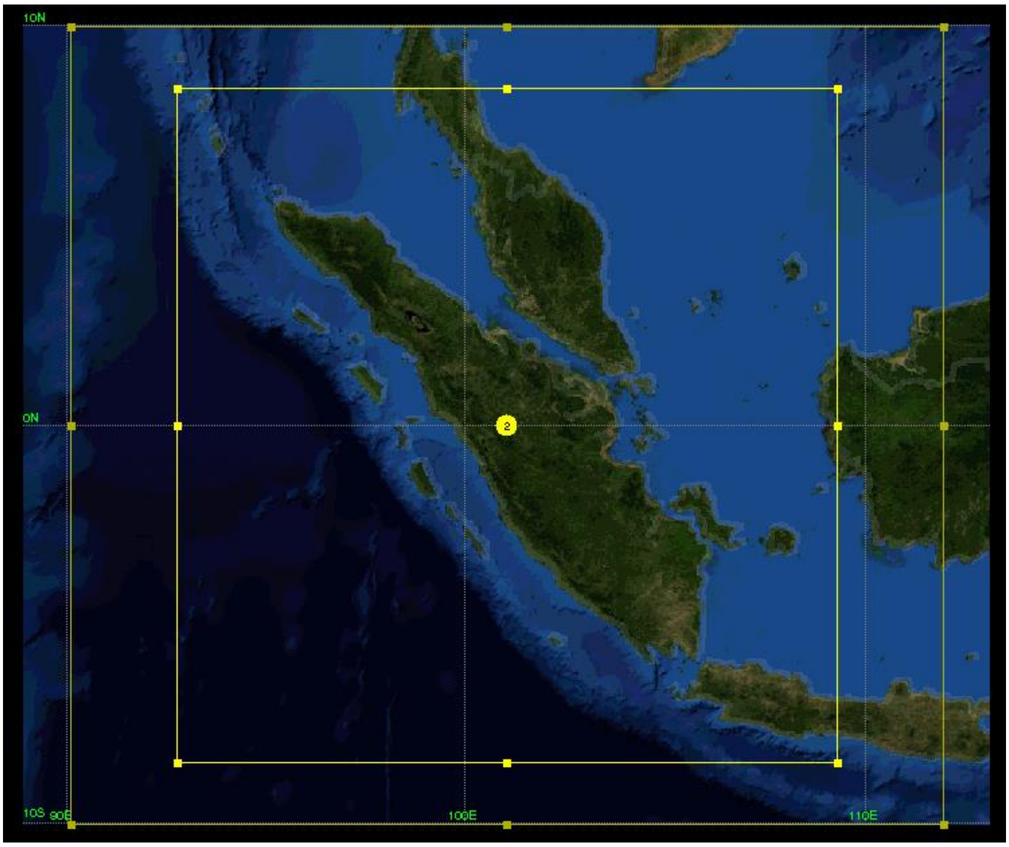

Figure 3.1 The coverage WRF domains configuration. The yellow lines indicate the coarser (30-km) and the finer (10-km) domains.

In addition to the boundary conditions that WRF needs to run, the difference in static fields also becomes the input to determine the domain. This field describes the topography, the soil type, and the land use. In this simulation to define the topography and land use category using U.S. Geological Survey (USGS) datasets (GTOPO30, Gesch *et al*., 1999). The USGS has 24 land use category that is characterized by the number of each properties (e.g., albedo, roughness length, and emissivity), and 30 resolution (~1 km) which convert to the model resolution by mean of interpolation.

Besides to the aforementioned static field, in the short-term simulations have also been ingested the Sea Surface Temperature (SST), the vegetation fraction and the albedo. However, in the climate simulations it is recommendable to enable the option that makes these fields to vary. The SST was obtained from the driving data and updated with same frequency as the boundary conditions, while the albedo and the vegetation fraction are characterized by monthly values.

3.2 The Weather Research and Forecasting Model Set-up

The WRF model is a mesoscale numerical weather prediction system that developed for the operational forecast and atmospheric research needs (Skamarock *et al*., 2008). The WRF model is a result of partnership that is collaborated more than 150 organizations and universities in the United States and abroad, such as the National Centre for Atmospheric Research (NCAR) or National Oceanic and Atmospheric Administration (NOAA).

There are two dynamical cores have been implemented in the model, namely the Non-Hydrostatic Mesoscale Model (NMM) and the Advance Research WRF (ARW). The NNM was primarily design for weather forecasting purpose, while the ARW is created to be suitable for a wide range of applications at varying time and spatial scale.

The WRF model system has been freely available online and has been designed to be more portable and more efficient in several platforms, included parallel environments that use MPI (Message Passing Interface). There are two factors have been permitted a fast growth of the user community which has played a part in the model improvement via the addition of new parameterizations, the coupledom with other models and the modification of the code with new applications in mind.

Two different kinds of simulations that have permits to study by WRF model: they are an ideal initialization and using real data. The WRF core is not altered by selecting one initialization or another, but the data pre-processing is different. Ideal cases comprise simulations of very particular conditions and simplified orography, usually when individual processes in the atmosphere are to be examined (i.e., Large Eddy Simulations, sea breeze, flow over a hill). On the other hand, to study an actual event on given area, so the real-mode simulations require different atmospheric and terrain data.

Three main modules that have been organized in the WRF software (real mode) that must be run successively: the WRF Preprocessing System, the data initialization module (real program) and the ARW solver.

3.3 The Boundary Condition

The driving data are an important component in dynamical downscaling because they are the main sources of information. Indeed, the WRF model downscales the low-resolution climate information that provided by the boundary conditions. In this situation, to projecting the future climate should be produced using different data sources to generate a sort of ensembles to reduce the uncertainty that covered a wide range of possibilities. The boundary conditions can be divided into two main groups, the observational re-analyses that describe current climate to evaluate the model and the GCMs that simulate the Earth climate under present and potential future conditions.

3.3.1 The observational reanalysis

The reanalysis observations data is referred as RCMs framework that have perfect boundary conditions because they have resulted in a better present global climate representation in mesh form. Reanalysis observation is a combination of data from measurement instruments and numerical models that produce synthesized estimates from atmosphere. A regional model driven by reanalysis data is useful for gaining a past-climate that is almost in its true evolution. The observation data was selected in this research to evaluate RCMs are CRU (Hulme *et al*., 1995), GPCC (Becker, A. *et al*., 2013), and UDELAWARE (Kalnay, E., 1996), and ERA-Interim reanalysis data (Dee, D. P. *et al*., 2011).

- ERA-Interim

ERA-Interim is a reanalysis models of the global atmospheric covering the data period since 1979 and continuing in real time. ERA-Interim provide the data between previous analysis of WCMWF, ERA-40, and the next-generation reanalysis at ECMWF. The ERA-Interim data have improved on some aspect of ERA-40 such as the representation of the hydrological cycle, the stratospheric circulation qualities, and the handling of biases and changes in the observing system. The ERA-Interim data assimilation and forecast have produced four analyses per day (e.g. at 00, 06, 12 and 18 UTC) and two 10-day forecast per day, initialized from analyses at 00 and 12 UTC. The analysis data that produced at 00 UTC on a given day include the observations taken between 15 UTC on the previous day and 03 UTC on the present day and the analysis at 12 UTC include observations between 03 UTC and 15 UTC. The forecast data on pressure levels (pl types in MARS) and for the surface and single level parameters (sfc types) provide at the 28 ranges of 3-, 6-, 9-, 12-, 15-, 18-, 21-, 24-, 30-, 36-, 42-, 48-, 60-, 72-, 84-, 96-, 108-, 120-, 132-, 144-, 156-, 168-, 180-, 192-, 204-, 216-, 228-, and 240-hours from twice daily forecast at 00 and 12 UTC. The forecast model level data (ml types) are provided at 3-, 6-, 9-, and 12-hour range from 00 and 12 UTC. The both isentropic level (pt types) and PV = ±2 PVU (pv types) levels are not available in the forecast data. On the ECMWF Data Server forecast are only available for surface and single level fields and only up to a range of 12-hours.

The ERA-Interim data in the either GRIB or NetCDF format can be downloaded from the ECNWF Data server at http://data.ecmwf.int/data. The ERA-Interim data include 11 surface invariants (at one analysis time only), remaining analyzed surface parameters (include vertical integrals), 3 analyzed wave parameters (significant wave height, mean wave direction and mean wave period), forecast surface parameters (except the invariants) at steps of 3-, 6-, 9-, and 12-hours, analyzed upper-air parameters at 00, 06, 12 and 18 UTC on 60 model levels and 37 pressure levels, on isentropic level (not 320K), on PV = ±2 PVU, synoptic monthly means (except for the upper-air forecast field), monthly means of daily means and monthly means of daily accumulations at step 0-12 only. The variables that provide of the data are albedo, evaporation, incoming solar radiation, planetary boundary layer height, sea level pressure, snow, snow/ice temperature, surface air temperature, terrain elevation, water vapor, cloud amount/frequency, gravity wave, longwave radiation, precipitable water, sea surface temperature, snow density, soil moisture/water content, surface pressure, tropospheric ozone, wind stress, convection, heat flux, maximum/minimum temperature, precipitation amount, shortwave radiation, snow depth, soil temperature, surface roughness and vegetation cover.

3.3.2 The General Circulation Models

The Global models are numerical models that can simulate system of the Earth. The complexity of GCMs are varies greatly depending on the components possessed by the Earth system. From the existing system, the model of the atmosphere and the oceans are the part of the earth system used, namely the atmosphere and oceans general circulations. The modern of GCMs is referred AOGCMs which tend to add more process to their formulations such as atmosphere, cryosphere, biosphere, oceans, and land surface.

In this time, the GCMs are the main generator informants of climate change. The Earth system is forced towards potential future changes (GHGs and aerosols concentration, land use, solar activity) and the climate responses are examined. The GCMs describes the overall evolution of the Earth's climate and a framework of regional models to produce high-resolution information of climate changes. Therefore, GCMs are basis of dynamical downscaling.

The global climate model is not a perfect model, it is necessary to do a deeper analysis of the climate model given in a particular region. The errors in GCMs may be caused by RCMs in dynamical downscaling then both models should be assessed by checking the output of RCMs. The examination of the models can be done by conducting a present climate simulation and comparing it with observations. This method can used to minimize errors in future climate projections.

The WRF shows highly agreement in present climate simulations when driven by a GCM which may not necessarily provide a good simulation of the future climate. As consequently, difference of boundary conditions can be used as a model driver, so different climate evolutions might be learned. This is not only various GCMs but different emission scenarios as well.

In this Thesis, the global model included in the last IPCC AR5 (Solomon *et al.*, 2013) and widely used by the dynamical downscaling community is employed, i.e., the CESM model (Gent *et al.*, 2011). The GCMs details are briefly described below.

- The NCAR CESM model

The NCAR's Community Earth System Model version 1 (CESM) is a coupled global climate model (GCM) comprised of four component models that simulate the atmosphere, ocean, land surface and sea ice. The CESM simulations used to generate the present dataset were performed in support of the CMIP5 and the IPCC (IPCC 2013). The CESM ranks at the top of all CMIP5 GCMs in its ability to simulate global patterns of observed temperature and rainfall (Knutti *et al*. 2013). The CESM dataset has all the variables required for boundary and initial conditions to simulate climate model using the WRF or the Model for Prediction Across Scales (MPAS). It is provided in the Intermediate File Format specific to WRF and MPAS.

The CESM dataset is divided into 26 vertical levels with 1-degree horizontal resolution. The data are provided in hourly files with six-hour intervals. The variables of CESM have been biases corrected using the European Centre for Medium Range Weather Forecasts (ECMWF) Interim Reanalysis (ERA Interim) fields for 1981-2005, following the method in Bruyère *et al*. (2014). The variables that exist at each level are temperature (TT), relative humidity (RH), zonal wind velocity (UU), geopotential height (GHT), and meridional wind velocity (VV). Additionally, the variables sea ice (SEAICE), mean sea-level pressure (PMSL), surface pressure (PSFC), temperature (TT), sea surface temperature (SST), zonal wind velocity (UU), relative humidity (RH), meridional wind velocity (VV), and skin temperature (SKINTEMP) are at the lowest level.

3.3.3 Spectral nudging and buffer zone

In addition to the driving data sources, other variables on the boundary data can be configured in the WRF model. Spectral nudging can be used to overcome the ill-posed-ness of the boundary conditions specification and reduce the impact of domain design in the results. Spectral nudging adjusts the RCMs to keep the large scale consistent with the driving data. This is still controversial in its use, and many reaserchs have discussed its value (Alexandru *et al*., 2008; Heikkilä *et al*., 2010; Míguez-Macho *et al*., 2004; Radu *et al*., 2008; Zahn *et al*., 2008). They claim that the spectral nudging has benefits in climate simulation and prediction, but the selection of the scale must be highly considered because too strong nudging can cause disturbance to development of internal variability models. In this case, a relatively spectral nudging was adopted outer domain of this simulations. In particular, the wavenumber of 3 was chosen, which corresponds to adjust only waves larger than 1000 km. The spectral nudging switched off in the PBL and only the levels above planetary boundary layer was used with the adjustment a frequency of 24 h. All variables (U, V, T and PH –geopotential perturbation–) are nudged except for moisture. Humidity is not nudged following Míguez-Macho *et al*. (2005) because its spatial gradients can be very pronounced and thus might be missed by coarse resolution reanalysis.

3.3.4 Time configuration and spin-up

Besides of Spectral nudging, a 1-year spin-up is also adopted to reach an equilibrium models between the external forcing and the internal dynamics. In previous researches (Fernández, 2004; Giorgi and Mearns, 1999) have shown that initial values provide a small effect on results after approximately one week, a longer spin-up period was chosen in this study to ensure that not only atmospheric fields become reasonably independent of the initial condition but soil variables as well, which normally require several months to do so. The selection of a several-month spin-up is even more important to remove the initial condition influence on the model results.

This research analyzes simulations for 20 years period. The simulations include the 1-year spin-up, however, the climate runs are design differently to optimize computational resources. In principle, the simulations should be run continuously to preserve the consistence of the integrations in time. However, this implies that a given year can only be simulated if the previous one has already been completed. This approach is rather inefficient from a computational point of view. An alternative procedure is here adopted to reduce the time required to complete the 20-year simulations and consists in splitting the climate runs into two decades simulations that are performed simultaneously. Each decadal simulation is then started using a 1-year spin-up to ensure independency from initial conditions and reduce the impact of model restarting. Figure 3.2 illustrates the design of the simulations in terms of time configuration for the climate runs.

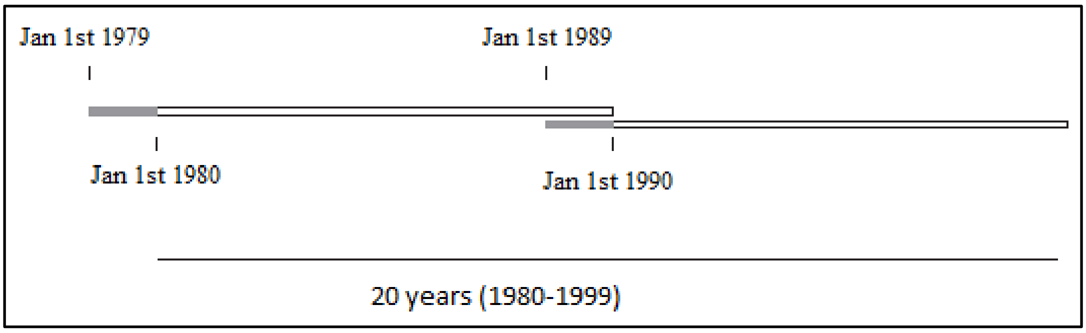

Figure 3.2 Time diagram of the 20-year simulations. The period is divided into two decades simulation with a 1-year spin-up (grey). The decadal runs are then integrated simultaneously.

3.4 Evaluation Model Performance

The evaluation of the model in order to assess its capabilities to correctly resolve temperature and precipitation over climate periods. The model evaluation will help to identify the uncertainties with respect to observations and it will then be possible to establish whether the model is adequate for future climate simulations over Sumatra. Dynamical downscaling and climate change studies in general rely on the assumption that an appropriate representation of present climate implies a correct description of future climate as well. This statement is founded on the idea that GCMs should represent present and future climate similarly, which is a fairly restrictive assumption. Unfortunately, present climate is the only available backdrop to validate our model estimates and verify our hypotheses. The model evaluation with present climate is not a guarantee that future projections are accurate, but the future projections will be unquestionably much more trustworthy than if the model is not validated at all.

Assessing the ability of climate models to accurately reproduce characteristics of present climate is an important stage in their continued development and improvement, and in assessing the uncertainty which surrounds the projections of future climate that are applied in climate impact assessment. To evaluate the WRF Regional Climate Model performances in this thesis, the mean annual accumulate precipitation and temperature over the 20 years of CESM-WRF at 10 km will be compared with Reanalysis-WRF and Observation datasets using correlation of the pattern (Walsh and McGregorn, 1997). Besides, the other statistical measures such as mean error (ME) and root mean square error (RMSE) will also be selected to evaluate the model performance.

The seasonal and annual precipitation and temperature will be calculated to get detail differences between the CESM-WRF, Reanalysis-WRF, and Observations datasets. Furthermore, extreme indices precipitation those provided by the Expert Team on Climate Change Detection and Indices (ETCCDI) will be also calculated. The extreme indices available on their web-site (http://cccma.seos.uvic.ca/ETCCDI). The extreme indices of CESM-WRF will compared with Reanalysis-WRF. These indices are the maximum 5-day precipitation (Rx5day), the number of wet days that exceed 10 mm (R10), the number of wet days that exceed 20 mm (R20), the percentage of precipitation explained by events within the 95th percentile (R95T), the number of maximum consecutive dry days (CDD), and the number of maximum consecutive wet days (CWD). The research flow chart in this Thesis is shown in the Figure 3.3.

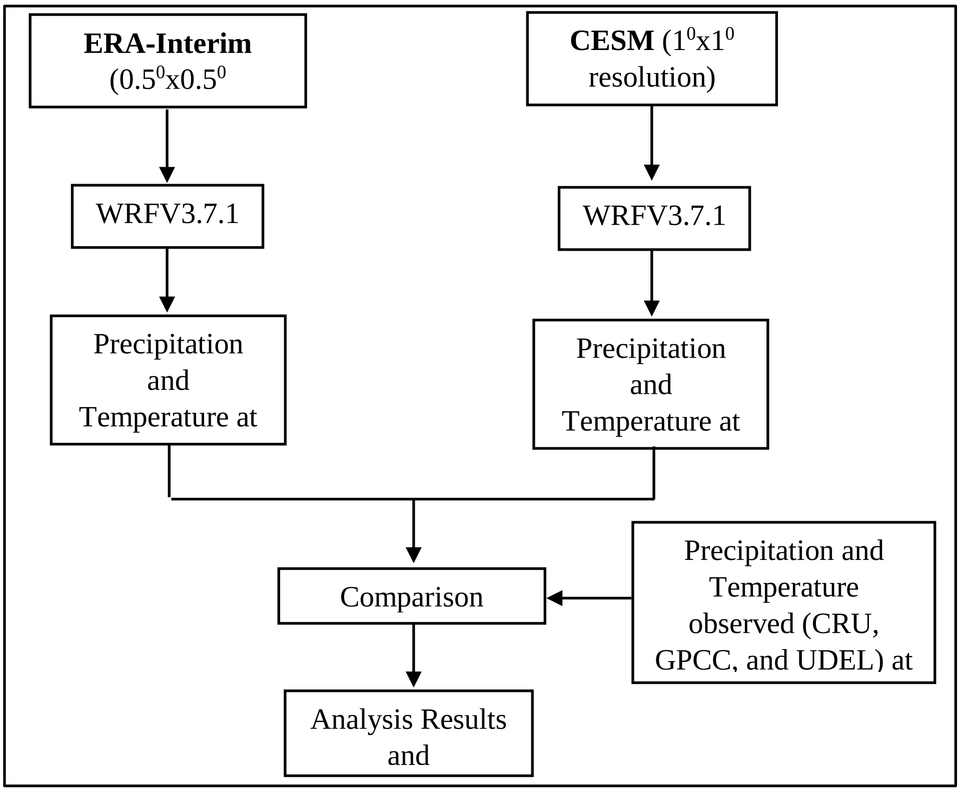

Figure 3.3 Research flow chart

CHAPTER 4
RESULTS AND DISCUSSION

This chapter describe the model evaluations to identify errors of observation and is able to establish that models can be used to predict future climate over Sumatra. Model evaluations focuses on precipitation and temperature at certain timescales only.

4.1 Present climate evaluation

Research on climate change and dynamical downscaling depends on the assumption that representation of the climate can provide an appropriate description of the future climate. It is based on an idea whereby GCMs should be able to show the present and future climate. Unfortunately, the present climate simulation is only to validate our model estimates. The evaluation of present climate models does not necessarily provide an accurate assurance of future climate projection. But the future climate projection is more unreliable if the model is not validated. Indeed, how can we rely on projected future climate of a model if we never know how the model's ability to produce the climate in the present.

Today, the validation process is often done indiscriminately, even to the point of removal, although it is essential to get more accurate results of climate change projections. Climate validation requires at least 20 to 30 years runs to be able to ensure that model can represent a local climate. Lately, computing resources have been used to evaluate models over long time period and produce future climate projections. The complete validation here has been a waiver of the validation timescale. There are several important factors in determining the climate and should be considered equal in the assessment of potential models such as mean value and high-frequency.

To evaluate the ability of a model to produce the current climate characteristic, difference 2 simulations over 20 years have been completed at high-resolution. These simulations are driven by CESM and ERA-Interim and will be called

CESM/WRF and ERA/WRF, respectively. To maximize the use of computing resources, 20 years of simulation divided in 2 decades with 1-year spin-up each simulated.

The evaluation of precipitation and temperature of the present climate is calculated by using some observation datasets such as CRU, UDELAWARE, and GPCC and ERA-Interim reanalysis dataset. The WRF output and observation datasets have been gradated on the same grid by using bilinear interpolation to be able to compare them. The evaluation of model is not only performed in long-term studies but also must be done on high-statistic, as has been confirmed by several researchers (IPCC, 2007; Leung *et al*., 2003). Even now, to solve the issue on different timescale, some researches are focused on RCM performance (Caldwell *et al*., 2009; Evans and McCabe, 2010; Herrera *et al*., 2010a; Jacob *et al*., 2007; Kostopoulou *et al*., 2009; Rosenberg *et al*., 2010).

4.2 Precipitation

Based on the patterns, precipitation of Indonesia is classified in three types depending on the regions as shown in Figure 2.3. The first type is unimodial monsoon rainfall pattern which the dry season occurs in June, July and August and wet month occurs in December, January, and February, while the remaining six months is a period of transition (three months transition of the dry season to the rainy season and three months turning the rainy season into the dry season). This pattern is located in southern Indonesia. The second type is a bimodial equatorial rainfall pattern where is located in northwest Indonesia including Sumatra. This pattern usually occurs around March and October or in the event of equinox. The lasts type is a pattern of local rainfall which is characterized by a unimodial rainfall pattern (one peak rain), but its shape is opposite to monsoon rainfall type. The region of local rainfall pattern is northeast Indonesia.

In this study, precipitation simulations have evaluated by employing 3 observation datasets and reanalysis data, i.e., CRU, GPCC, UDEL, and ERA-Interim reanalysis dataset. The observation datasets are available for land only. The ERA-Interim reanalysis dataset was treated as observations.

4.2.1 Annual precipitation

To validate the precipitation in the study area, the total annual precipitation has been calculated for observation datasets and WRF simulations over 20 years period (1980-1999). The total annual precipitation can determine the capacity of the model to be able to distribute precipitation throughout Sumatra island and also can determine the deviation of precipitation from certain areas. In addition, the correlation between simulations and observations is also calculated to evaluate the annual precipitation pattern of WRF with respect to observation.

The Illustration models of annual precipitation patterns can be seen in the Figure 4.1 below. This figure shows that the annual precipitation of the model CESM simulation using WRF has the same pattern with observation datasets as compared to the original CESM models (GCMs). The similarity of the pattern is seen in both land and sea areas. From the figure of the annual precipitation model below, the simulated model by using WRF can increase the precipitation value from the range about 1000-4000 mm/yr to the range about 700-7000 mm/yr from original model. The figure of model comparisons indicates that downscaling GCMs employing WRF model significantly improve the resolution of precipitation simulation in the study area. The precipitation pattern of WRF model simulation agree well with observation. Precipitation patterns over study areas have high values along the west coast of Sumatra island and over the sea southwest of Sumatra. The lowest values of precipitation are over the sea northeast of Sumatra. Downscaling GCMs using WRF can produce more detailed precipitation patterns and provide more accurate information on precipitation for specific region in the study area.

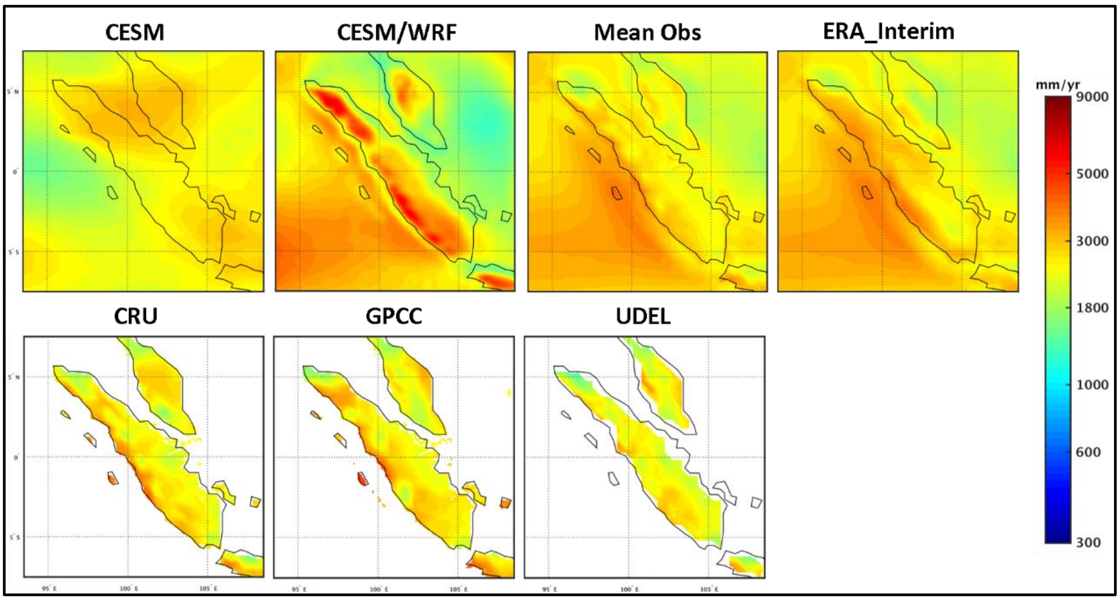

Figure 4.1 Illustration of Annual precipitation (mm/yr) over 20-year period (1980-1999) for observation datasets and those global models and WRF model simulation

The global model simulations by using WRF also shows value of precipitation for Sumatra region is very high. This is in line with the fact that precipitation in the tropics has a high value in the Earth's, including Sumatra. The high precipitation values of a region are greatly influenced by the location of latitudes (equator), where the closer an area at latitude then the precipitation will be higher. This occurs because of the high air temperatures in the area where is located close to the latitude. The evaporation is also higher. Sumatra is one of the Indonesian islands where is located in the tropics that crossed by the equator. This is one of reasons for the high precipitation that occurred in the region of Sumatra. The global models and regional models is very different in term of resolution, pattern, and intensity. The regional model at high-resolution much agree with observation. The precipitation patterns of regional climate at high-resolution is better than global model which the resolution is low. Based on this, it can be said that downscaling using WRF can be applied to the study area as shown in the Figure 3.1.

Beside of the latitude locations, the high precipitation values that occurs in Sumatra are also affected by the height of areas from the sea surface. The higher land will be the lower precipitation that occurred in the area, while the lowest land will be the higher precipitation. The land surface of Sumatra island is more than 2500 meters above sea level. This altitude is one of the low values among the islands in Indonesia. Therefore, this is also a factor in the high precipitation that occurs over Sumatra.

To validate the model simulations, the statistic values of annual precipitation have also calculated between WRF model simulation and observations. Downscaling GCM by using WRF increase the statistical values of annual precipitation that respected to observational data such as correlation coefficient (CC), mean errors (ME), and root mean square error (RMSE), these can be seen in the Table 4.1. From the table, the correlation coefficient value of annual precipitation over 20-year in 1980-1999 period of model simulation significantly increases from -0.36 to 0.69 respective to mean observation. Mean observation is average of the 4 observation datasets in this study. Both mean errors (ME) and root mean square error (RMSE) also significantly decrease. ME was decreased from 264.05 to 72.79 and the RMSE has been decreased from 733.22 to 589.46 over 20 years in the last 20^{th} century. It can be concluded that the simulated precipitation by using WRF show good results. In other hand, climate model simulation at high resolution is better than the global model simulation which is still low resolution.

Table 4.1 Statistic values of annual precipitation 20 years period (1980-1999) over Sumatra.

Statistic value	**Model**	**Observation**					
		ERA/WRF	Mean Observation	ERA Interim	CRU	GPCC	UDEL
ME	CESM	-110.7457	264.0539	300.1508	-87.29	-44.2651	-246.018
	CESM/WRF	0	72.7943	-108.8913	-364.4002	-304.4537	-746.949
RMSE	CESM	1038.2	733.2251	744.6798	495.3305	532.5727	479.1607
	CESM/WRF	435.9786	589.4642	551.7613	995.0786	1000.1	1214.4
CC	CESM	-0.0845	-0.3622	-0.3271	-0.1827	-0.2081	-0.054
	CESM/WRF	0.9349	0.6937	0.7557	0.3513	0.2944	0.2043

Both CESM and ERA-Interim model simulations by using WRF shows similarity results in the annual precipitation patterns, it presented in the Figure 4.2. Both CESM/WRF and ERA/WRF have strongly high precipitation values along the west coast of Sumatra island and over the sea southwest of Sumatra. The low value is in the entire sea northeast of Sumatra. Beside of the factors that mentioned above, the high precipitation in Sumatra is also influenced by the direction of the winds and its location close to the ocean that became the primary source of the water evaporation which subsequently became rain. This shows that the high precipitation of the west coast of Sumatra island is also influenced by the location directly opposite the Indian Ocean and the west winds that brought the water vapor to the mainland. In addition, the high precipitation along the west coast of Sumatra island is in mountainous area, which is caused by the water vapor carried by the winds to hit the mountainous area, so that the water vapor will reach a certain height and condense. Furthermore, water evaporation is saturated, it will fall into rain in the mountain areas. This is the reason of the mountainous area become one of the areas that have high precipitation.

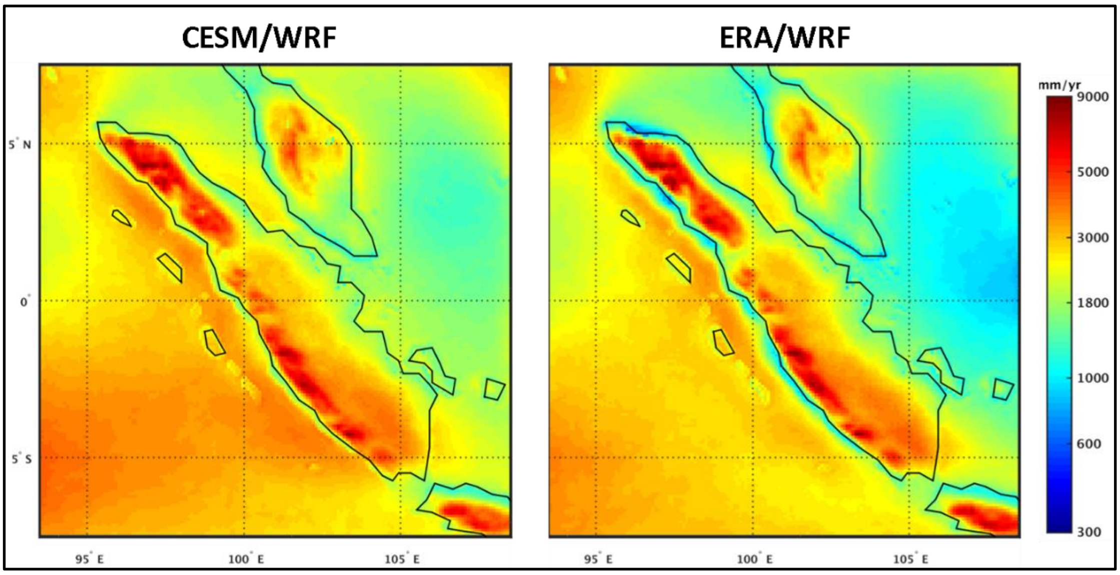

Figure 4.2 The comparison annual precipitation over 20 years period (1980-1999) of both CESM/WRF and ERA/WRF simulations

Both models of WRF runs simulation shows very good performance against precipitation pattern in the study area especially Sumatra. From the comparison of both model simulations using WRF, we get clearer, more detailed, and accurate information on the Sumatra precipitation patterns over 20-year in 1980-1999 period.

According to previous study in tropics regions (Nguyen Kim, C., *et al*., 2012), South East Asia (Chotamonsak *et al*., 2011; Sentian and Kong, 2013), and over Indonesia (Katzfey *et al*., 2010), precipitation in Indonesia is high especially Sumatra region. The highest precipitation is over Sumatra island and the west of Sumatra. However, their results cannot provide detail information of precipitation in the specific area in the Sumatra due to spatial resolution of simulation employed are still at low resolution (60-km). Therefore, precipitation simulations at 10-km resolution in this study is a good performance. The results provide clearer and detail information of precipitation in particular area in Sumatra.

The accuracy information of precipitation in Sumatra over the last 20-year period in the 20th century was also shown by the statistical values of both model simulations using WRF. The statistical values calculated between those WRF runs model simulation include the value of CC, ME, and RSME as shown in Table 4.1. The coefficient correlation and mean error between the two WRF models is 0.935 and 0, respectively. This is a very good value. Both CESM/WEF and ERA/WRF have a high similarity in the pattern and intensity. In addition, RMSE also has the lower values between the both regional climate models (CESM/WRF and ERA-Interim/WRF), i.e., 435.98. This value has significantly decreased form 1038.2. The comparison of two regional models at high-resolution is good idea to get more accurate model and detail information of climate simulation such as precipitation.

Figure 4.3 shows scatter plots between observed annual precipitation and those simulated by global climate models and regional climate models over 20 years period in the two last decades of the 20th century. The downscaling GCMs by using WRF extends the range of precipitation values for the study area from the range of about 1000-3000 mm/year to range of about 700-7000 mm/year range respected to observations. The RCMs show good performance than global CESM models.

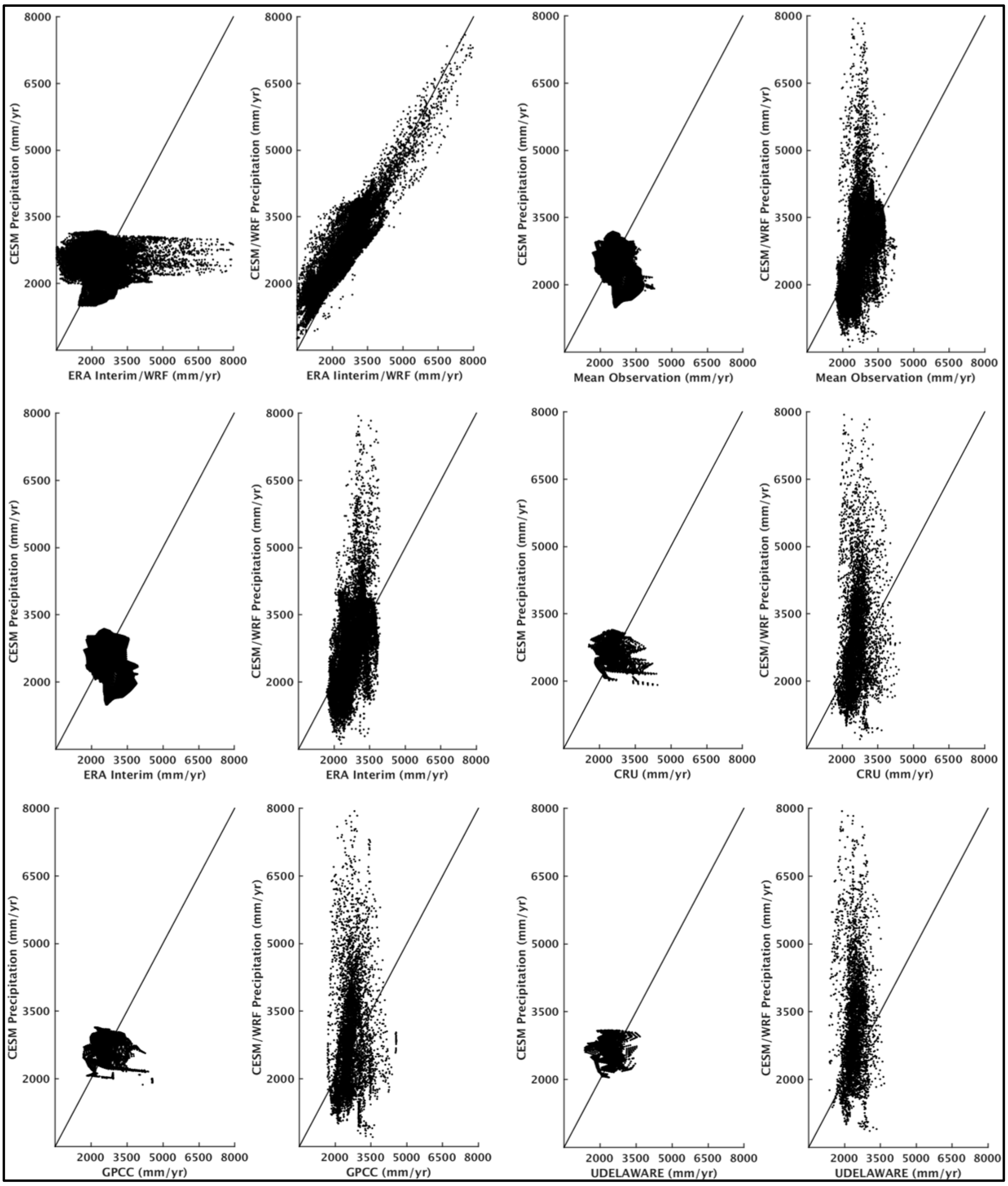

Figure 4.3 Scatter plots of annual precipitation 20 years period (1980-1999) between observation and those CESM and CESM/WRF model simulation over Sumatra

In addition, the scatter plots between the two model simulations using WRF also shows excellent performance as seen in the Figure 4.3. Scatter plots performance between CESM/WRF and ERA/WRF shows precipitation values increase linearly. The precipitation value in study area is very high in range of about 500-7000 mm/year. This scatter plots describe the annual total precipitation over 20 years of both WRF model simulations is similar to each other.

The comparison of pattern models and table statistics of annual precipitation shows that downscaling using WRF can work very well for the tropics area, especially the Sumatra region. The high-resolution of regional models can provide clearer and more accurate information on annual precipitation patterns. Thus, the downscaling of GCMs by using WRF can be applied to simulate future precipitation over Sumatra.

4.2.2 Seasonal precipitation

Precipitation patterns in every region of Indonesia vary widely due to various factors such as geography, topography, and others. Indonesia is a country that has 2 climate seasons in a year. These are rainy season and dry season. There is no clear time limit between the rainy season and the dry season. This is due to the location of Indonesia in the Inter-Tropical Convergence Region. However, the rainy season occurs in the period of October to April, while the dry season occurs in May to September period. In the rainy season, precipitation between model simulations at high-resolution and observation datasets shows the same pattern data as shown in the Figure 4.4. RCMs shows good performance against to observation. From the figure simulations, it shows precipitation value in the rainy season is very high over study area. The high value of precipitation occurs along the western of Sumatra island. The high precipitation values of the areas are also reinforced by the high value of precipitation in the sea southwest of Sumatra.

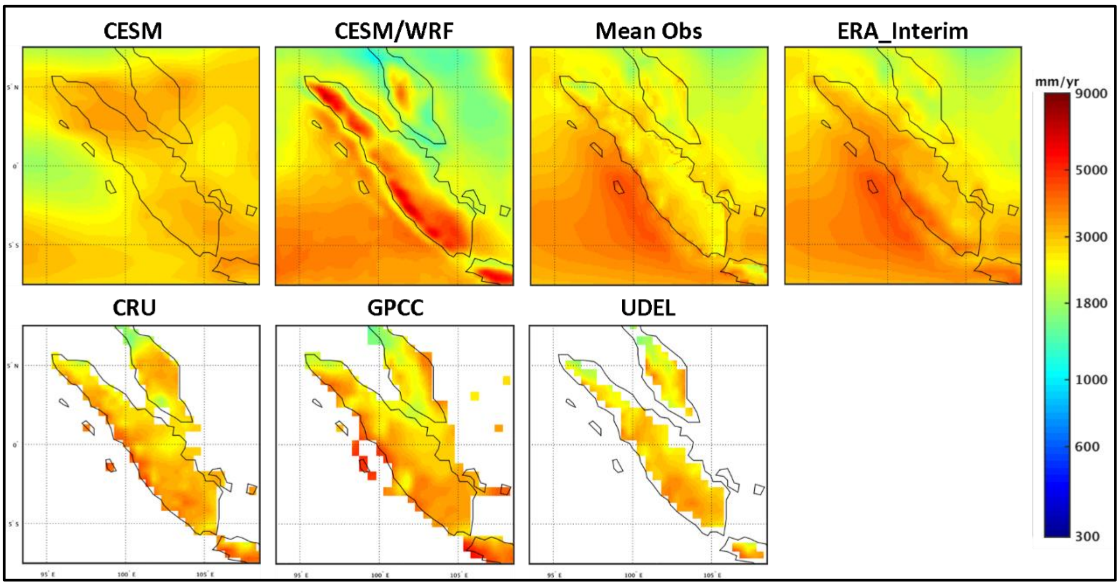

Figure 4.4 Climatological rainy season precipitations over 20 years (1980-1999) for observation datasets and those global models and WRF model simulations

From the Figure 4.4, RCMs shows that precipitation value in rainy season in study is very high about 1000-7000 mm/year. This indicates that the Sumatra island is very vulnerable to natural disasters, especially in this season such as floods, and landslides. Natural disasters caused by high precipitation values are highly likely to occur in highland areas. Currently, almost all the mountains in the Sumatra illegal logging and even converted function as a plantation area. In this condition, based on the high value of precipitation does not close the possibility of natural disasters in the future.

In addition to the comparisons between climate simulation at high-resolution and observations, to validate precipitation in the rainy season can be seen from the comparison of both CESM and ERA-Interim data reanalysis by applying WRF models such as shown in Figure 4.5. The accuracy of precipitation patterns in this season is shown very good from the comparison of the both WRF model simulations. Both CESM/WRF and ERA/WRF models show excellent agreement. From the comparison of the two models at high-precipitation can provide more detailed and accurate information about precipitation in the rainy season over Sumatra. In other hands, simulated climate models at high-resolution provide clearer and more detailed information on observing precipitation patterns. The WRF works very well for tropics, particularly Sumatra.

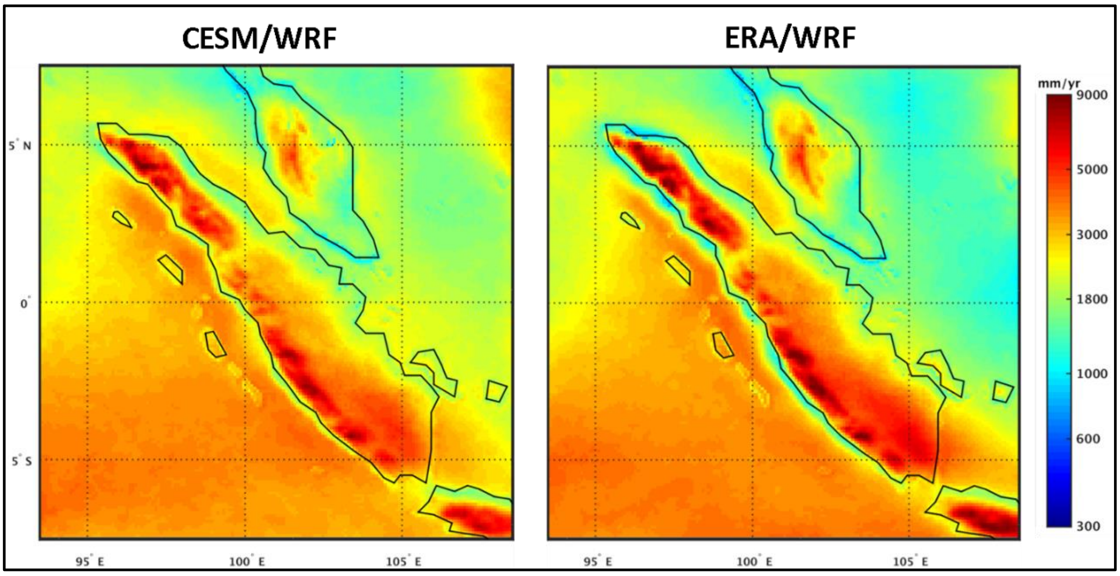

Figure 4.5 The comparison of rainy season precipitation over 20 years (1980-1999) for CESM/WRF and ERA/WRF model simulations

In addition to the rainy season as described above, to validate the model can also be demonstrated in the dry season in Indonesia. In the dry season, precipitation at high-resolution also shows patterns which corresponding to observation datasets as shown in the Figure 4.6. The CEMS/WRF model has a pattern that complies with the ERA-Interim reanalysis dataset. But the comparison of two these models have not given a good accuracy model due to the resolution of the two models are still different. Although the ratio of both models has the same pattern which the rather high value is shown in some areas in the west coast of the Sumatra island especially in the high mountains, and the low value is along the eastern of Sumatra. In addition, the figure also shows the similarity of the ocean precipitation patterns in the study area, where the higher value of precipitation is in the sea southwest Sumatra, and the lower value of precipitation is in the sea eastern of Sumatra.

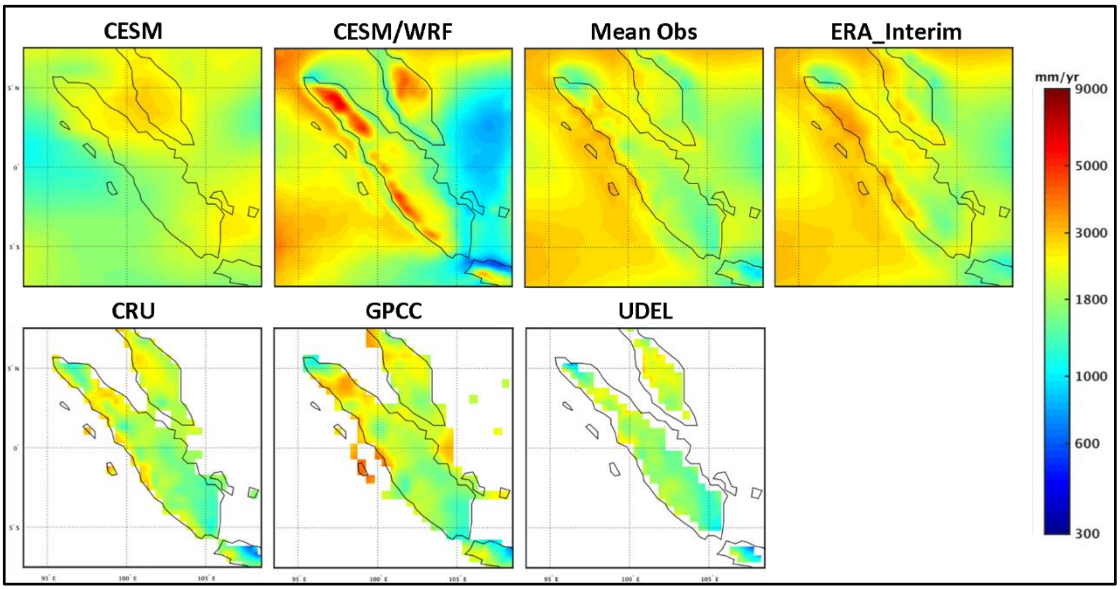

Figure 4.6 Climatological dry season precipitation over 20 years (1980-1999) for observation dataset and those global models and WRF model simulations

Therefore, to get more accurate information on precipitation in the study area, we need to compare these two models at the same resolution. The comparison of both models at high resolution is shown in the Figure 4.7. From this comparison, regional climate at high resolution can provide more detailed and more accurate information on climate simulations. In dry season, precipitation values over study area are still high. Precipitation in the western of Sumatra island is still more than 3000 mm/year. It described precipitation in Sumatra is high during a year. In addition, downscaling using WRF models can be used to validate a climate model.

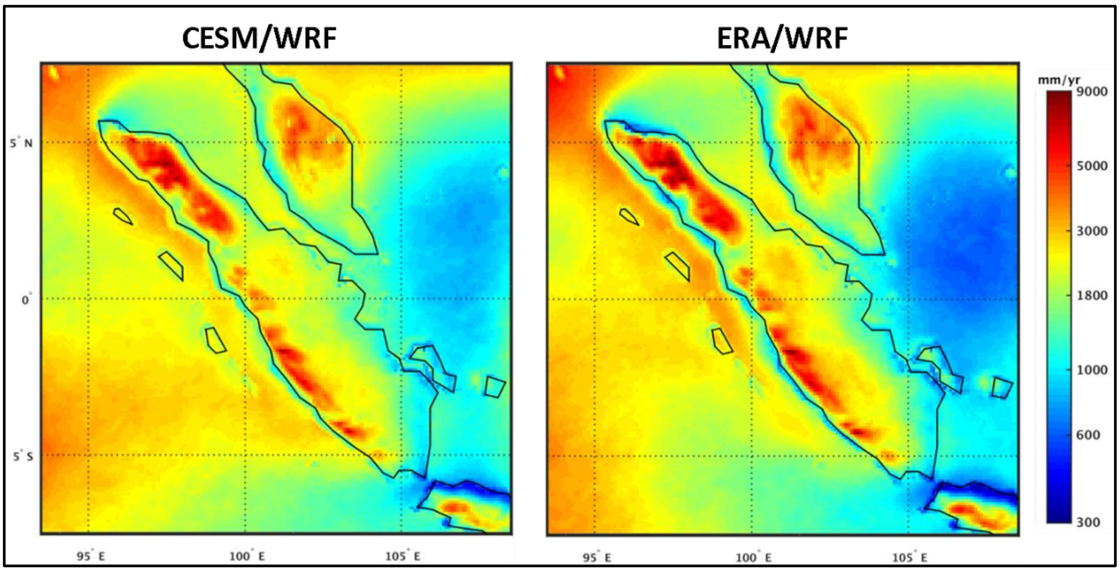

Figure 4.7 The comparison of dry season precipitation over 20 years period (1980-1999) for both CESM/WRF and ERA/WRF model simulations

4.2.3 Index precipitation

Some phenomena of daily precipitation are calculated. First, a percentile analysis of the daily precipitation contributions of different intensities for total rainfall is performed. Furthermore, some extreme precipitation indices from both WRF simulations (CESM/ WRF and ERA/WRF) were also estimated to see potential models. The calculation of these phenomena can also be used as reference of spreading and the potential of precipitation that occurred in the study area. In the daily calculation of the precipitation is only done for both simulations using WRF because the observation datasets were used in this study only provide in the form of monthly data.

First, the phenomena of daily precipitation performance of WRF is seen from precipitation percentile. In this study is estimated percentile to 95 (95^{th} percentile). The percentage illustration of 95^{th} percentile can be seen in the Figure 4.8. The comparison of both CESM/WRF and ERA/WRF extreme events indicates their compatibility. High percentages of extreme events are in the western of Sumatra, where extreme events point to range 50% of total precipitation. Exactly, this extreme event is in a high mountains area of Sumatra. From this extreme event also determine that the low percentage occurs in the eastern Sumatra where is located in the sea northeast of Sumatra. This low percentage range is less than 5%.

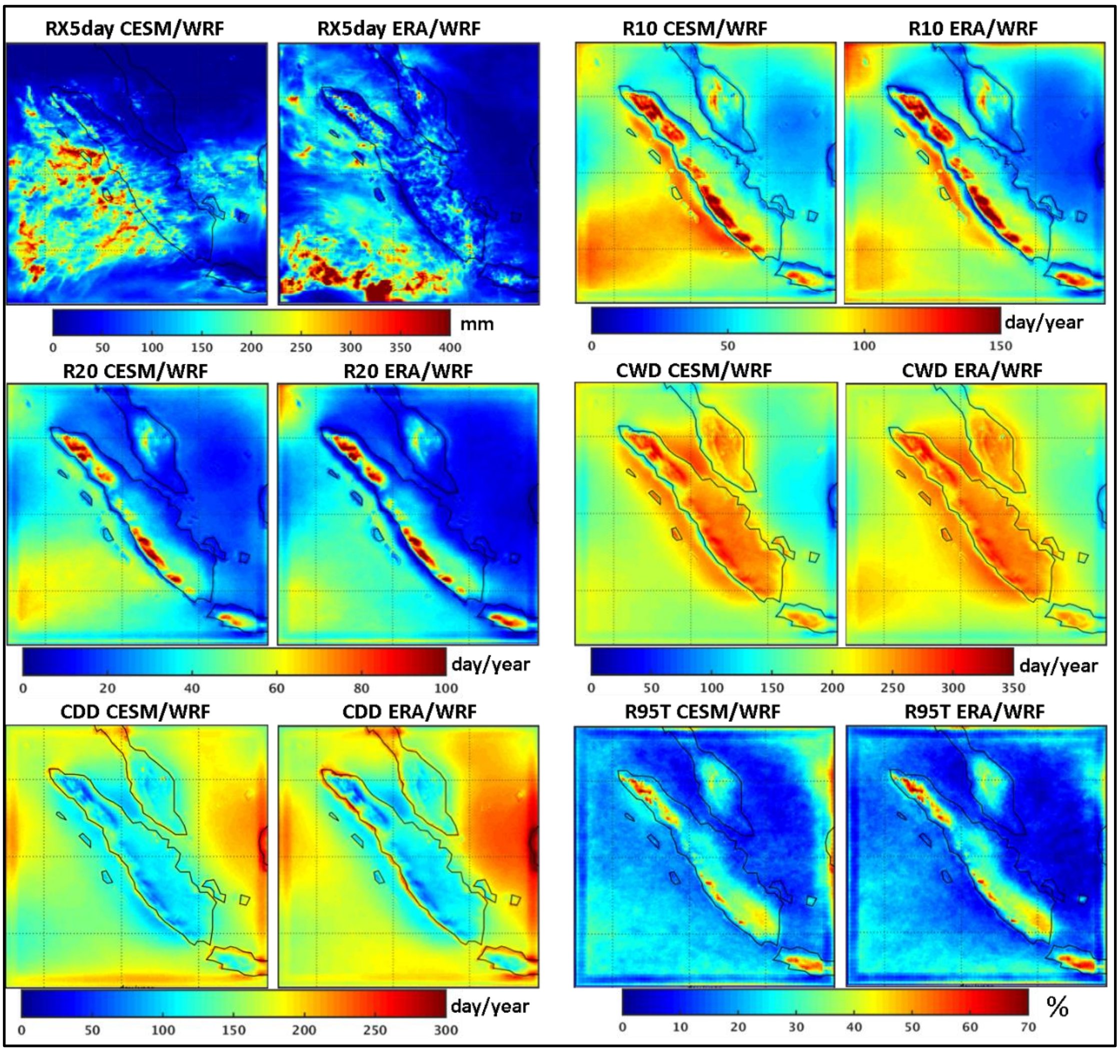

Figure 4.8 Extreme indices between CESM/WRF and ERA/WRF for present climate (1980-1999)

In addition to calculating the characteristics of extreme precipitation from their intensities over a 20-year period, there are some extreme indices of precipitation that are also interesting to calculate and analyze. These extreme indices are provided by The ETCCDI which is the subject of extreme views. In their web-pages, ETCCDI provides 11 different extract indexes from precipitation. In this study was selected 6 extreme indices analyzed. These extreme indices can be seen in the Table 4.2

Table 4.2 Selection extreme indices of precipitation (ETCCDI)

No	**Index**	**Description**	**Units**
1	Rx5days	Maximum precipitation in consecutive 5-days	mm
2	R10	The number of day when precipitation more than 10mm (RR≥10)	day/year
3	R20	The number of day when precipitation more than 20mm (RR≥20)	day/year
4	CWD	The number of day when precipitation more than 1mm	day/year
5	CDD	The number of day when precipitation less than 1mm	day/year
6	R95T	The percentage of precipitation when precipitation above a site-specific threshold value for very wet days (RR>50mm)	%

The Figure 4.8 shows an illustration of the extreme indices calculation. Rx5days shows the value of high precipitation is in the high mountainous and sea southwest of Sumatra. The Rx5days comparison between CESM/WRF and ERA/WRF has the same pattern although it does not show the same value. The low Rx5day pattern is in the eastern of the Sumatra island and also in the sea east of Sumatra.

Based on the day of the precipitation intensity is more than 10 mm and 20 mm (R10 and R20), both model WRF runs simulation have a large gradient along the western of Sumatra island precisely located in the high mountains of Sumatra and also in the sea southwest of Sumatra. CESM/WRF has a total number of days whose precipitation intensities is more than 10 mm (R10) about 140 days/year almost all high mountainous. In the northwest of Sumatra, CESM/WRF has a number of days which is approximately 110 days/year on R10. The day's numbers of this index are more than those occurring on the ERA/WRF. The number of R10 in the high mountains occur for 120 days/year, whereas in the sea northwest seas of Sumatra occur for 95 days/year. The similarly in the northeastern region of Sumatra, precipitation intensities of more than 10 mm are more common in CESM/WRF about 50 days/year compared to ERA/WRF occurring about 20 days/year. However, both CESM/WRF and ERA/WRF models show the same pattern.

Additionally, a similar case occurs in precipitation intensities greater than 20 mm (R20). CESM/WRF has more number of days than ERA/WRF in the area mentioned above. However, both WRF runs model simulation still show the same pattern of events. This shows that the precipitation events in present climate can be used as a reference. In addition, from both R10 and R20 described above, it can be said that high intensity of precipitation (more than 10 mm) often occurs in research areas within a year.

Other extreme indices such as the number of wet and dry consecutive daily (CWD and CDD) contribute substantially in analyzing the daily occurrence in the study area. CWD index is the number of days of precipitation phenomenon above 1 mm ($RR \geq 1mm$), while CDD is the number of days of precipitation phenomenon below 1 mm ($RR<1mm$) that occurred in the study area. From the estimates of the indices, CWD shows that precipitation is more frequent on the mainland of the Sumatra island than in the oceans. It is also supported by CDD indices which indicate a drier phenomenon often occurs in ocean areas than inland.

During the last 2 decades of the 20th century, CESM simulations using WRF showed that the number of wet consecutive days (CWD) occurred for 270 days/year in the mainland area of Sumatra especially in high mountains, whereas in the sea area. CWD indices were occurred 230 days/year in the southwest of Sumatra. The frequent occurrence of precipitation in the mainland can be affected by the difference temperature between land and sea, where if the sea temperature is higher than the mainland then the precipitation will more often occur in the mainland. In addition, the frequent occurrence of precipitation in the mainland is also caused by the winds which brought water vapor to a certain place. The more often a region traversed by the winds, the more often the area occur precipitation. The CSEM/WRF model has a similar pattern and value to the land area but is slightly different in the ocean areas where is lower value. But overall, CWD indices comparisons of both CESM/WRF and ERA/WRF is very good and is compatible to each other.

As well as the CWD indices that has been described above, the CDD index between the both WRF run model simulations also shows similarity pattern to each other. However, there is little difference value in the sea of Sumatra. In the southwestern region, ERA/WRF has dry days 190 days/year more than CESM/WRF which only has dry day of 110 days/year. While in the western, ERA/WRF has a total of 280 days/year more than CESM/WRF which has a total of 220 days/year. In the mainland regions of the Sumatra island, both CESM/WRF and ERA/WRF have nearly as dry days as 100 days/year. From the two indices indicates that the atmospheric conditions above Sumatra are more often wet or in other words, the potential for occurrence of precipitation above 1mm (RR≥1mm) often occurs in Sumatra within a year.

4.3 Temperature

To validate the climate model, the calculation of the temperature pattern is also very necessary given which the main model in viewing climate change is not only from the precipitation models, but also determined by the temperature models. To access WRF performance at temperatures, it is to refer to the precipitation values that previously analyzed. The patterns and values of annual and seasonal temperatures can explain the climate models that exist in the study area. The temperature calculations can also determine the accuracy of the climate occurring in a particular region of Sumatra and can provide more detailed information about the climate of a region. In addition, the temperature models can also provide important information in dealing with a disaster risks such as forest burning, and so forth.

To evaluate WRF model simulated climatological temperature, 2 observation datasets, i.e., CRU and UDEL, and ERA-Interim reanalysis were employed in this study. The ERA-Interim has been used as observation data. To get more accurate model and climatological temperature, ERA-Interim was also downscaled by using WRF model at same resolution of CESM/WRF.

4.3.1 Annual Temperature

To validate the model and check the temperature results, the annual average temperature has calculated during 20 years of 1980-1999 period in the study area. Similarity as has been done in the preceding precipitation analysis. To get the accuracy of the temperature, the model simulation using WRF compared to observation datasets, including CRU, UDEL, ERA-Interim reanalysis, and the mean of observation which is the average of the three observations datasets. Annual average temperature can provide an overview of climate models for the Sumatra region. In addition, in order to analyze the accuracy of the models, statistical values such as CC, ME and RMSE have been performed between the simulation model and the observation dataset.

The description of the annual average temperature patterns of the simulation model using WRF and observation data can be seen in the Figure 4.9 below. The annual average temperatures in the CESM model simulation by using WRF shows the same pattern with observational data as compared to the original CESM model. Regional models have annual average temperature values and patterns that are very much different from global models. Overall, global climate models have very high temperature values on both land and oceans, about 23-27 ^{o}C and 28-31 ^{o}C, respectively. In global models we cannot distinguish the temperature values in a particular region. Global models cannot provide clear information about the temperature in a particular area of the study area.

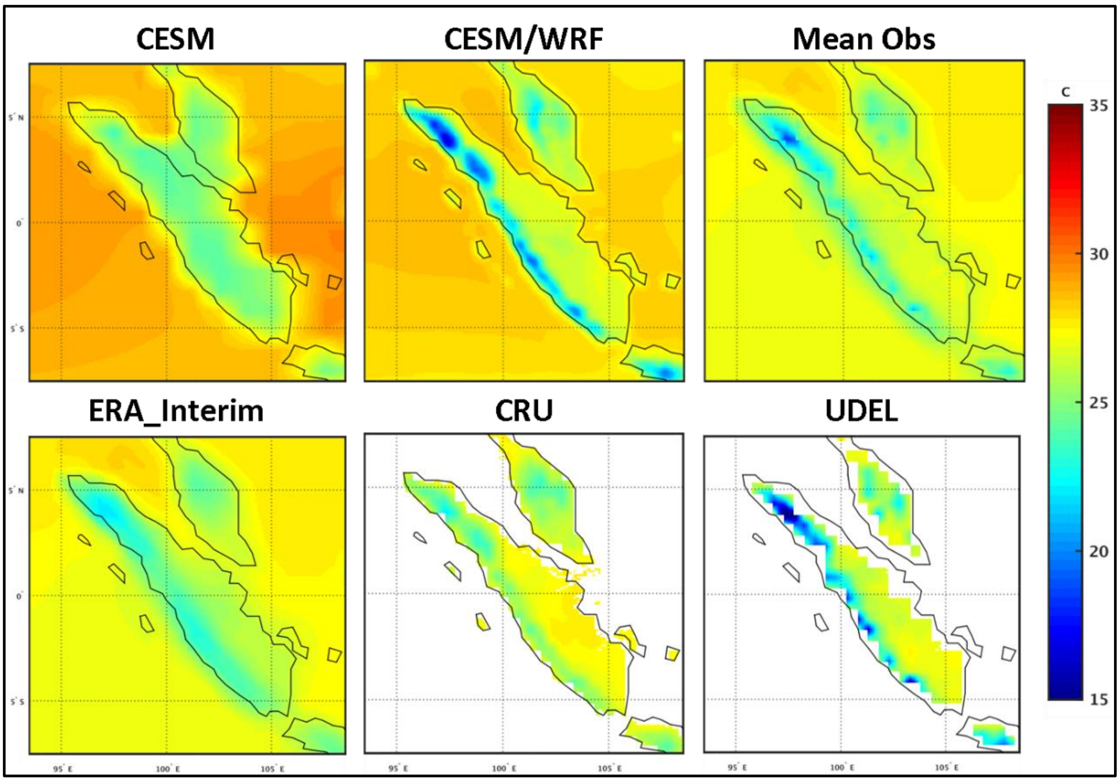

Figure 4.9 Illustration annual average temperature over 20 years period (1980-1999) for observation datasets and those global models and WRF model simulations

Downscaling GCMs using WRF model provide a very good performance of the temperature patterns in the study area. The annual average temperature of the CESM model simulation by using WRF shows that the lowest value is along the west coast of Sumatra, especially in the mountainous area. This temperature pattern is very much in line with the fact that temperatures in the highlands have a low value. The lowest temperatures in the mountains area follow the characteristics of the atmosphere, especially the troposphere, where every 100 meters rise of altitude then the temperature decrease by 0.5 ^{o}C. Regional model with high resolution shows good performance with observations. Downscaling global model using WRF significantly improve the range of temperature values. Regional models have a wider range of temperature values from about 16 to 29 ^{o}C. This shows that downscaling using WRF is able to work well against temperature pattern simulation in study area, especially for Sumatra.

The accuracy of the simulated model temperature at high resolution, it is also shown by the performance metrics as shown in the Table 4.3 below. The downscaling global model by using WRF increases the coefficient correlation value to the observed data (mean observation) to 0.86 of annual average temperature. This is a very good value against the comparison of regional models with observations. It value has also been a very significant increase of the comparison global model with observation. In addition, both ME and RMSE values have improved greatly. This proves that regional models at high resolution have good performance and in accordance with the observation data. The regional models agree well with observation.

Table 4.3 Statistic values of annual average temperature 20 years period (1980-1999) over Sumatra

Statistic value	**Model**	**Observation**				
		ERA/WRF	Mean Observation	ERA Interim	CRU	UDEL
ME	CESM	-0.5801	-1.1830	-1.2818	0.7302	-0.1843
	CESM/WRF	-0.0912	-0.6867	-0.7855	1.0081	-0.0061
RMSE	CESM	1.4671	1.6517	1.6026	1.5811	2.6033
	CESM/WRF	0.1684	1.0624	1.1473	1.5460	1.1827
CC	CESM	0.6485	0.6617	0.7843	0.2069	0.1286
	CESM/WRF	0.9960	0.8695	0.8489	0.8673	0.8932

To validate the model, this study not only compared simulation models using WRF and data observation. However, to obtain the accuracy of the pattern and value of temperature in the study area, the two model simulations by using WRF at the same resolution have compared. The comparisons of CESM/WRF and ERA/WRF are shown in the Figure 4.10 below. The comparison of the annual average temperatures shows the same pattern which is very cold patterns in high mountains along the west

Sumatra island. CESM/WRF and ERA/WRF also shows the similarity range of annual average temperature value from about 16-29 ^{o}C. These two regional modes show excellent performance. These two models much agree well to each other.

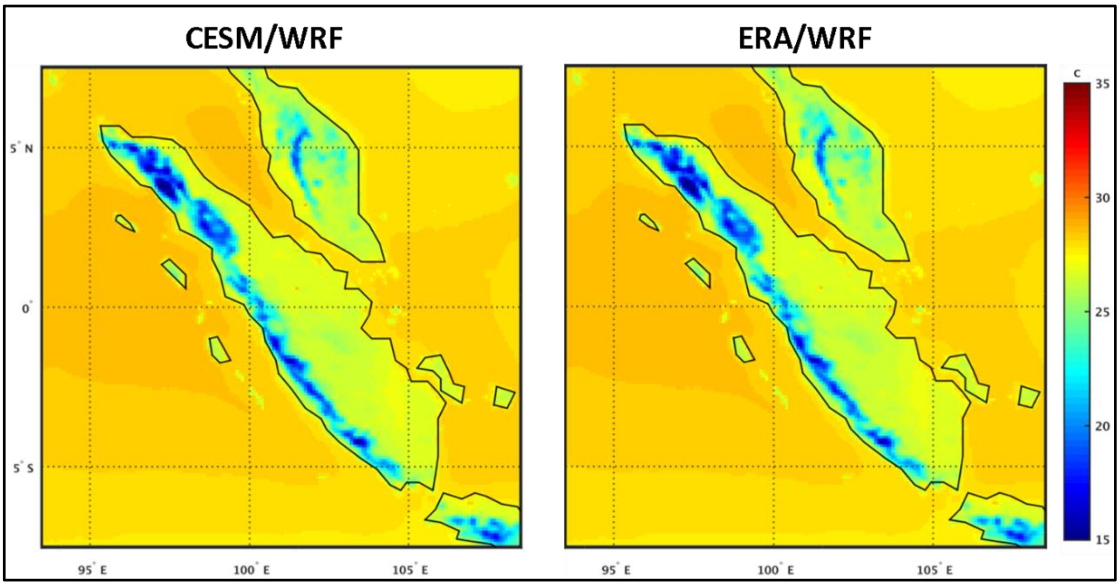

Figure 4.10 The comparison of annual average temperature 20 years period (1980-1999) for both CESM/WRF and ERA/WRF model simulations

To get more accuracy models, performance metrics between CESM/WRF and ERA/WRF has also calculated as shown in Table 4.3. The value of correlation coefficient is very high between the both model simulations at high-resolution. The CC value is 0.996 (close to 1) which is the higher value statistic performance. This shows a very good model performance and gives more accuracy of pattern and temperature values in the study area. Both ME and RMSE values also shows CESM/WRF and ERA/WRF models have a very high compatibility. CESM/WRF is very high agreement with ERA/WRF.

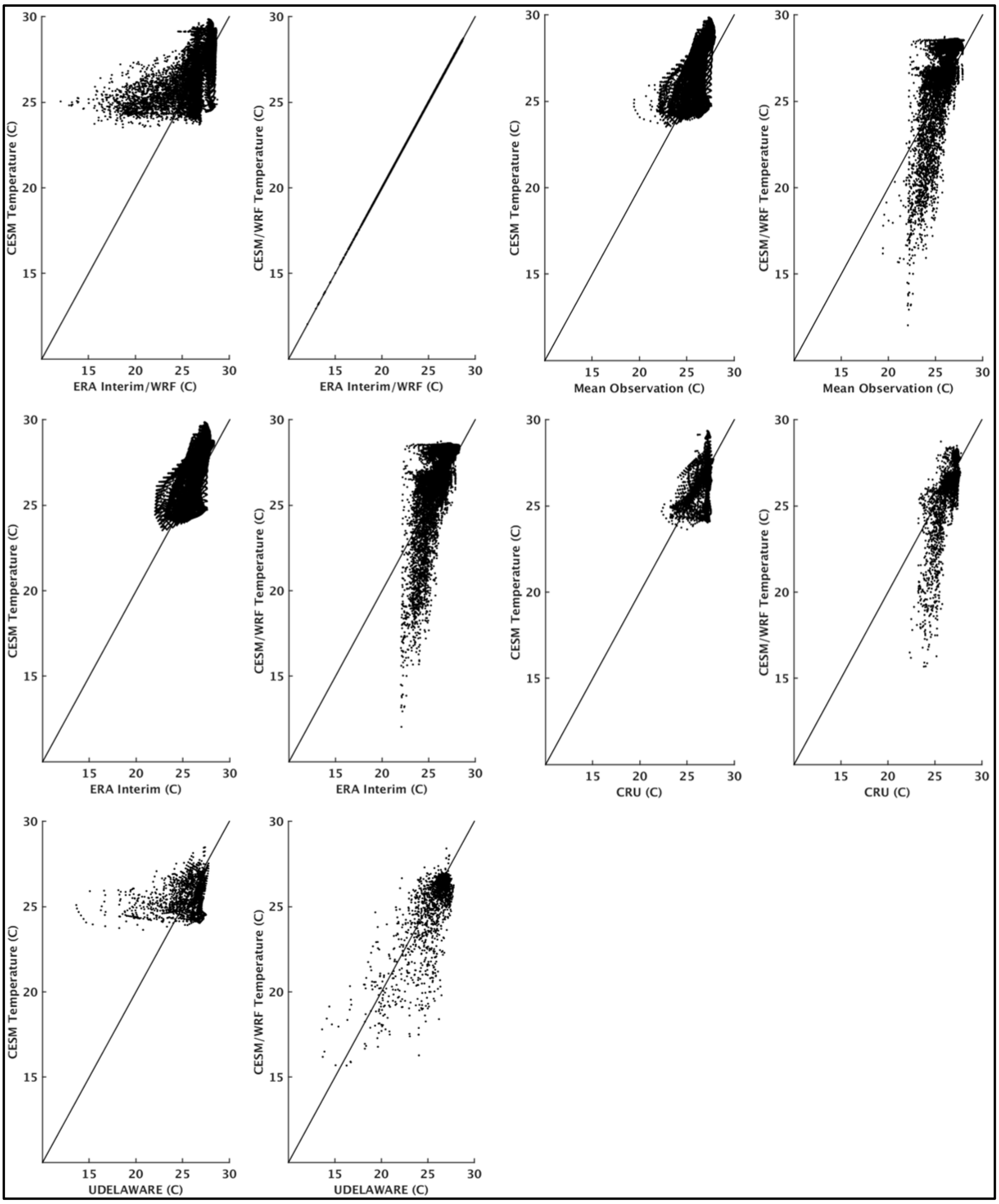

Figure 4.11 Scatter plots of annual average temperature between observed and those CESM and CESM/WRF simulation 20 years period in 1980-1999 over Sumatra

The scatter plots figure between the simulation of annual average temperature and observations is shown in the Figure 4.11. From the figure shows that downscaling using WRF increase the range of temperature values from range about 24-30 ^{o}C to range about 16-28 ^{o}C. Regional models show good performance than global models, and the simulation of temperature at high resolution is also very well suited to observations.

In addition to the scatterplot between the simulation models and observation datasets, the scatter plots between the two simulation models has also been calculated. As the figure above, CESM/WRF and ERA/WRF shows the similarity values and also have a very good performance. The values of CESM/WRF and ERA/WRF are on linear straight line. This describe that temperature values of both CESM/WRF and ERA/WRF are similar, and it shows the accurate temperature in 20 years period of 2 last decades of 20th century over Sumatra. The comparison of both CESM/WRF and ERA/WRF model simulations are helpful to determine the accuracy of the model and temperature in certain area.

From the comparison of annual average temperature patterns and performance metrics between simulation models and observations datasets, and also between the both regional models at high resolution, it can be said that downscaling global model by using WRF shows excellent performance in the study area. Downscaling using WRF can be applied to validate a model and can also provide more detailed and more accurate information on climate models.

4.3.2 Seasonal temperature

As an annual temperature, the comparison between WRF models and observation has also been calculated for both wet and dry season temperatures. The estimates of these season's temperature aim to provide more accuracy of climate models in specific study areas of temperature patterns. In the rainy season, the temperature of the model simulation using WRF shows the same pattern with the observation as shown in the Figure 4.12. Temperature patterns of the WRF model simulations have a cold pattern in mountainous areas along the west coast of Sumatra. The global model shows a high temperature pattern almost all the island of Sumatra. From global models we cannot distinguish temperature patterns that occur in areas that have high and low altitude. In the global model, the rainy season temperatures have a range of temperature values for both land and sea is 24-26 ^{o}C and 29-31 ^{o}C, respectively. Downscaling using WRF improve the performance of the model and provide clearer information about the temperatures occurring in the study area.

In the rainy season, downscaling global model by using WRF increase the range temperature values for both land and ocean about 16-25 ^{o}C and 27-29 ^{o}C, respectively. In addition, model simulations at high resolution made the temperature patterns in the rainy season seem more real and in line with the facts.

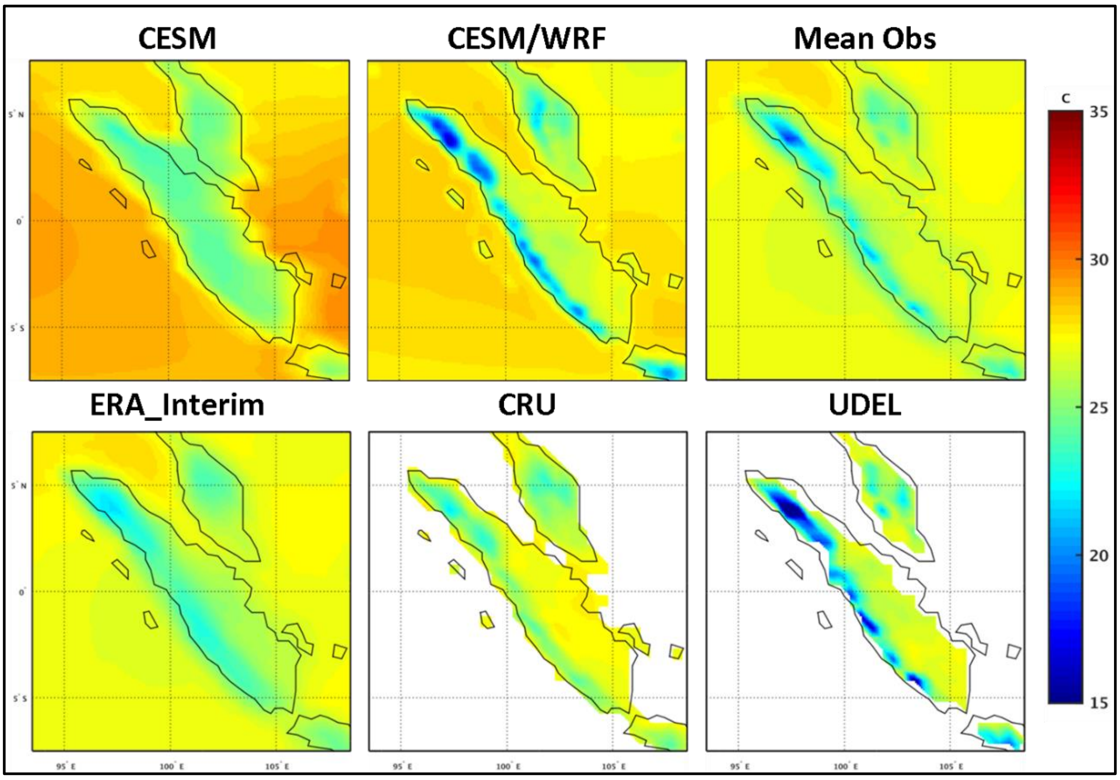

Figure 4.12 Climatological of rainy season temperatures 20 years (1980-1999) for observation datasets and those global models and WRF model simulations

To validate the existing temperature models in the study area, the estimation of rainy seasonal temperature is not only done between the model simulation and observations, but also between the two model simulations using WRF. The comparison of temperature patterns of both model simulations at high resolution during the rainy season is shown in the Figure 4.13. The figure shows that the downscaling global and reanalysis models by using WRF contributes a very good model and has the same rainy season temperature patterns. CESM/WRF agree well with ERA/WRF. CESM/WRF shows a very good performance and a very suitable pattern to ERA/WRF. It can be said that the temperature patterns of the rainy season during the 20 years period in the study area is very accurate. This temperature patterns can be used as reference temperature in the rainy season over Sumatra.

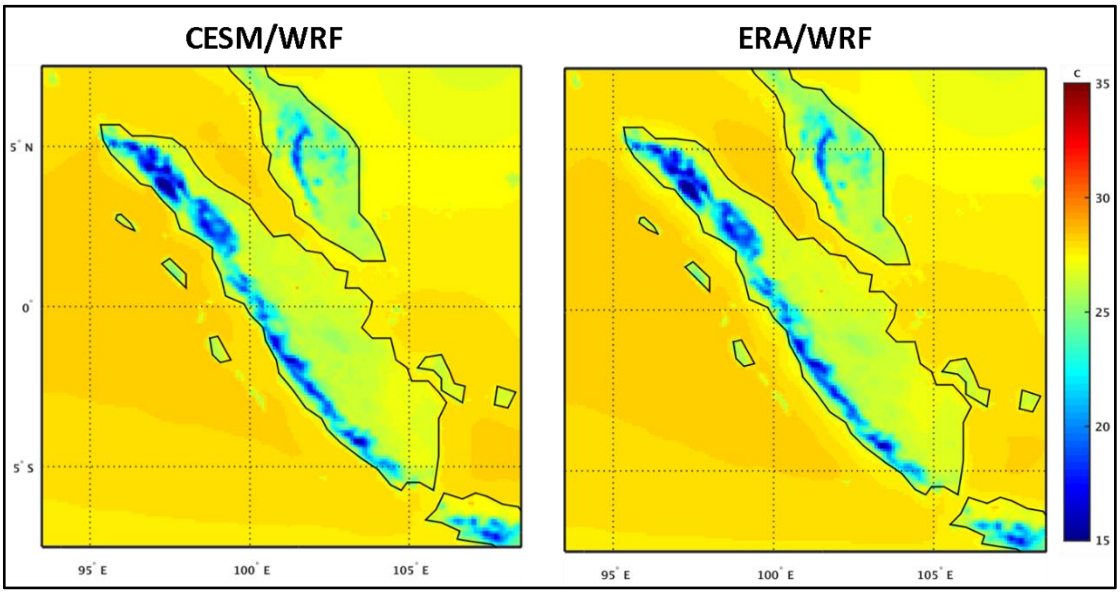

Figure 4.13 The comparison of rainy season temperatures 20 years period (1980-1999) for CESM/WRF and ERA/WRF model simulations

As mentioned above, the comparison of dry season temperature patterns over a 20-year period between the simulation and observation models can be seen in the Figure 4.14. Similarity in the rainy season, the temperature of the model simulations in the dry season has a pattern corresponding to the observation. Regional models also show good performance as compared to global models. Temperature patterns and values between regional models and global models are very much different. Global model has a very high temperature values throughout the ocean of the study area. Global model also does not show different patterns between areas with high and low altitude. In other words, the patterns and values of the temperature of the global model are almost the same for all the mainland regions of the Sumatra island.

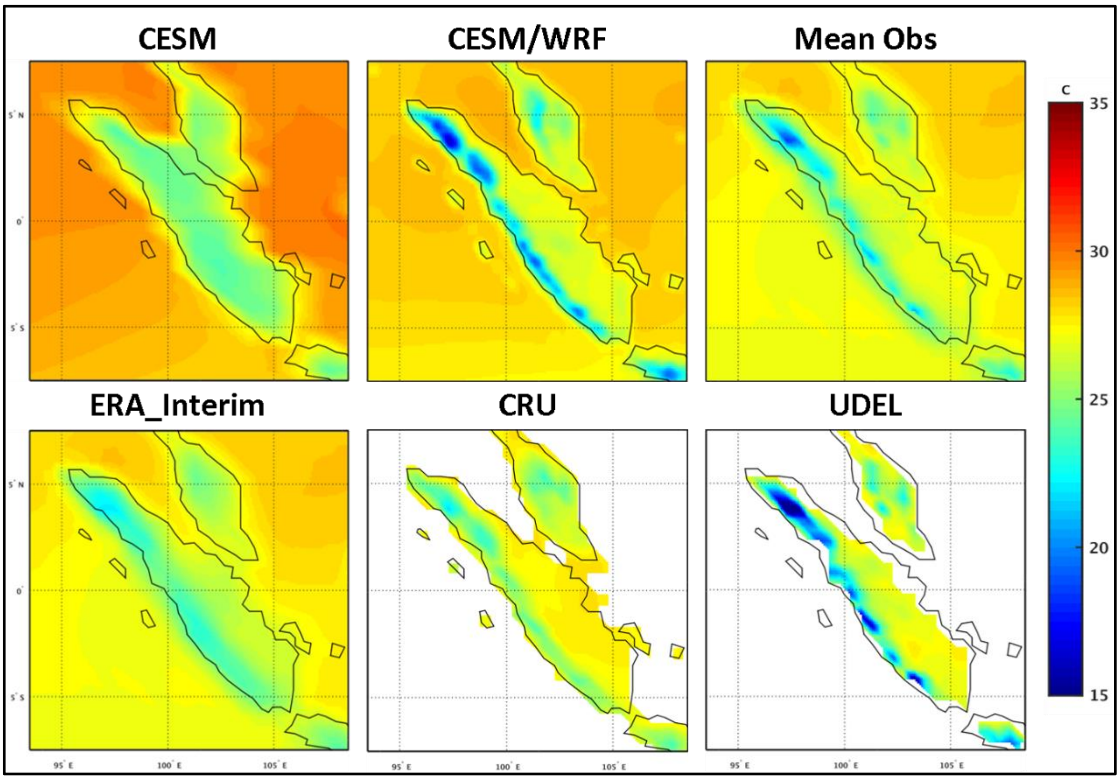

Figure 4.14 Climatological of dry season temperatures 20 years period (1980-1999) for observation datasets and those global models and WRF model simulations

To obtain the accuracy of the model and information, the temperature in the dry season is not only compared between the simulation model and observations, but between the both model simulations by using WRF model as well. CESM/WRF and ERA/WRF also show the suitability of patterns and temperature values in the dry season as shown in Figure 4.15.

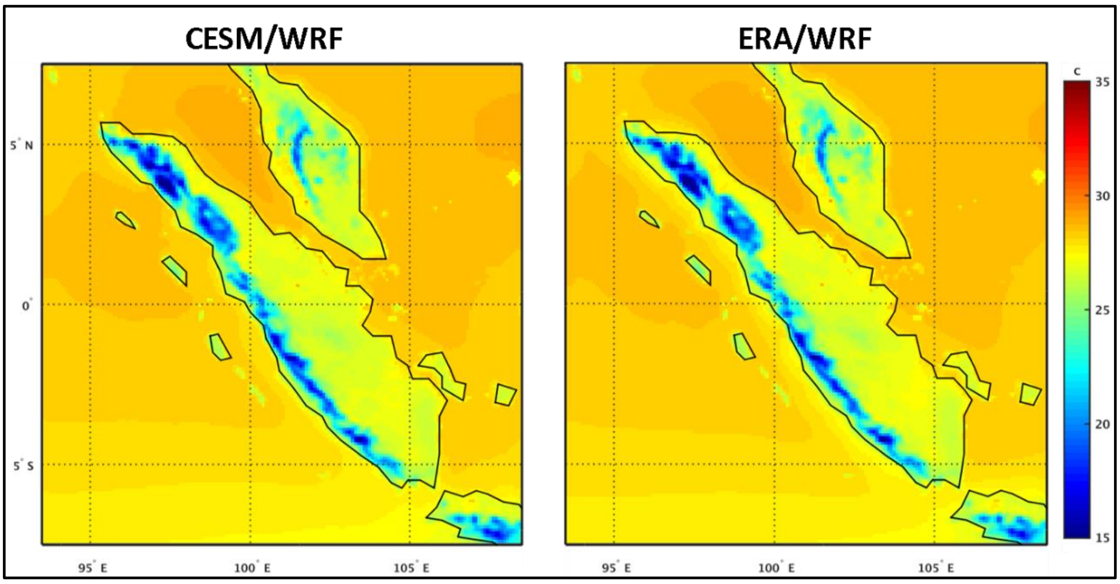

Figure 4.15 The comparison of dry season temperature 20 years period (1980-1999) for both CESM/WRF and ERA/WRF model simulations

In the dry season, both CESM/WRF and ERA/WRF show the temperature still low along the west coast of Sumatra. The low temperature is located in the high mountains area. Besides, the high temperature is over the sea of study area. from this comparison, CESM/WRF and ERA/WRF show agree well temperature pattern of dry season, and we get more information about climatological temperature models in specifics area over Sumatra. The WRF model's performance very well to simulated climatological precipitation and temperature model over study area.

CHAPTER 5
CONSCLUSION

5.1 Conclusion

Climate model 10-km resolution has been completed using WRF to simulate and evaluate climate model at regional scales over Sumatra. Both global models (GCMs) and reanalysis data have been dynamical downscaled by WRF to produce high-resolution present climate simulation (1980-1999) over Sumatra. The GCM and reanalysis data driven by CESM and ERA-Interim reanalysis, respectively. This thesis has been simulated precipitation and temperature, including annual and seasonal. The conclusions of evaluation climate model in this thesis are:

1. The WRF model is a very useful tool to simulate regional climate models for Sumatra. The WRF is able to improve spatial scales that cannot provided by GCMs. The WRF in its use is able to distribute precipitation and temperature across Sumatra accurately. It does not only capture the broad gradients that characterized the large scale but also incorporates the topographical effects on regional climate.
2. The WRF model enable the study of climate on annual, seasonal, and extreme event. WRF a suitable tool to address changes in both the long-term means and the extreme events. Downscaling GCM using WRF improves the performance of climate simulations, it is not only on the range of climate model values but also performance metrics of climate simulations.
3. The annual and seasonal cycle of local precipitation are produced at high resolution. Local precipitation at high resolution produce details information and more accurate. The high precipitation is along the west coast of Sumatra and over the sea southwest of Sumatra. Furthermore, the low precipitation is over the sea northeast of Sumatra. The precipitation simulations at regional agree well with observations in the pattern but different in the value. The comparison of WRF model precipitations between CESM-driven and ERA-Interim-driven is excellent

agreement with the correlation coefficient is 0.935. The CC significantly improve from -0.086 by CESM global model.

4. Local temperature is highly accurately simulated at all timescales. The most of differences between the simulations and observations due to resolutions, which is still low resolution of observation datasets. The WRF model improve the temperature range to about 16-29 ^{o}C from short range about 24-30 ^{o}C of global temperature. Regional temperature is very strong cold pattern over high mountains along the west of Sumatra. CESM/WRF provide highly similarity temperatures with ERA/WRF in pattern and values, and high correlation. The CC between both of WRF model simulations is 0.996. It is extremely high correlation in a comparison model data.
5. The WRF model work well to simulate climate model in the Sumatra. WRF model provide detail information and more accurate climate model simulation. WRF can be apply to downscale, simulate, and evaluate climate model in tropics. Furthermore, CESM global model can be using to predict climate change in the future climate especially for Sumatra.

5.2 Suggestion

To prove the global CESM model capabilities simulates and predict climatological models such as precipitation and temperature more accurately and more precisely in a region specially in Sumatra, it is best to evaluate the climatological model of the CESM model for the first decade of this 21st century over Sumatra using WRF model at high resolution so that get the CESM model performance on the climatological model in certain areas accurately for the future climate and more obtained information.

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