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The Impact of Explicit Convection on the Asian Monsoon and the Indian Ocean Wet Bias

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THE IMPACT OF EXPLICIT CONVECTION ON THE ASIAN MONSOON AND THE INDIAN OCEAN WET BIAS

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Dayang Norazila Awang Bima

Abstract

The performance of general circulation models (GCMs) in predicting monsoon is still remain challenging particularly for Asian summer monsoon. Progressive development of parameterization schemes which are the simplified technique that able to represent the monsoon physical process in GCMs are needed for better monsoon prediction. However, many GCMs simulate unrealistic location, size and its intensity which will cause the biases in model-simulated monsoon precipitation. This study is conducted to investigate the sensitivity of the model when the convective parameterization is turned on and off during Asian summer monsoon. In order to comply with these objectives, the output data for June to September (JJAS) over 4 years period at 0.176° latitude x 0.234° longitude resolution of Unified Model (MetUM) were analyzed. We examine whether model without convective parameterization shows a higher dependence of precipitation on moisture. The study is specifically focused on three regions namely India, Indian Ocean and warm pool with three different parameters: precipitation, column water vapour and wind. It is found that several changes were observed when the parameterization is turned off and the changes are more obvious over the warm pool and Indian Ocean compared to India region. The intensity and location of the precipitation and water vapour also affected with the model without parameterization. Less changes in wind pattern was observed over Indian Ocean and warm pool but changes are more obvious over India region. Precipitation from explicit convection has a higher dependence on moisture than parameterized convection.

CHAPTER 1: INTRODUCTION

The monsoon is an important element of the global circulation and its precipitation provides water needed by more than 60% of the global population. Apart from become as a main source for hydrological cycle, the impacts of monsoon also can cause property damage and loss of thousands of lives. We have witnessed the recent monsoon extreme event occurred over India involving thousands of lives and great number of properties destroyed. The impact of monsoon variability is significantly associated with the source of economy for certain countries such as India, whose agricultural sector depends largely on the monsoon variation. More reliable monsoon prediction is needed in order to minimizing the impacts as well as maximizing the benefits from monsoon. In this first chapter, we will discuss about the monsoon and its characteristics.

1.1 Definition of monsoon

Monsoon originated from Arabic word ‘mausim’ which refers to a season and is used to describe the seasonal reversals of wind direction between winter and summer along the shore of Indian Ocean, particularly in the Arabian Sea (Das, 1972). Ramage (1971) defined existence of monsoon by referring to an earlier work by Khromov (1957) as discussed in his study with these criteria; prevailing wind direction shifts by at least 120° between January and July, prevailing wind direction persists 40% of the time in January and July by average, mean wind in either month exceed 3 m s^{-1} and fewer than one cyclone-anticyclone alternation occurs in a 5° latitude-longitude rectangle for every two years in either month. Ramage emphasized that the monsoon region is between 35°N and 25°S and between 30°W and 170°E which is the only region that satisfy the aforementioned monsoon criteria (Figure 1).

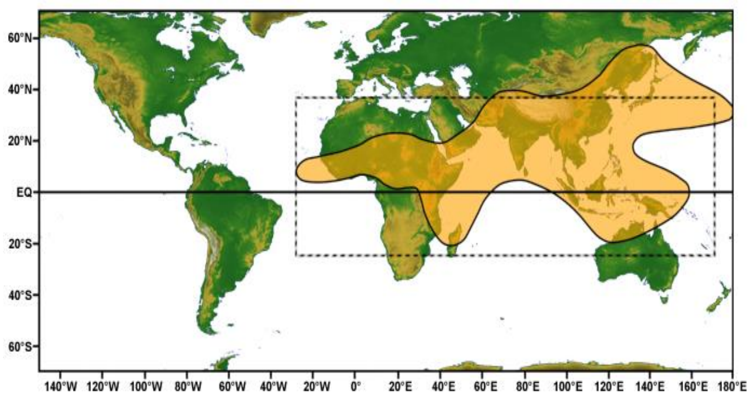


Figure 1: Rectangle encloses monsoon region (hatched areas are monsoonal according to Khromov, 1957) that satisfy the surface wind criteria as defined by Ramage (35°N and 25°S and between 30°W and 170°E). Image is reproduced by MetEd (https://www.meted.ucar.edu/).

Slingo (2003) instead characterized monsoon as a wind regime that is steady, sustained and driven by seasonally evolving sea and continental temperature. Slingo further agreed with Ramage in which she described the major monsoon areasover India and Southeast Asia, northern Australia and West and central Africa (Figure 1).

Figure 2 below show how the monsoonal flow pattern in winter and summer. Note that winter monsoon of one hemisphere feeding the summer monsoon of the other and this closely linked caused the dry air from winter continent flows across equator heading to summer hemisphere and moves rainfall to the opposite hemisphere (Slingo, 2003).

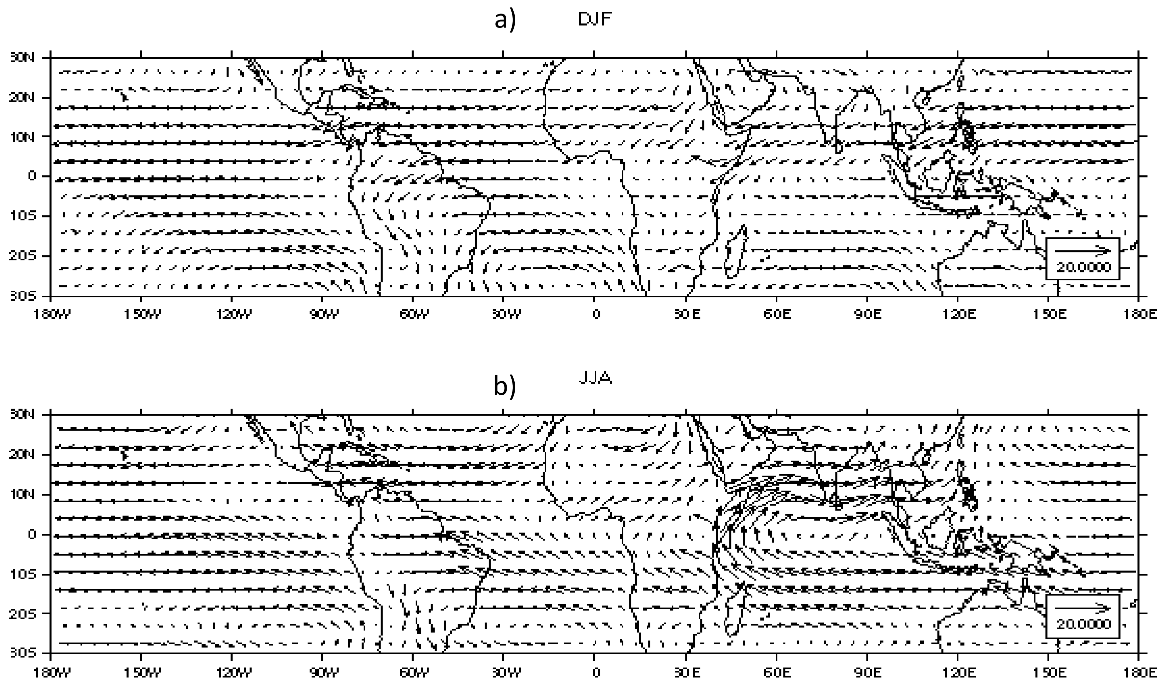


Figure 2: Reanalysis ERA-40 mean winds at 850 hPa with magnitude 20 m s^{-1} for (a) northern winter (DJF) and northern summer (JJA) averaged over 1957-2002.

1.2 Driving mechanisms of the monsoon

Monsoons arise due to the development of cross-equatorial pressure gradients that result from the land-ocean heating contrast, which was produced by different heat capacity of land and water and the rotation of the earth (Webster, 1987). Other than the natural dynamical processes and rotation of the earth, influence of local effects such as geography or orography has to be considered since they affect monsoon circulation. This section will discuss the most fundamental driving mechanism of the monsoon and further details on effect of orography will be discussed in the next section.

1.2.1 Differential heating between land and ocean

Geographical orientation of lands and oceans play an important role in determines the establishment of the monsoon. As the large land masses, e.g. Asia and Africa, heat up during spring and summer, this generates the monsoon due to the thermal contrast between land and ocean (Slingo, 2003). In northern summer, sun lies over Tropic of Cancer and during this time the winds blow from oceans to the continent (Das, 1968). This is opposite with northern winter where the wind blows from continent to oceans as the sun located over Tropic of Capricorn during that time.

Das (1986) described that changes in wind system which blowing from the southwest during a part of the year and from the northeast for the rest of the year (refer Figure 2 section 1.1) are primarily brought about by differential heating of the land and the ocean. Oceans and lands respond differently towards the heat received from the sun because of their different capacities. Heat capacity is defined as the amount of heat required to raise the temperature of 1°C of a given mass of a substance. There is approximately a factor of four difference between the heat capacity of water (~4218 J kg^{-1} K^{-1}) and dry land (~1300 J $kg^{-1}K^{-1}$). Thus for some net heating rate, the temperature for a mass of dry land will increase nearly four times more than in a similar mass of water (Webster and Fasullo, 2003).

According to Das (1968), most of solar energy is used up in heating the air rather than the earth's surface. Solar energy hardly penetrates into soil rather than oceans and this is due to the structure and soil composition that caused a slow process of heat conduction into the earth. In consequence, the air temperature much increases over land than over the oceans in the northern summer and the process is reversed in northern winter (Figure 3), where the larger heat storage of water result to warmer temperatures over oceans than land.

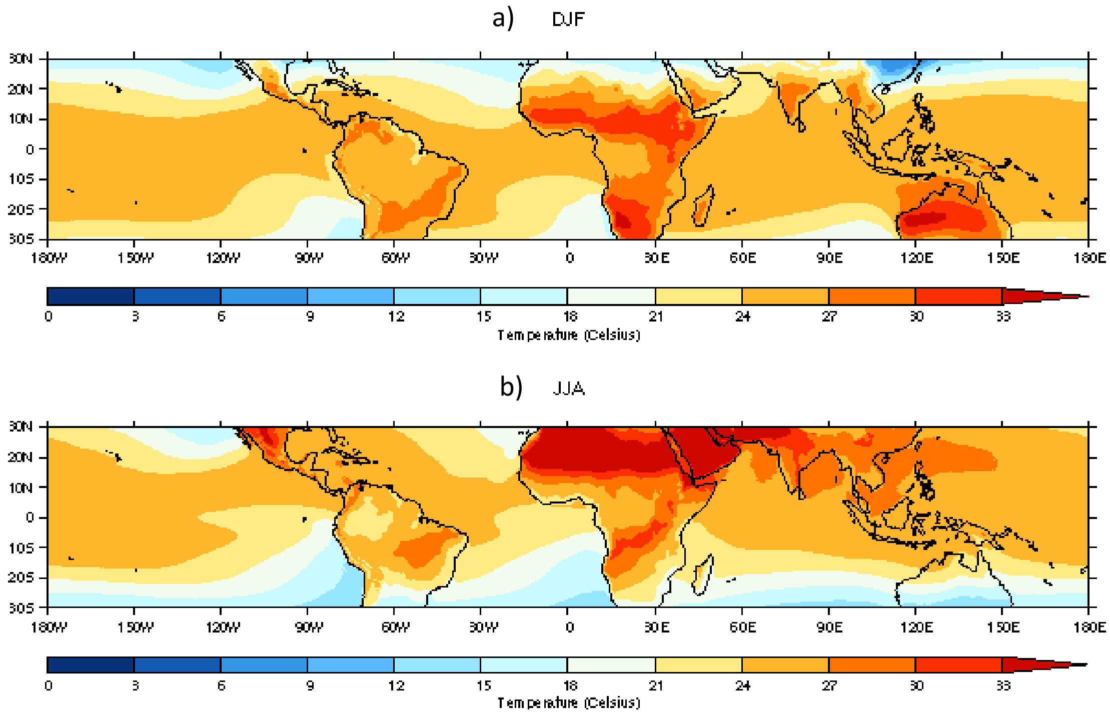


Figure 3: Mean surface temperature (units: °C) from ERA interim reanalysis for (a) winter and (b) summer from year 1979-2008.

Webster (1987) has outlined a similar argument to Das where he discussed how different capacities produce motion and monsoon circulation. Figure 4 summarized the process of the heating as described by Webster. The air over the land is heated continuously during late spring and early summer, while the air over ocean continues to cool. Furthermore, this continuous differential heating helps to maintain the column of denser air over the ocean and less dense column over the land. Hence, a pressure gradient force (PGF) between land and ocean is maintained and this drives the winds from high to low pressure. The combination of the resulting pressure gradient with continuous differential heating will then create a continuous vertically-overturning monsoon circulation.

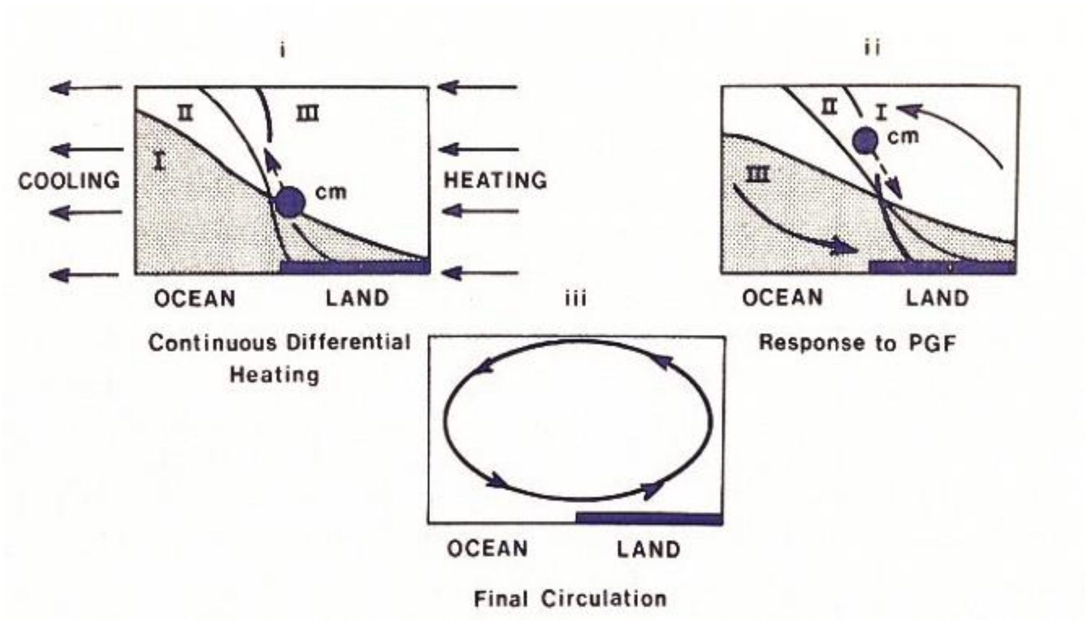


Figure 4: Continuous differential heating that creates monsoon circulation as described by Webster (1987). (i) Differential heating raises the system center of mass (cm) thus increases its potential energy. PGF is maintained by stages as signified with I, II and III and this (ii) will then causes motion which reverses the process and lowering the center of mass of the system and potential energy will decrease. (iii) Monsoon circulation established results from the combination of continuous differential heating and motion induced by PGF. Image by Webster (1987).

The changes of the winds system are similar to the sea breezes except sea breezes occur on small scales of space and time and are unaffected by the Earth's rotation as well as seasonal variations in the position of the sun. For monsoon, the warm land masses drag in the humid air released by the surrounding oceans and when the humid air reaches the warm land, it ascends and condenses. This triggers the beginning of rainy season.

1.2.2 Impact of Earth's rotation

Previous part (section 1.2.1) explains the mechanism that drives monsoons: triggered by the processes of differential heating, followed by the uneven heat capacities between land and ocean and influence of PGF that drives the winds from high to low pressure region. Another most fundamental driving mechanisms of monsoon as described by Webster (1987) is the swirl introduced to the winds that caused by earth's rotation. Webster claimed that swirling is caused by Coriolis force formed by earth rotation that deflects motion to the left in Southern Hemisphere and to the right in Northern Hemisphere. The magnitude of Coriolis force is maximum at the poles and equal to zero as at equator. The direct flow of air near equator from high to low that triggered by PGF is result from the weak Coriolis force in low latitudes.

However, at higher latitudes, the same PGF will deviate the motion and caused swirling substantially thus result an anti-clockwise flow around low pressure regions and clockwise flow around high pressure regions (Figure 5). Webster further explained this flow concept of motion by portraying it to Asian summer monsoon. During Asian summer monsoon, the cold air from high pressure areas of the winter hemisphere moves northward approaching the equator under the action of PGF.

The strong Coriolis force at middle latitudes deflects the flow to the left or west and reaches the equator as southeasterly winds. Weak Coriolis force over low latitudes caused the flow crosses the equator thus parallel to the PGF. As the flow crosses the equator, the Coriolis force deflects the flow to the right and reaches warm continent over Asian as strong southwesterly monsoon. This sequence flow of the air is the reason for the monsoonal flow patterns as shown in Figure 2 in earlier section.

a)

b)

c)

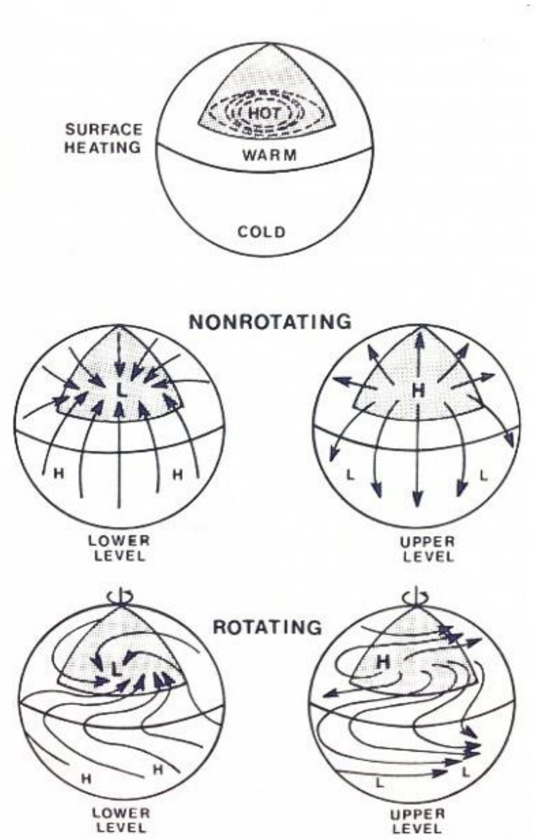


Figure 5 : The effect of earth rotation on monsoon circulation as described by Webster (1987) where the lower and upper tropospheric response during Northern Hemisphere summer due to the (a) differential heating of continent (light shaded triangular area) and ocean . Figure (b) show flows of air (represent by arrows) from high (H) to low (L) in nonrotating situation as a response to differential heating, while figure (c) represent the air flow pattern relative with rotating condition in lower and upper level. Image by Webster (1987).

1.3 Orography and the monsoon

The Eurasian continent and ocean basin includes the presence of the Tibetan Plateau; one of the most complex geographical features in the world. This highest ridge extends over the latitude-longitude domain of 25-45°N, 70-105°E and with a size approximately one-quarter of the Chinese territory and mean elevation that exceeds 4000m above sea level (Yanai and Gu, 2006). Tibetan Plateau, acts as an elevated heat source at the mid-tropospheric level that influences the establishment of Asian monsoon circulation. Despite the role of continents and oceans that provides the fundamental basis for monsoon existence, orography can serve as a large upper-tropospheric heat source for atmospheric motions besides act as a mechanical barrier to the air currents (Murakami, 1987). Murakami (1987) emphasized that during the summer monsoon, cloud development and occurrence of rainfall over southeastern Tibetan Plateau caused condensational heating that can act as sensible heat source at the mountain surface.

However, previous study conducted by Li and Yanai (1996) argue that the onset of Asian summer monsoon is occurs simultaneously with the reversal of meridional temperature gradient in the upper troposphere south of the Tibetan Plateau. They claimed that this reversal is the result of large temperature increases during early summer over Eurasia centered on the plateau with very small temperature change over Indian Ocean. During spring, the Tibetan Plateau is act as a heat source which is different from the heat source that associated with the rain belt in the equatorial Indian Ocean. Li and Yanai agreed that the Tibetan Plateau heat source is the influenced by sensible heat flux from the ground surface while the oceanic heat source is mainly contributed by the release of the latent heat of condensation which does not result in tropospheric warming due to being offset by adiabatic cooling of ascending air.

In addition, Murakami (1987) further argued that upper-tropospheric warming is cause by the combined effect of the direct heating of elevated surface and the release of latent heat in the ascending air. The combination of this upper-tropospheric warming and thermal wind balance result in upper westerlies weakening, which circulate around the southern edge of the Tibetan Plateau during winter and spring. Murakami summarized that the continuous upper-tropospheric warming causes the westerly jet to be replaced by easterly jet during early summer and the shifting occurs nearly concurrent with the onset of monsoon rains over central India.

1.4 Monsoon rainfall variability

The monsoon primarily divided into two distinct phases: wet and dry. The wet phase is normally associated with warm and moist winds blow inland from the oceans causing the rainy season, in contrast to the dry phase in which the wind reverses bringing cool and dry air from warm land. Many regions of the tropics and subtropics experience a rainy summer season and dry winter season.

The Asian summer monsoon plays an important role in moisture transport and the distribution of precipitation over the Asian monsoon region. Winds transport moisture across the Indian and Pacific Oceans during summer and produce heavy rains over adjacent land regions. The Asian monsoon that occurs from June to September, embracing the eastern hemisphere tropics and subtropics, is highly reliable on many temporal and spatial scales as a result of the dependable seasonal heating of the land with the solar cycle. The comparison between the precipitation in the two seasons depicted in Figure 6.

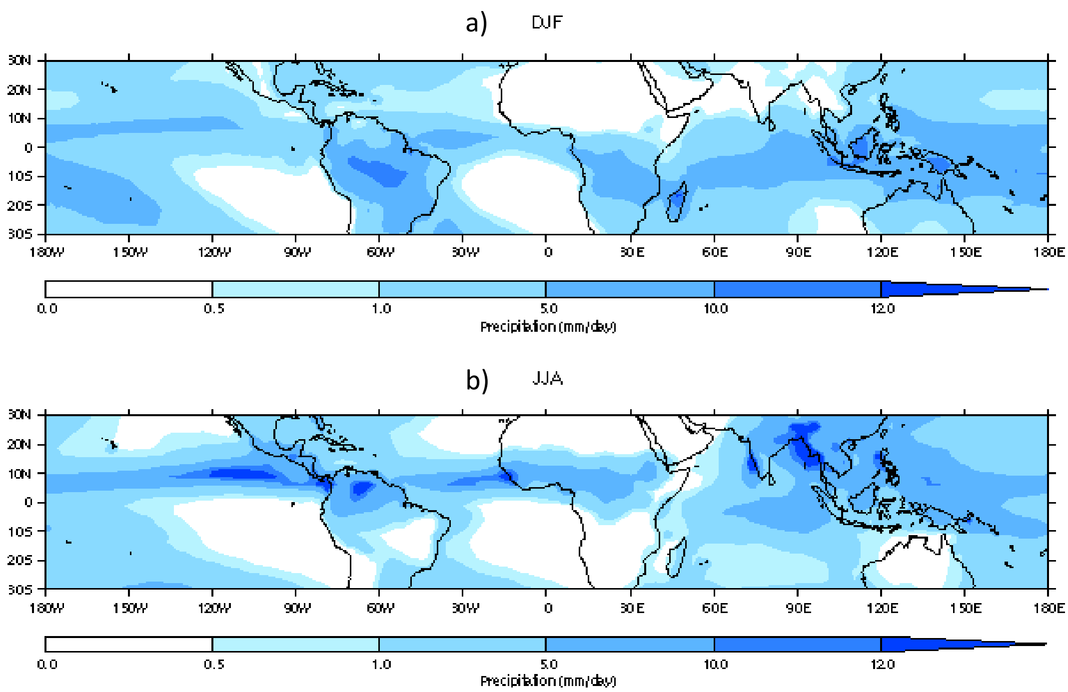


Figure 6: Mean precipitation (mm/day) distribution for (a) northern winter and (b) northern summer for year 1979- 2009 (Data source: Global Precipitation Climatology Project).

However, the large variations in the circulation and rainfall within the monsoon season influence the intensity of the seasonal mean monsoon (Shukla, 1987). Shukla has listed several factors that caused intraseasonal variability of the monsoon where the author classified them in four broad categories namely; synoptic-scale, monsoon troughs, quasi-periodic oscillations and effects of mid-latitudes. Based on the listed categories, Shukla generally related the rainfall distribution to the propagation characteristics of the synoptic-scale disturbances such as monsoon low, monsoon depressions and storms that affect particular areas. Earlier study that discussed in his paper claimed that the higher number of monsoon lows means the greater instability of monsoon trough.

The author further added that the monsoon trough position influences the monsoons condition. One case study over India as discussed by Shukla mentioned that during the break monsoons conditions, where most of central Indian regions experienced reduce rainfall for a short period, the monsoon trough shifts to its northernmost position and enhanced rainfall near the southern tip of India. However, the weakening of the trough over North India is related to the strengthening of the convergence zone near the southern tip of India and the northward shift of the monsoon trough could be associated with the mid-latitude effects and changes in the intensity of the near-equatorial trough. Shukla (1987) however summarized that in spite the impacts of intraseasonal variability of the monsoon, role of unpredictable day-to-day changes that caused by instabilities should not be ignored as the changes can influence the changes seasonally from one year to another.

Understanding the variability of monsoon is one of the approaches to improve the prediction of the date of onset and withdrawal of the monsoon and this can help in minimizing the effects and maximizing the benefits of the monsoon. According to the previous studied that been discussed in Sperber *et al.* (2012), the early warning of extreme subseasonal variation is essentially important to enable the suitable selection of alternative crops, well-planned planting times and water distribution management to help cope with the extreme monsoon events. Sperber *et al.* (2012) agreed that the improvement in monsoon predictability at any time scale requires the further understanding in the monsoon physical and dynamical processes, enhancing the observation process for a better model initial condition and more realistic of monsoon simulation in numerical prediction and climate model. Next chapter will discuss the development and several studies that have been conducted in order to achieve better prediction on monsoon.

CHAPTER 2: LITERATURE REVIEW AND METHODOLOGY

2.1 Mean state precipitation bias

Numerous research has been conducted in order to develop understanding of monsoon predictability as well as to improve the accuracy of predictions. Over the past few decades, several attempts have been made to improve the representation of the monsoon in numerical models. However, the portrayal of monsoon features in the model at regional scale still remains challenging particularly for Asian summer monsoon. Many global circulation models (GCMs) show significant biases in their simulation of monsoon rainfall and dynamics where they often simulate unrealistic location, size and intensity of the monsoon.

Boos and Hurley (2013) argued that monsoon simulations can be assessed by their skill in reproducing precipitation. Based on earlier work by others, the authors claimed that the precipitation fields are difficult to compare due to the occurrence of numerous maxima and large variance on short spatial scales. For example, they stated that even though the most of the climate models reasonably represents the regional-mean precipitation amount over South Asian and African monsoons, but the models poorly simulate the exact location and intensity of observed precipitation maxima particularly over that regions.

Bollasina and Nigam (2009) conducted a study where they examined the accuracy of the modelled air-sea interactions in the Indian Ocean during South Asian summer monsoon by using the model data from the World Climate Research Programme (WRCP) Coupled Model Intercomparison Project phase 3 (CMIP3) which involved five representative models at five different resolutions. According to their study, they found the presence of large systematic biases that frequently exceeding half of climatological values in coupled simulations of boreal summer rainfall, evaporation and sea surface temperature (SST) over the Indian Ocean. They also found that the coupled models tend to emphasize local forcing in the Indian Ocean, produce different representation of evaporation-SST correlations and misrepresented of Indian monsoon rainfall-SST relationships. They further conclude that coupled models are lacking in presenting local and non-local air-sea interactions in Indian Ocean during boreal summer.

In another case study, Bollasina and Ming (2012) argued that the bias is common for either coupled or uncoupled model thus indicating that the causes lie within the atmospheric component of the models and not stem from the way boundary conditions are specified. In one case study over Indian Ocean, they compared the GFDL (Geophysical Fluid Dynamics Laboratory) AM3 atmospheric model at 2° x 2.5° horizontal resolution with observations and found that the oceanic bias, which develops during spring but reduces in the monsoon, is linked to the precipitation and circulation of anomalous pattern of April-May sea surface temperatures (SST) for Indian region. They found that the model overestimates precipitation by a factor of two particularly over the central and western sections of the equatorial Indian Ocean while in the observational datasets, the heaviest April-May precipitation occurs over the eastern equatorial Indian Ocean.

The authors further emphasized that precipitation bias over the southwestern Indian Ocean is forced by the model excess response to the local meridional sea surface temperature gradient. Thus, they suggested that improvement in GCM simulations of the South Asian monsoon could be achieved by reducing the spring time model bias over southwestern equatorial Indian Ocean particularly by more focus on studying the deficiencies in atmospheric model such as issues in convective parameterization which will be discussed later in Section 2.2.

Annamalai *et al.* (2007) examined the data output from eighteen models at different resolutions in order to analyse the monsoon precipitation climatology in the twentieth century integrations. They simulated the June-September (JJAS) rainfall climatology over India and a larger monsoon domain which encloses a region between 25°S-40°N and 40°E-180°E. They used the pattern correlations and root-mean-square differences (RMSDs) that relative to the observed rainfall to further analyse the data and found that six out of the eighteen models produced simulations of JJAS rainfall with highest pattern correlation and lowest RMSD. They also found that the modelled rainfall has a stronger correlation with observed rainfall over eastern equatorial Indian Ocean (10°S-0°, 90°-110°E) but not for India summer monsoon region (10°-25°N, 70°-100°E). The models also difficult to capture the regional details in precipitation over India where they showed a high rainfall along the west coast and a weaker JJAS rainfall intensity when compared to observed.

Gadgil and Sajani (1998) agreed that simulation of the monsoon rainfall over India is sensitive to the physical parameterizations and resolution. They analysed monsoon precipitation in the 30 Atmospheric Model Intercomparison Project (AMIP) models with resolution of T62L28 (approximately 200 km resolution) that associated with the African, Indian and the Australian-Indonesian monsoon as well as the interannual variation. They argued that almost all models reasonably simulated the migration of the major rainbelt observed over the African region. However, for the Asia Pacific the situation is more complex due to the presence of warm oceans equatorward of heated continents. Following this result, they divided the models into 2 categories according to the basis of the seasonal variation of the major rainbelt over the Asia-West Pacific sector. Class I described models with a realistic simulation of the seasonal migration of the major rainbelt over the continent in the boreal summer, while Class II contains models with a smaller amplitude of the seasonal migration than observed. They found that skill in simulation of excess or deficit summer monsoon rainfall over the Indian region is larger for models of Class I when compared to Class II. The authors further analysed seasonal mean patterns based on the classification and found that the mean rainfall pattern of models in Class I is highly correlated and closer to the observed pattern than Class II models. Furthermore, Gadgil and Sajani concluded that in order to obtained realistic simulation of the interannual variation of all-India monsoon precipitation which associated with ENSO events, the focus should be on improvement of the simulation of the seasonal variation over the Asia-West Pacific sector rather than further improvement of the simulation of the mean rainfall pattern over the Indian region.

2.2 Parameterization of cumulus convection

Theoretical understanding of climate is still incomplete and the imperfections of the model in representing simulation have become major issues that draw attention and criticism. In building a model, a complete set of dynamical equations such as equations of motion, continuity equation, thermodynamics and moisture equation is needed in order to describe the evolution of the atmosphere. Calculations of the equations using global models can still only afford grid-spacing where many of the important physical processes such as radiation, condensation, transfer of heat as well as cloud processes remain unresolved (Jakob, 2010). Such physical processes occur at a scale much smaller than the grid interval cannot be eliminated and simplifying technique to achieve this representation is called parameterization. However, models with high-resolution e.g 1-2 km can be run without parameterization convection due to the grid spacing that small enough to resolve the convective process but this will require a very large computing resources and also will cause a limitation in the domain size that will be covered.

During the last few decades, impressive progress in the improvement of parameterizations schemes has been achieved. Even though there are progressive development of parameterizations schemes and some successes in representation of subgrid-scale processes, the solution to long-standing model problems remain elusive (Jakob, 2010) where most of the global climate model show significant biases in their simulation of monsoon rainfall and dynamics. Since the focus on this research is on the explicit convection in the Asian monsoon and its sensitivity upon parameterization, studies of parameterizations schemes will not be reviewed in depth, and only referred when appropriate.

2.2.1 Sensitivity to parameterization

The areas of clouds must be defined before starting to simulate any rainfall. Cloud, especially cumulus is an important ingredient of convection that determines precipitation and key processes of the hydrological and energy cycles (Rooy *et al.*, 2013). Rooy *et al.* (2013) summarized that one of the most common ways to parameterise the vertical transport of heat, moisture and momentum which develops cumulus convection is via mass flux schemes. This scheme quantifies the amount of mass that is transported in the vertical. However, previous studies found that models simulated different sensitivity of monsoon according to their parameterization schemes.

Ratnam *et al.* (2005) conducted a study on the sensitivity of the simulated monsoons to three convective parameterization schemes; Betts-Miller Janjic, Kain-Fritsch and Grell. In their study, they used mesoscale model (MM5) version 3.5.2 with a domain covering the area 10°S–40°N, 39°–111°E and a horizontal resolution of 45 km to simulate the Indian summer monsoon between two years, 1987 and 1988. They found that those three schemes are able to reasonably simulate the interannual and intraseasonnal variability in the monsoon. However, each scheme showed significantly different spatial distribution of rainfall and its quantity. This has been agreed by Yavinchan *et al.* (2011) where in their study they used the same mesoscale model and parameterization schemes but with 5 km resolution and addition of unparameterized or explicit (EX) scheme. However, their study focus on three heavy rainfall events in the northeast monsoon which causing floods and damage in southern Thailand and compared it with Tropical Rainfall Measuring Mission (TRMM) maps and found that the model underestimated the heavy rainfall amounts and the widely different rainfall patterns were produced by the different schemes used.

Generally, the improvement of models is strongly associated with the improvement of convective parameterizations. Several studies showed impressive progress in the development of parameterization. For example, Zachary *et al.* (1999) have tested some modifications to the parameterization in their study. They investigated the dependence of the Asian summer monsoon on parameterized physical processes in a Colorado State University (CSU) general circulation model (GCM) with a fairly coarse horizontal grid spacing of 4° in the meridional and 5° in the zonal direction. In this study, they replace the cumulus parameterization, land-surface parameterization and the stratiform cloud parameterization to examine the sensitivity of Asian summer monsoon simulation. They changing the baseline version, which they referred as oldest version of model components under study that include a 'bucket-model' land-surface parameterization, 'large scale saturation' of stratiform processes and 'low-α' version of cumulus parameterization. The improve land-surface that they use as the replacement is SiB2 which will consider the effects of vegetation on the surface fluxes of energy and water which is completely different with baseline version.

They argued that baseline version of the general circulation model failed to simulate the precipitation, wind and temperature fields and gave a very poor simulation of monsoon. Furthermore, they found that improvements in the component tested and altered had improved the representation of monsoon and represented a much more realistic geographical pattern of precipitation along with more realistic lower tropospheric winds except with some serious errors remaining for upper tropospheric wind and temperature fields.

A recent study conducted by Holloway *et al.* (2012) argued that global climate and weather models tend to produce too frequent low intensity rainfall over the tropical ocean. In their study, they simulated the different runs for the same model using different horizontal resolutions in order to examine the comparison between parameterized and unparameterized convection, which for this whole study we will refer it as explicit convection, for large cases over the Indian and West Pacific oceans domain. They found that parameterized convection with 12 km grid length simulated too many occurrences of light rain but underestimate heavier rain when interpolated onto 1° grid and compared with TRMM while, explicit convection with 4 km grid length produce rainfall distributions much more similar to TRMM observation. In addition, the authors further concluded that coarser resolution models with explicit convection tend to have even more heavy rain than observed.

This finding is quite similar with research done by Yavinchan *et al.* (2011) which have been discussed earlier where they run MM5 with three different parameterization schemes; Betts-Miller (BM), Grell (GR) and new Kain-Fritsch (KF2) and also with explicit scheme (EX) then evaluated it with TRMM. They concluded that the new Kain-Fritsch and explicit schemes generally gave better representation of monsoon precipitation than other two and found that BM and GR schemes are not suitable for precipitation predictions at 5 km. However, they expected that explicit scheme will give good rainfall prediction at sufficiently high resolution and also suggested that a parameterized cloud model as new Kain-Fritsch scheme may still help to improve the result if it is run at 5 km resolution.

2.2.2 Observed relationship between precipitation and moisture

Developing a better parameterization of cumulus convection, as well as regional moisture convergence on which the tropical precipitation is critically dependent is needed to enhance a model ability to more realistically represent monsoon rainfall. This can be achieved by understanding relationship between precipitation and column water vapour. Previous observational studies have shown a close relationship between tropical precipitation and column-integrated water vapour. A study conducted by Holloway and Neelin (2009) analysed the vertical structure of the relationship between water vapour and precipitation from five years of radiosonde and precipitation gauge data from Nauru Atmospheric Radiation Measurement (ARM) site which located in Republic of Nauru, an island in Micronesia. They found that there was a strong relationship between rainfall and moisture variability in the free troposphere as well as little boundary layer variability. They observed the slow increase of precipitation below 60 mm and a sharp pickup or increase in the precipitation occurring near a critical value of column water vapour at 66 mm and further concluded that amount of rainfall is dependent upon column water vapour.

An earlier study by Bretherthon *et al.* (2004), which retrieved 4 years of gridded daily Special Sensor Microwave Imager (SSM/I) satellite microwave radiometer data to investigate the relationship between water vapour path *W* and surface precipitation rate *P* over 4 tropical oceanic regions namely: Indian Ocean, west Pacific, East Pacific and Atlantic Ocean on daily to seasonal time scales. They observed that all the four regions showed a rapidly increasing in precipitation *P* with water vapour path *W* and also found that west Pacific and Indian Ocean give a smaller *P* for a given *W*. Furthermore, they also observed the number of gridpoint months in each region is well-distributed in *W* bins between 30-50 mm and rapidly fall toward zero when *W* exceed 55 mm especially in the Atlantic region.

One study conducted by Neelin *et al.* (2009) outlined a similar result and they agreed that rainfall and column-integrated water vapour are closely related in the tropics. They claimed that the column water vapour is temperature dependence and following the observation from previous studies, they investigate the relationship between precipitation and column water vapour with further analysed the effect of SST on the relationship. They found that precipitation increases with column water vapour and a sharp increase was observed near a critical value which they related it to a peak in precipitation variance near critical column water vapour. They claimed that the sharp pickup of the precipitation is not affected much by SST. They found that the SST has a large impact on the column water vapour values where they observed that the column water vapour will reach its critical value at warmer SST. In their study, they obtained critical value (at 56-70 mm) of column water vapour at SST around 268-274 K. However, they further concluded that at near of above the critical value, where most precipitation occurs, the column-integrated water vapour distribution is highly constrained by the interaction with convection and this will cause a dramatically drop of precipitation.

Following this observation, Muller *et al.* (2009) created a physically-based two-layer model that can reproduces the observed humidity-rainfall relationship in order to investigate the sharp increase in rainfall at critical value of column water vapour as shown by Neelin *et al.* (2009). Their observation agreed with previous studies where they found that the amount of rainfall is depends on column-integrated humidity. Furthermore, their model also showed the rapidly increasing in rainfall when column-integrated humidity close to a critical value and decreases at very high humidity.

2.2.3 Parameterized relationship between precipitation and moisture

Generally, many parameterizations are not sufficiently sensitive to tropospheric humidity variability. Several studies have been conducted to identify the impacts of mid-tropospheric humidity on convection; however, the implication for parameterization is still not well understood. A study conducted by Derbyshire *et al.* (2004) seeks the sensitivity of cumulus convection to humidity in the free troposphere by using cloud resolving models (CRM) and comparisons with parallel single-column model (SCM). CRM can be defined as a model which have enough resolution to represent individual cloud elements as well as large enough to encompass many cloud systems over long lifetime of the cloud (Randall *et al*., 2003). This CRM is different with SCM in which SCM are the single grid column-physics components of GCM which are extracted from their main GCM and isolated.

In their study, Derbyshire *et al*. (2004) firstly specified the humidity intercomparison case between CRM and SCM by using target profiles for potential temperature and humidity where they divided the specification into three layer namely: a ‘boundary layer’ below 1 km, a ‘transition layer’ approximately 1-2 km and ‘free troposphere’ above 2 km. They found that two tested CRMs show a strong deep precipitating convection in more humid case but not in driest case. They also found that all the tested SCMs show some humidity sensitivity in precipitation but in different humidity environments that shown by CRMs.

Del Genio (2012) argued that the insufficient sensitivity of parameterized to tropospheric humidity can be caused by underestimated entrainment of environmental air into rising convective clouds and also insufficient evaporation of rain into the environment. Here, the entrainment rate is generally described as inflow of air into cumulus clouds and it is an important element in the aforementioned mass-flux approach to the parameterization of moist convection (de Rooy *et al*., 2013). This cause the parameterizations to produce deep convection too easily and at the same time stabilizing the environment too quickly in order to allow the occurrence of convective mesoscale organization effect which is more organized convective elements that develop longer than individual convective elements. He further emphasized that the lack of sensitivity of the models to tropospheric humidity will cause perturbation in model ensembles that this can affect global climate model simulations of climate sensitivity. These are used to measure the changes in temperature of the climate system to external forcing. This perturbation also affects the continental diurnal cycle of clouds, precipitation and the variation of intraseasonal precipitation.

2.3 Sensitivity of High Resolution model

In previous section, we have discussed the sensitivity of the monsoon simulation to parameterization. However, the appropriate parameterization may depend on the resolution of the model. Climate models require fine resolution to represent the climate processes. Based on previous studies, Mukhopadhyay *et al*. (2010) summarized that high resolution regional models embedded in a GCM are able to show an improvement in the spatiotemporal distribution of monsoon precipitation with increased in models resolution. However, Mukhopadhyay *et al*. (2010) argued that simulation of precipitation is mainly dependence upon convective parameterization in the model and it is crucial to identify the most suitable convective parameterization schemes for the resolution of the model in order to realistically represent monsoon rainfall climatology.

Yihua *et al*. (2002) emphasized that the most excellent horizontal model resolution that provides the best representation of the model physics is always desirable. They further argued that despite the fact that sub-grid processes cannot be represented very well in a model with coarse resolution, the reason for horizontal model resolution affecting mesoscale circulation features and rainfall prediction is because almost all physical parameterizations in numerical model are too sensitive to the horizontal resolution of the model. In their study, they investigate the effect of horizontal model resolution and topography on the simulated summer monsoon flow and rainfall. With one case study of the India region, they found that both the distribution and intensity of simulated southwest monsoon precipitation over India is highly sensitive to model horizontal resolution and topography. They used a triple-nested regional model, a modified version of the regional weather prediction model that originally developed at the Naval Research Laboratory and North Carolina State University. The triple-nested domain enclosed: (i) coarse resolution domain (CR) is of 8580 × 9900 km^2 size (61 × 53 grid points) with horizontal grid resolution 165 km and covering most of the monsoon region; (ii) a middle resolution domain (MR) has a size of 5280 × 3960 km^2 (97 × 73 grid points) with 55 km horizontal grid resolution and encompassing the Indian subcontinent and its surrounding oceans and (iii) an innermost fine resolution domain (FR) with 18 km horizontal grid resolution located over the middle region of India, with a size of 1320 × 1980 km^2 (109 × 73 grid points). They concluded that their model with a finer resolution is able to predict mesoscale organization of rainfall over the land mass and thus simulate better orographic mesoscale features, whereas over the coarse domain there is much less rainfall predicted than that observed due to its poor representation of orographic effects and mesoscale forcing.

A similar issue regarding the improvement in high resolution model was also addressed by Lal *et al*. (1996). They examined the ability of ECHAM3 global climate model in one case study of Indian Monsoon climatology at three different horizontal resolutions. They performed the simulation at T21 (low), T42 (medium) and T106 (high) horizontal resolutions which correspond to 600 km, 280 km and 120 km grid size respectively and found a distinct improvement in the spatial distribution and total area-averaged summer monsoon rainfall in the model with finer resolution. Furthermore, they related the underestimation of the total seasonal rainfall in the model at higher resolution with the sensitivity of simulated precipitation to local climate forcing and deficiencies of parameterization scheme for convection and land surface processes. An earlier study conducted by Martin (1998), where he investigates the quality of the simulation of the Asian summer monsoon using two atmosphere-only model that runs forced with observed sea surface temperatures (SSTs) and sea ice extents at different horizontal resolutions which are 2.5° latitude x 3.75° longitude, about 300 km at mid-latitudes and 0.833° latitude x 1.25° longitude, approximately 100 km at mid-latitudes. Martin (1998) argued that models with increased horizontal resolution have a tendency to overestimate the strength of the monsoon, and also exhibits an early monsoon onset as well as magnitude of the inter-annual variability of precipitation. However, Martin (1998) further described that the inter-annual variation in circulation and precipitation as well as the intraseasonal variability are not greatly altered and remain unaffected.

Yet, there is no single model that best portrayed all of the aspects of monsoon such as time-mean state, climatological annual cycle, inter-annual variability and intraseasonal variability. However, a recent study conducted by Sperber *et al*. (2012) comparing Coupled Model Intercomparison Project-5 (CMIP5) and Third Coupled Model Intercomparison Project (CMIP3) which are generally used in studying the output of coupled atmosphere-ocean general circulation models. Comparison between CMIP5 and CMIP3 GCM simulations showed that the CMIP5 multi-model mean(MMM,) which have higher horizontal and vertical resolution as well as have more complete representation of earth system than CMIP3 MMM is more skilful in simulating the pattern of monsoon features with respect to observations.

2.4 Motivation of the study

Current climate models are highly sensitive to the development of clouds, hydrological cycle and land surface processes. The monsoon is often associated with cumulus convection that determines precipitation. However, climate models are unable to resolve cumulus cloud-related process explicitly and in order to overcome this the process needs to be parameterized but this parameterization process is notoriously difficult. In preceding section, we have discussed the sensitivity of the monsoon simulation to the different parameterization schemes. Based on previous studies, these subgrid-scale processes need to be reformulated and must be suitable with increased horizontal resolution of the model in order to obtain a better representation of monsoon rainfall.

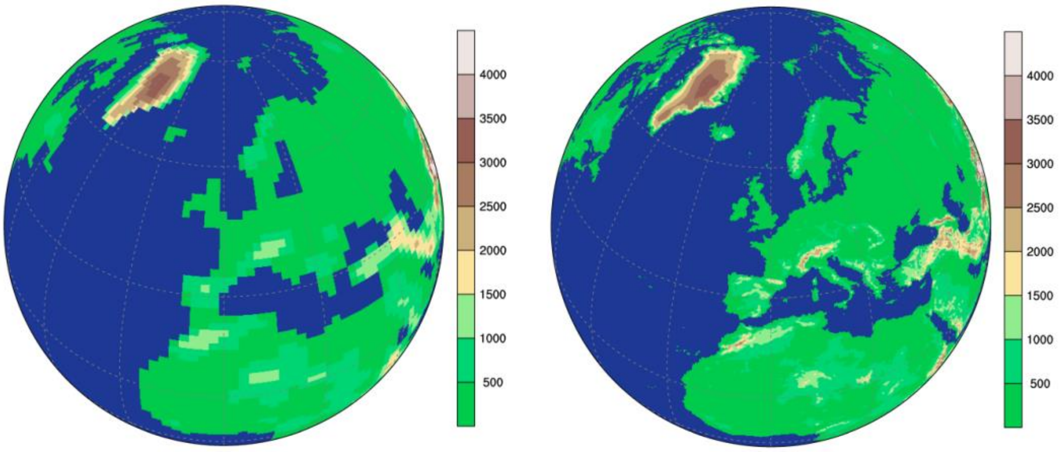
Several studies argued that the intensity and amount of monsoon precipitation produced at a grid-point is not sensitive enough to the moisture due to the bias and large errors in the monsoon precipitation simulation mostly over Indian Ocean and India region. This study will investigate the sensitivity of the model when the convective parameterization is turned on and off during Asian summer monsoon and will focus particularly over warm pool, India and Indian Ocean region. This study also examines whether model without convective parameterization shows a higher dependence of precipitation on moisture than a model with parameterized convection. Understanding the differences between parameterized and unparameterized convection which we refer as explicit convection can help us to improve convective parameterization to obtain more realistic and better simulation of the monsoon. As parameterization development remains a crucial factor for model improvement (Jakob, 2010), this investigation hopefully can be an approach to have a better weather prediction as well as more reliable climate projections in the near future.

2.5 Data and methodology

This study analysed data over three different regions namely India, Indian Ocean and warm pool with three different parameters: precipitation, column water vapour and wind. The relationship between parameters is examined later in order to investigate the effect of parameterized and explicit convection of the model. In this study, we analysed June to September (JJAS) output data from the Unified Model (MetUM), the UK Met Office's general circulation model over the period 2008-2011 (4 years). In particular, we used Global Atmosphere 4.0 (GA 4.0); a configuration of the Met Office Unified Model used in climate research and weather prediction globally and regionally according to previous studies as discussed in Walters *et al*. (2013).

Walters *et al*. (2013) defined global configuration is on 2n longitude and 1.5n + 1 of scalar grid points with scalar and zonal wind variables at the north and south poles. The integer n represents the maximum number of zonal 2 grid point waves that defined the model horizontal resolution. A model with n equal to 1024, known as N1024, has 2048 longitude points and 1537 latitude points.

Generally, in this study we used high resolution model at 0.176° latitude x 0.234° longitude resolution known as N1024. This is the highest resolution global climate model run at the Met Office to date. This is different to the standard climate model resolution of N96. The comparison between orography in these 2 different resolution is represented in Figure 7. The model has a 4 minute time step and the current runs were started with climatological initial condition in March 2008 and run for minimum 4 years using daily sea surface temperature or sea-ice analysis from Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA). The explicit convection run uses a blended scheme by Adrian Lock, which combines the 1D boundary layer with the 3D Smagorinsky subgrid-scale turbulence model (M. Roberts, private communication).



(a) (b)

Figure 7: Different between orography in (a) N96 and (b) N1024 mode resolution where the colour bars is in meters. Imaged provided by R. Scheimann.

CHAPTER 3: RESULTS AND ANALYSIS

3.1 Changes with explicit convection

3.1.1 Analysed regions

In first chapter, we have described dynamics and features of the monsoon while in Chapter 2 we have discussed the deficiencies of models in simulating monsoon precipitation. Several studies found that models poorly simulate the location and intensity of observed precipitation over particular region such as India and equatorial Indian Ocean. However, in this study, our interest is on the three regions shown in Figure 8 namely: warm pool, Indian Ocean and India region. Models frequently simulate more precipitation over equatorial Indian Ocean but low precipitation over India region and according to Bollasina and Ming (2013) and Gadgil and Sajani (1998), they agreed most of monsoon rainfall over India is sensitive to the physical parameterization and they suggested that the precipitation bias can be overcome by improve GCM simulations especially the convective parameterization. Therefore, we will analyse the changes of precipitation, column water vapour and winds during summer (JJAS) periods in terms of precipitation and moisture distribution and wind direction or convergence with and without parameterized convection. Henceforth, we will study the different behaviour of parameterized and explicit convection and compare the general difference in the warm pool region (I) to specific regions of bias in the Indian Ocean and India regions (II and III).

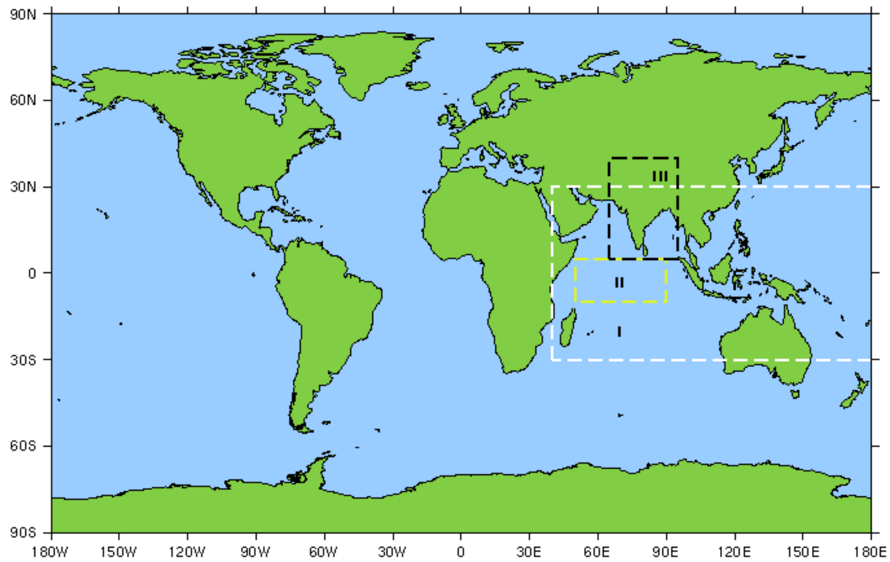


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Figure 8: The three analysis regions (labelled and separated by white, yellow and black dash line (I) warm pool, (II) Indian Ocean and (III) India.

3.1.2 Precipitation

This part will analyse differences in simulated summer (JJAS) precipitation between the parameterized and explicit convection models.

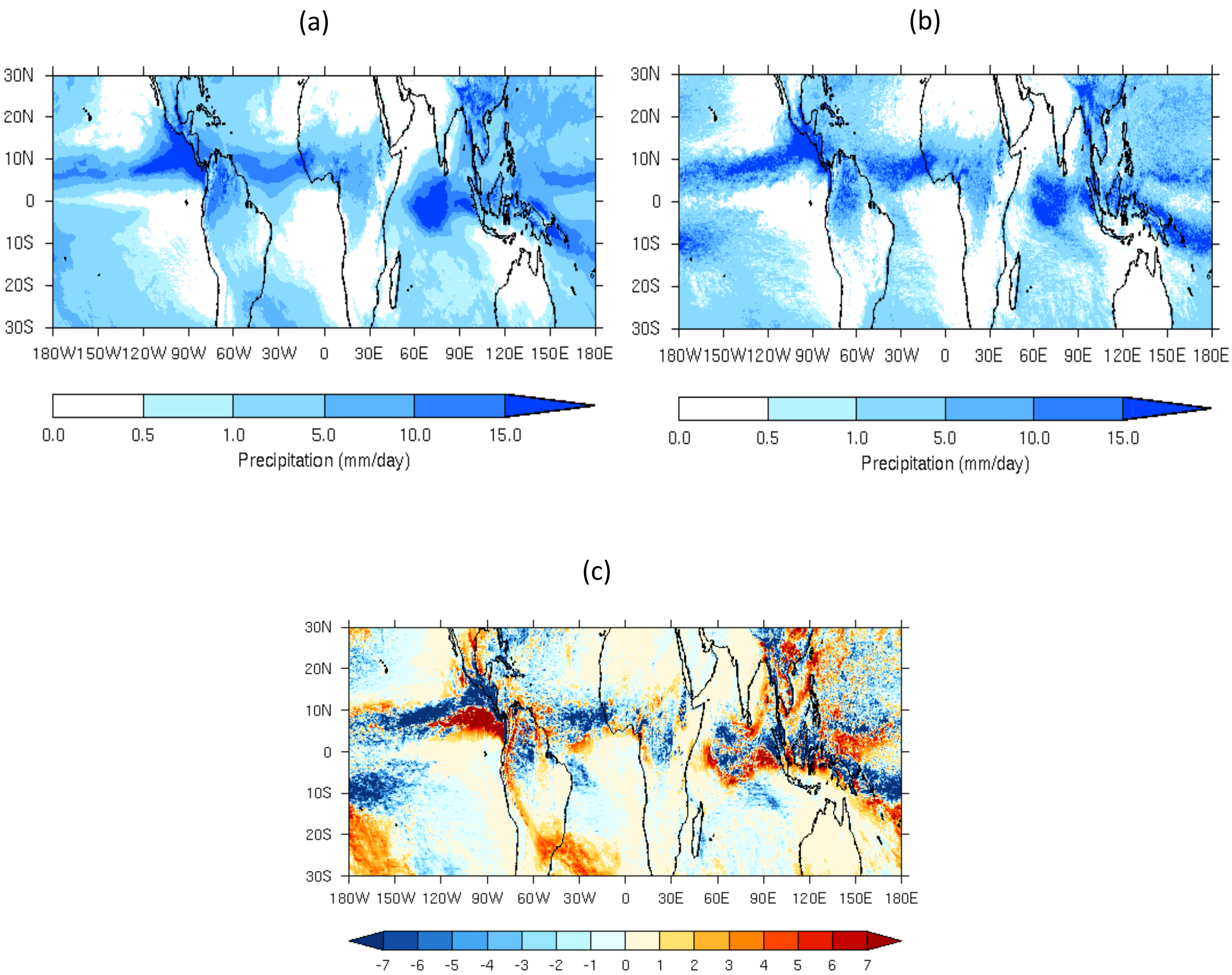


Figure 9: JJAS precipitation (mm/day) for year 2008 (a) parameterized precipitation (b) explicit precipitation and (c) difference between parameterized and explicit convection (positive colour range represent more rainfall in parameterized convection while negative colour range represent more rainfall in explicit convection).

Figure 9 depict JJAS precipitation for parameterized and explicit convection for year 2008 and the difference between them. In Figure 9a, convective parameterization simulates precipitation around 10-15 mm/day in some areas over Pacific Ocean, Atlantic Ocean and Indian Ocean. It shows that a rainfall band resides between 20°N-20°S and most of the intense precipitation occurs near to the equator. However, if we compare to mean observed rainfall distribution in Figure 6 in Chapter 1, it shows that parameterized model simulates less rainfall over India region around 0.5-1 mm/day while in the observation it was more than 5 mm/day of rainfall. Note that over coastal India especially along the shore at Arabian Sea, it was observed that in parameterized model the rainfall intensity is less than 0.5 mm/day while in Figure 6 the intensity was more than 10 mm/day. Similar result observed over Bay of Bengal and especially along the coastal area of Myanmar where in Figure 6 the rainfall was observed to be more than 12 mm/day but in parameterized and explicit convection model it is less than 1 mm/day. In addition, the parameterized model overestimates rainfall over Pacific Ocean, Atlantic Ocean and Indian Ocean when compare to Figure 6. In parameterized and explicit convection, the rainfall over equatorial Indian Ocean is observed to be more than 15 mm/day while in Figure 6 the rainfall intensity was only 5 mm/day. Explicit convection (Figure 9b) shows a similar result in terms of rainfall distribution over the same regions but the distribution is less smooth compared to parameterized convection.

In Figure 9c, it was observed that the continuous zonally elongated rainfall bands that were identified as ITCZ show abrupt northward shift as the parameterization turned off. The shifting is approximately consistent across Pacific Ocean, Atlantic Ocean and Indian Ocean. The Southern Pacific Convergence Zone (SPCZ) that lies south of the Equator also show northward shift for explicit convection.

The difference between parameterized and explicit convection has been further analysed for years 2009-2011. As shown in Figure 10, the changes of summer precipitation for parameterized and explicit convection are similar although magnitudes are different throughout the year 2008-2011 where all 4 years show the ITCZ move northward consistently. Based on Figure 10, the different intensity of rainfall changes for year 2008 and 2011 are similar over the Pacific Ocean and Indian Ocean. Rainfall in year 2009 is similar to 2010 especially over Indian Ocean. The ITCZ in explicit convection model resides at similar latitudes as in observation (Figure 6).

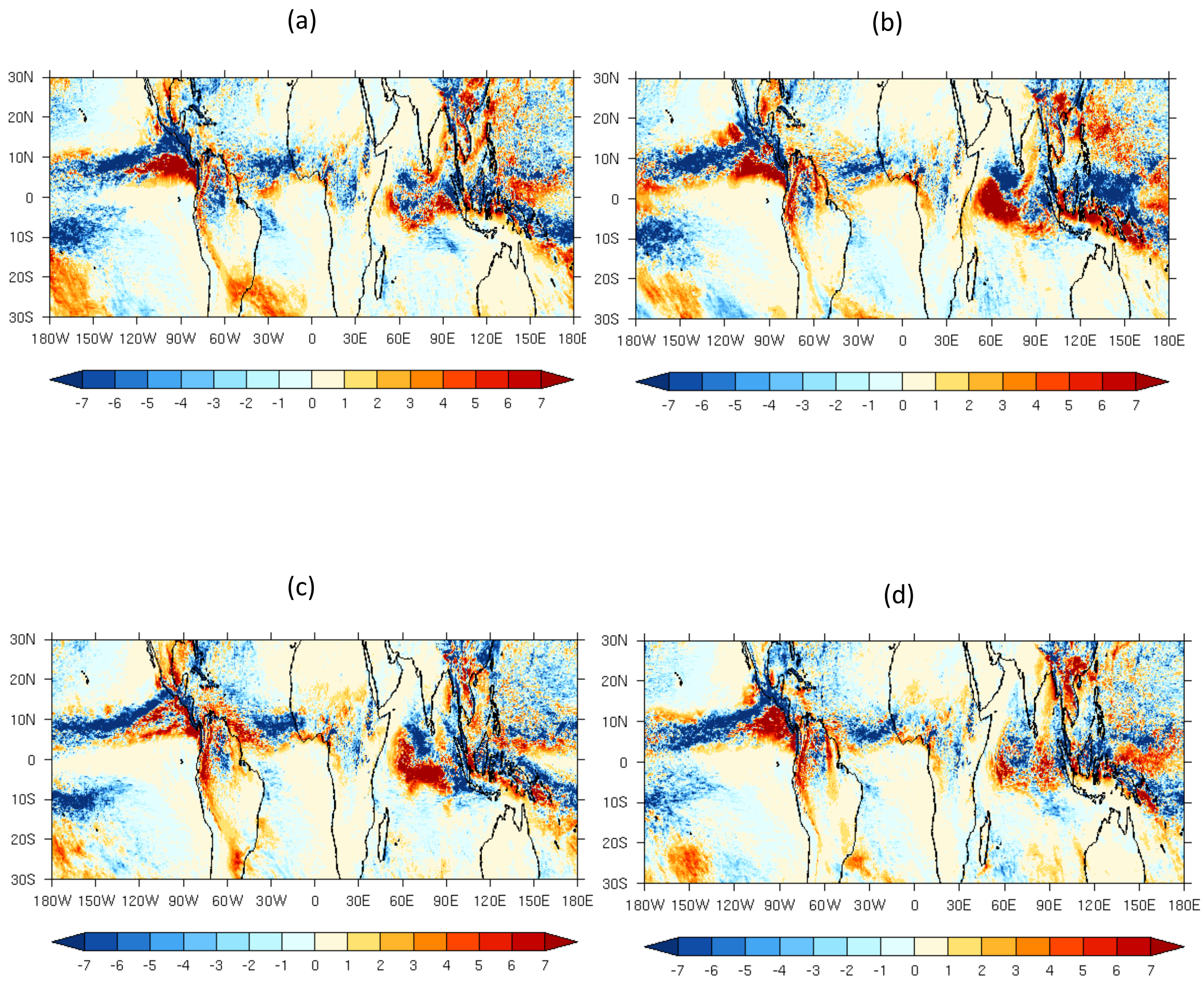


Figure 10: Difference between parameterized and explicit summer precipitation (mm/day) for year (a) 2008, (b) 2009, (c) 2010 and (d) 2011. The positive colour range represents more rainfall in parameterized convection while negative colour range represents more rainfall in explicit convection.

3.1.3 Column water vapour

In this part, we will analyse column water vapour (CWV) during summer and find the differences between parameterized and explicit convection for all 4 years tested. By analysing the changing in column water vapour between two convective models, we can investigate the relationship between column water vapour and precipitation during summer. Further details on the relationship will be discussed in next chapter.

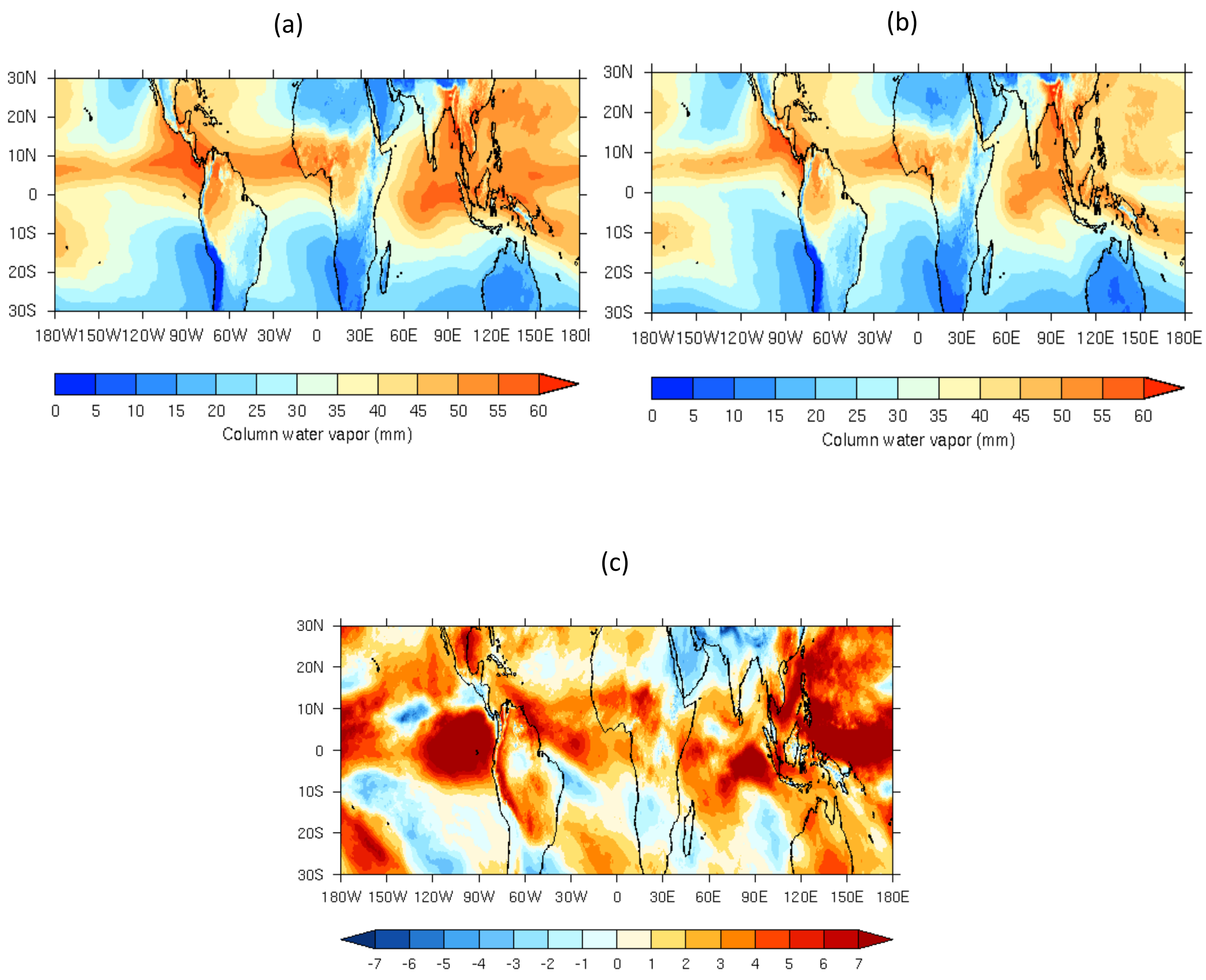


Figure 11: JJAS column water vapour (mm) for year 2008 (a) parameterized column water vapour (b) explicit column water vapour and (c) difference between parameterized and explicit convection (positive colour range represent more CWV in parameterized convection while negative colour range represent more CWV in explicit convection).

Figure 11 show JJAS column water vapour for parameterized and explicit convection for year 2008 and the difference between them. Figure 11a shows that parameterized convection simulate column water vapour with more than 50 mm over the Pacific Ocean, Atlantic Ocean and Indian Ocean. The similar results obtained by explicit convection as shown in Figure 11b but with low intensity of column water vapour as compared to parameterized. We observe that in the parameterized version of the model, the summer mean atmospheric column contains approximately 7 mm more water vapour (Figure 11c) compared to explicit especially over Pacific Ocean and Indian Ocean.

The relationship between precipitation and column water vapour changes is complex. Figure 9a and 11a show that there is increase in rainfall with increase in column water vapour over Pacific Ocean, Atlantic Ocean and Indian Ocean in parameterized convection model. In explicit convection model, the column water vapour seems to decreases with increasing in rainfall over the same aforementioned regions. However, note that the intensity of column water vapour off the equator (10°S-20°S) is seems to increase in explicit model with mean rainfall intensity. This result show that the changes is more affected over near equator rather than off equator. This is true throughout all 4 years examined (Figure 12) but with different magnitude respectively.

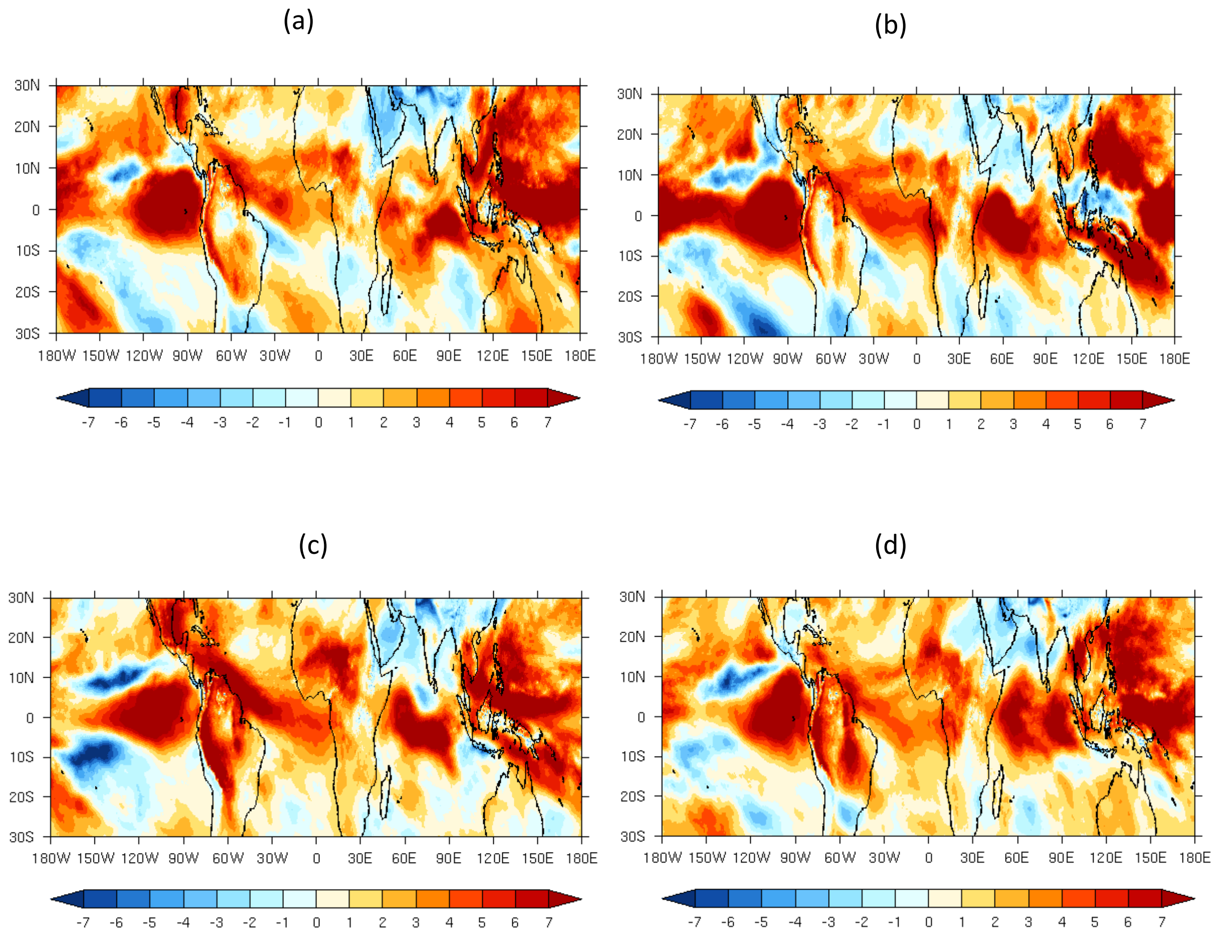
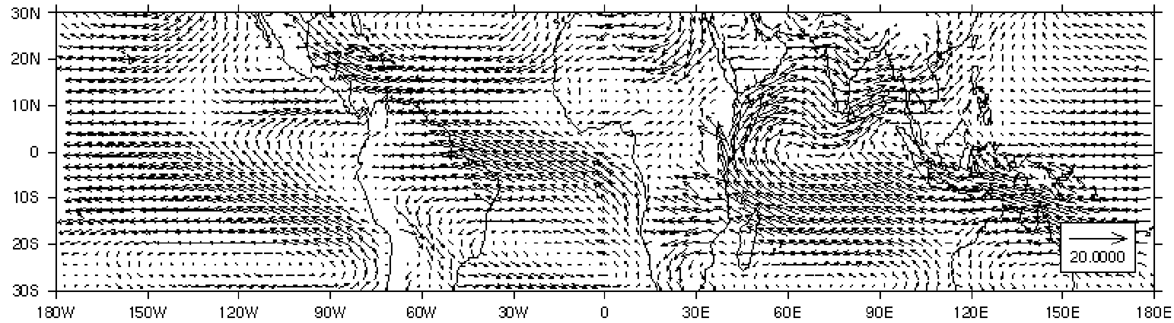


Figure 12: Difference between parameterized and explicit column water vapour (mm) for year (a) 2008, (b) 2009, (c) 2010 and (d) 2011. The positive colour range represents more CWV in parameterized convection while negative colour range represents more CWV in explicit convection.

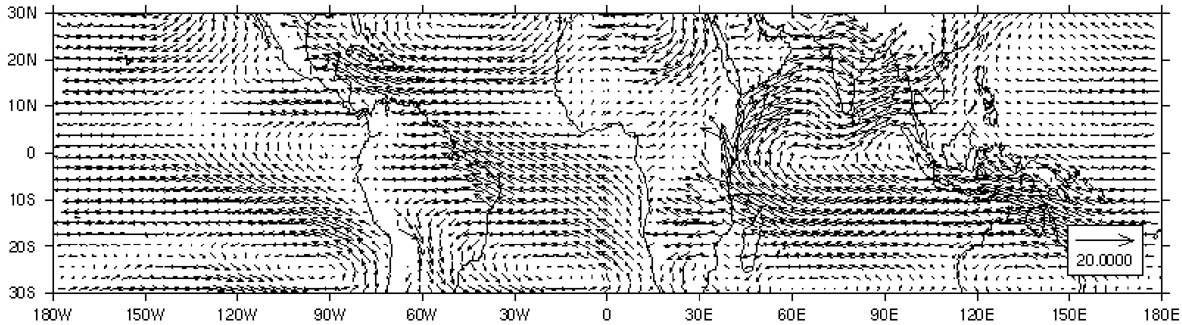
3.1.4 850 hPa winds

This part will examine winds behaviour during summer monsoon for both parameterized and explicit convection model and study the differences between the two models convection.

(a)



(b)



(c)

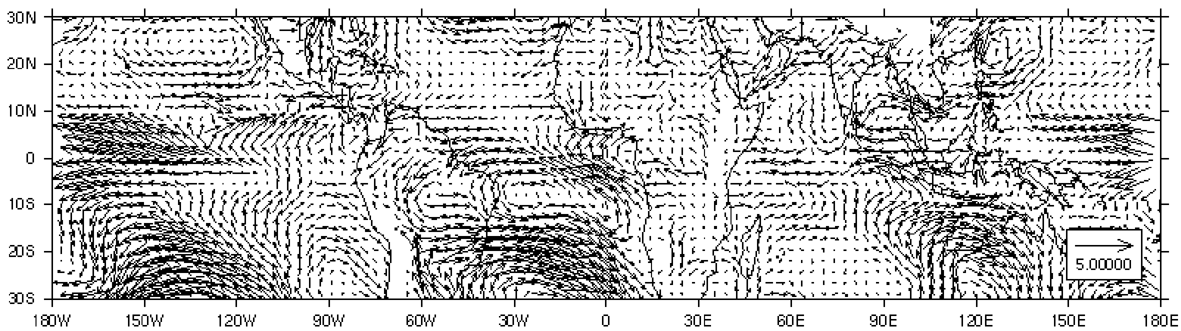


Figure 13: 850 hPa winds for year 2008 (a) parameterized winds (20 ms^{-1}) (b) explicit winds (20 ms^{-1}) and (c) difference between parameterized and explicit winds with magnitude of 5 ms^{-1} (Note that for Figure 13c more winds convergence represents stronger wind flow in parameterized while less winds convergence represents stronger wind flow in explicit convection model).

Figure 13 depicts the parameterized and explicit winds at 850hPa with the difference between them for year 2008. Figure 13a show the wind reversals observed over Indian Ocean during summer and wind convergence occur over equator as simulated by parameterized convection. By comparing to Figure 2, there are not much different of winds pattern over Indian Ocean. The zone of converging winds in Figure 13a and 13b is at similar latitudes as shown in Figure 2b. However, in Figure 2b westerly winds was observed over India region while in Figure 13a and 13b there are northwesterly winds observed over that region.

Figure 13c show the different between parameterized and explicit convection winds with magnitude of 5 ms^{-1}. Note that there is more winds convergence particularly over equatorial Indian Ocean shown by parameterized convection model. This observation shows that in parameterized convection model the winds are stronger over equatorial Indian Ocean compared to explicit convection model. The same result observed over Pacific Ocean and Atlantic Ocean where the winds are stronger over the regions compared to explicit convection.

The zone of converging wind for parameterized convection model (Figure 13c) is consistent with the ITCZ simulated by parameterized convection in Figure 9c. In Figure 9c, we observed a northward shift of ITCZ when the parameterization is turned off. The ITCZ shifting is consistent with the wind convergence zone in Figure 13c simulated by explicit convection where less wind is observed at the convergence zone. Similar result but different strength also observed in all years examined (Figure 14).

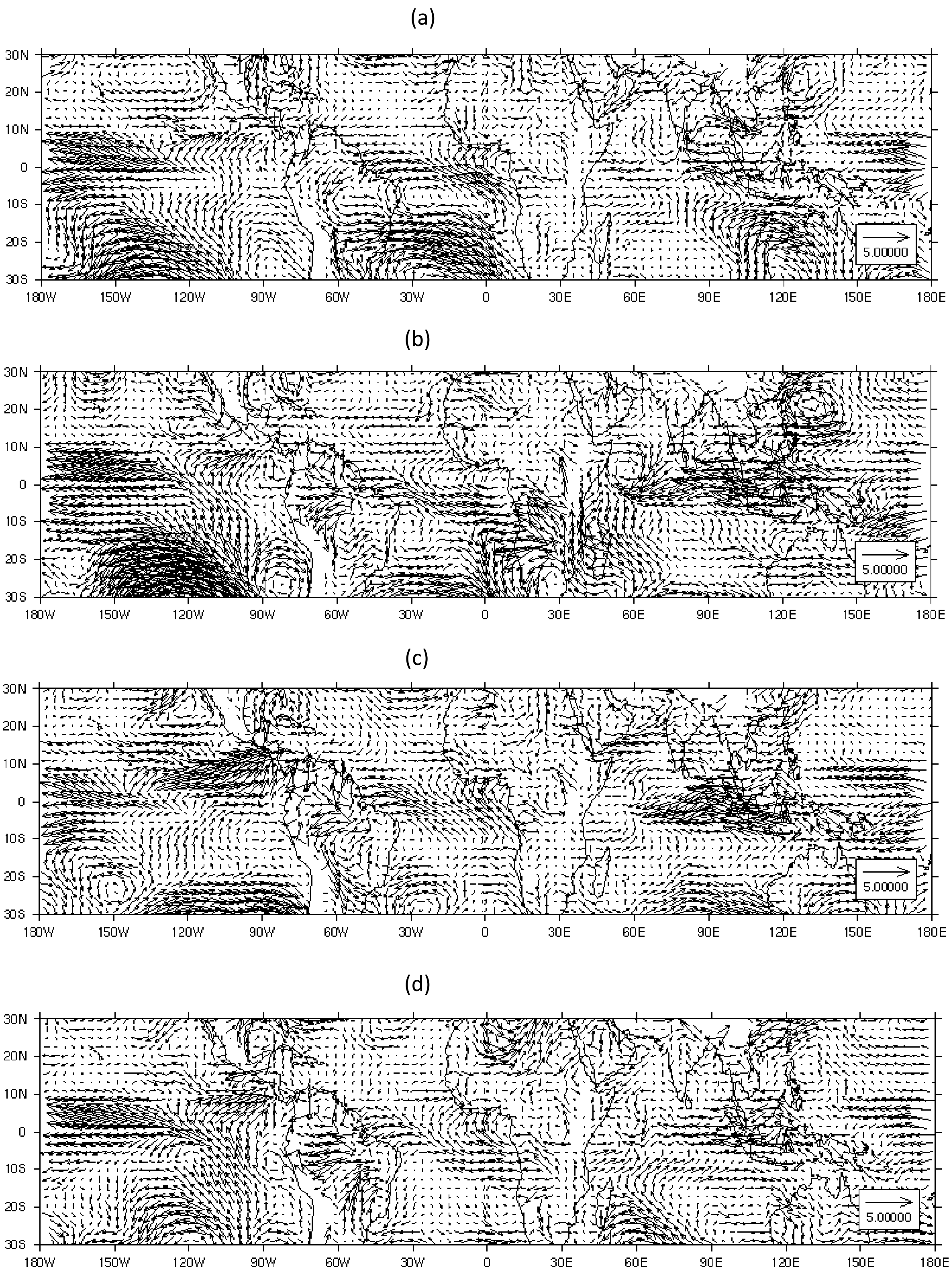


Figure 14: Difference between parameterized and explicit 850hpa winds during JJAS with magnitude of 5 ms^{-1} for year (a) 2008, (b) 2009, (c) 2010 and (d) 2011. (Note that more winds convergence represents stronger wind in parameterized while less winds convergence represents stronger wind flow in explicit convection model).

3.2 Regional JJAS precipitation

In preceding section, we have seen the general view on how convection is behaving differently in the explicit and parameterized model. In this section, we will more focus on the three regions: warm pool, equatorial Indian Ocean and India. We will compare the warm pool region's sensitivity towards parameterization to the smaller Indian Ocean and India region.

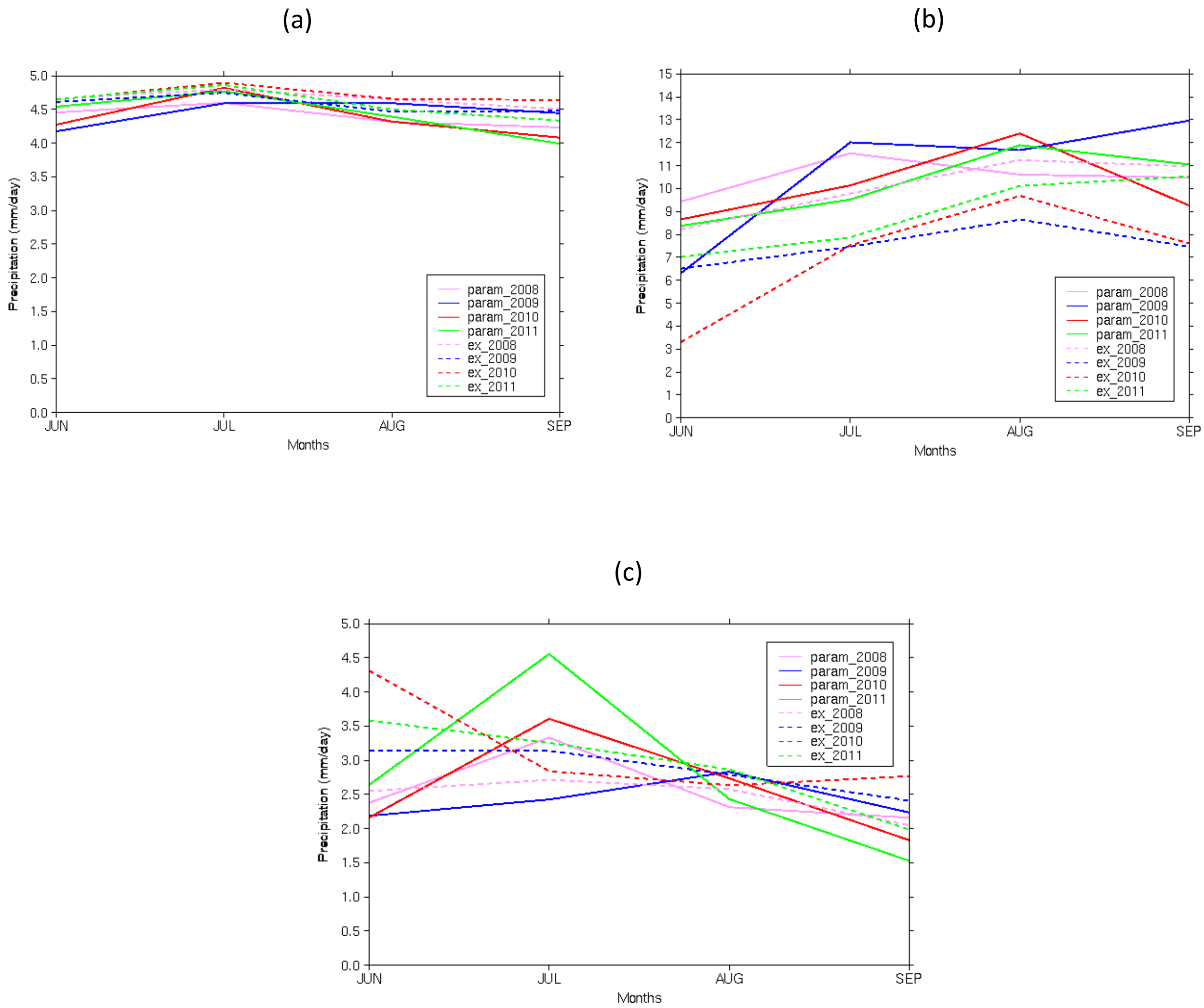


Figure 15: Time series of parameterized and explicit average JJAS precipitation (mm/day) over (a) Warm pool, (b) Indian Ocean and (c) India for year 2008-2011. Solid line represents parameterized convection model while dashed line represent explicit convection model. Different line colour show each year respectively. Regions are shown in Figure 8 in Section 3.1.

Throughout the summer, there are increasing in average precipitation observed as the parameterization is turned off for warm pool region (Figure 15a) while average precipitation decreases over Indian Ocean region (Figure 15b). However, each month show different changes in precipitation over India region when the parameterization is turned off. We observed that there are increasing in precipitation during June, August and September but decreases during July in explicit convection model.

Each region shows different changes in precipitation when parameterization is turned off. More details on the sensitivity to the parameterization and relationship between precipitation and column water vapour for these three regions will be discussed in the next chapter by histogram analysis.

CHAPTER 4: RELATIONSHIP BETWEEN COLUMN WATER VAPOR AND PRECIPITATION

Realistic representation of monsoon rainfall in a model is most desirable. The relationship between monsoon precipitation and moisture is a key process to obtain an accurate monsoon representation. As deep convective rainfall is commonly associated with humid atmosphere (Bretherton *et al*. 2004) and as discussed in previous chapter, simulation of monsoon rainfall is very sensitive to parameterization. Generally, we have seen how the precipitation and column water vapour respond when we turned off the parameterization and narrow the study by analyzing the sensitivity to parameterization or explicit convection for more specific regions. In this chapter, we will perform histogram analysis for precipitation and column water vapour to study the relationship between the two parameters in parameterized and explicit convection.

This chapter will be divided into 4 different section where in the first section we will analysed the precipitation frequency at different rates for each region and relate the frequency with the contribution to the rainfall amount in that region from year 2008-2011. Next, we will look at the column water vapour frequency distribution before we focus more on the changes in the relationship between precipitation and column water vapour with 2-dimensional histogram analysis and analysed the relationship between the two parameters.

4.1 Histogram analysis for daily JJAS precipitation

In this section, we construct a histogram to analyse the changes in rainfall distribution frequency for three aforementioned regions in parameterized and explicit convection cases. The frequency will be analysed in bins from 0 to 120 mm/day with 2 mm/day wide. Here, we will classify the bins into three categories which are lower (0-4 mm/day), medium (40-80 mm/day) and higher (80-120 mm/day) rate.

Figure 16a and 16b showed the rainfall frequency distribution and contribution of each rainfall rate to overall mean rainfall for warm pool region. In Figure 16a, we observed a large different occurs between parameterized and explicit convection. Rainfall is more frequent in lower rate bins for both cases compared to medium and higher rate bin. The frequency in lower bins is observed to be higher in parameterized convection model. However, explicit convection shows higher frequency than parameterized in medium and higher bins rate at 48-80 mm/day and 80-120 mm/day respectively. Both parameterized and explicit convection model show the rainfall frequency distribution is decreasing as it reaches to higher rate bins.

The frequency of rainfall in Figure 16a contributes to amount rate of precipitation in Figure 16b for warm pool region. It showed that highest amount rate of rainfall over warm pool region is at the rate of approximately 0-12 mm/day for parameterized and evenly distributed for the explicit convection model.

Figure 16c and 16d showed the frequency distribution for Indian Ocean region. We also observed a large different when the parameterization is turned off. The frequency in lower rate bins is higher in parameterized convection model when compared to explicit. Similar to warm pool case, both parameterized and explicit convection have higher frequency in lower rate bins compared to medium and higher rate bins. However, explicit convection model tends to distribute higher frequency in medium rate bins at 62-80 mm/day and higher rate bins at 80-120 mm/day when we compared to convective parameterization. Figure 16d showed highest daily amount rate of rainfall over Indian Ocean is at the rates of 12-36 mm/day and this is largely different as in explicit convection where the rainfall is evenly distributed over rates.

Similar result observed over India (Figure 16e) where the highest frequency is well-distributed in lower rate bins for both parameterized and explicit convection. Furthermore, the explicit convection also shows higher frequency in medium bins at 40-80 mm/day and higher bins at 80-120 mm/day rate compared to parameterized convection model. The results show that similar changes observed in all three regions.

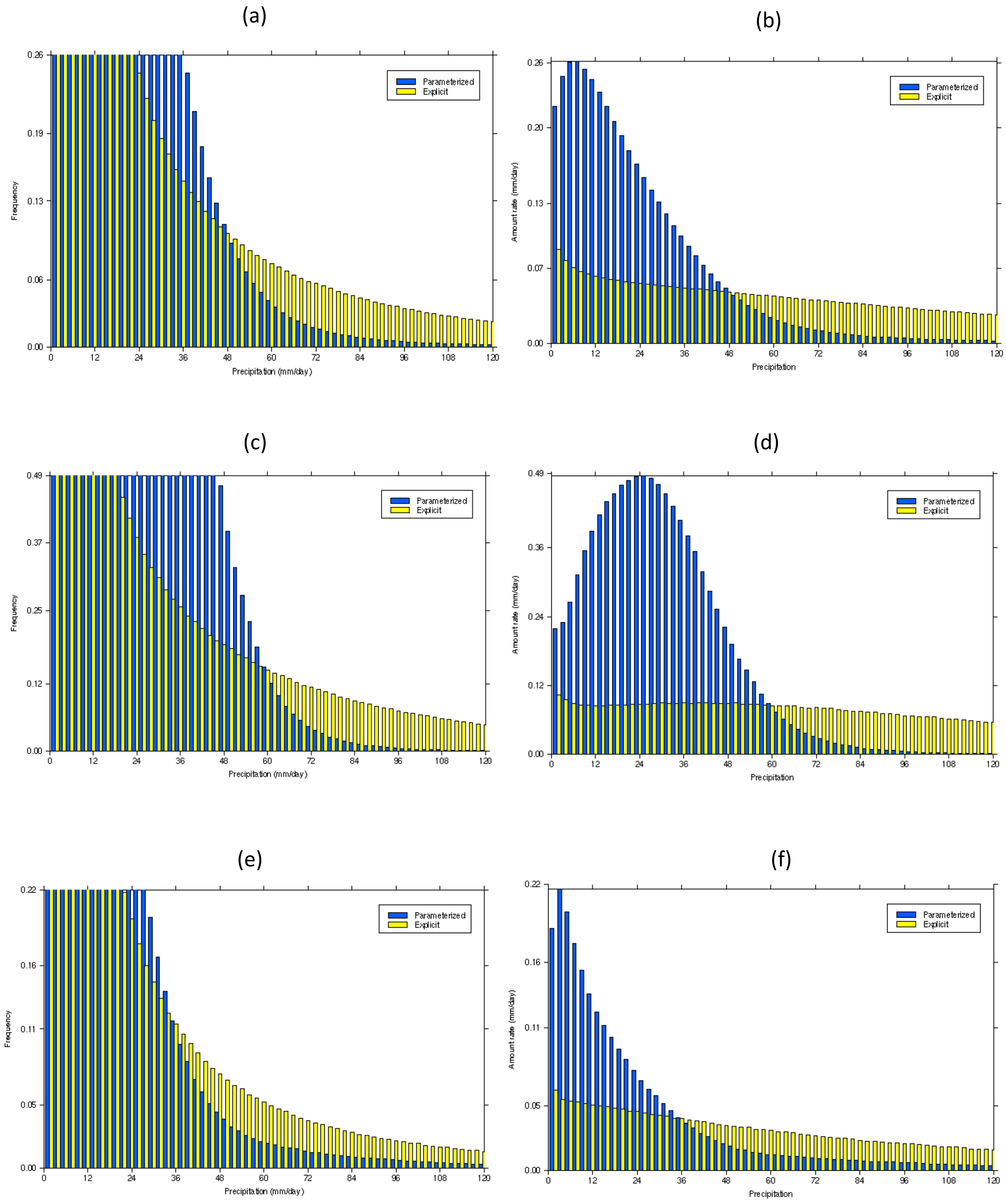


Figure 16: Histogram showing frequency of precipitation (in left column) in 2mm/day wide bins for (a) warm pool, (c) Indian Ocean and (e) India and the contribution of each of those bins (in the right column) to the total rainfall (mm/day) for (b) warm pool, (d) Indian Ocean and (f) India region respectively.

4.2 Histogram analysis for daily JJAS column water vapour

In this section, we will examine the changes of daily column water vapour for year 2008-2011 over the three regions in histogram analysis for parameterized and explicit convection cases. Here, column water vapour frequency will analysed in bins with 2 mm wide from 0-120 mm and categorized into three different categories lower (0-40 mm), medium (40-80 mm) and higher (80-120 mm) bins.

Figure 17a showed the frequency distribution for column water vapour over warm pool region. The histogram showed that there are 2 peaks of column water vapour in parameterized convection case. The first peak is observed to be approximately at 12-24 mm while the other is at 48-60 mm bins rate. The column water vapour frequency is mostly distributed in lower and medium bins but no column water vapour values at higher bins for both convection models. However, we observed that explicit convection shows higher frequency than parameterized convection in the medium bins. In explicit convection, the first peak is in the same range with parameterized. However, a large different observed where we can see the second peak shifted to the right and falls in 36-48 mm when we turned off the parameterization.

In Figure 17b, we further analysed the changes of column water vapour frequency between parameterized and explicit convection over Indian Ocean. For both cases, the frequency is well-distributed between lower in medium bin. We observed two peaks for parameterized case where the first peak falls approximately between 30-40 mm and the second peak is in the range of 54-60 mm. However, in explicit convection, the second peak is slightly shifted to the left and falls in between approximately 42-50 mm while the first peak is remaining at 30-40 mm similar as in parameterized convection. Note that the frequency distribution for column water vapour in the explicit is higher than parameterized at the first peak but less in the second peak. Results obtained for warm pool and Indian Ocean region show that the column water vapour tends to moves to lower rate bins when we turned off the parameterization and this is consistent with observation in Figure 12 where the column water vapour decreases over the two regions in explicit convection.

Figure 17c depicted frequency distribution of column water vapour over India. Large changes observed where the frequency of column water vapour for parameterized convection is well-distributed in lower and medium bins rate while in explicit convection it falls into all three categories of bins. This region show different result compared to other two where we observed there are three peaks of column water vapour frequency. In parameterized convection model, the first peak is observed at 0-12 mm, second peak is approximately at 36-48 mm and the third peak is at 50-58 mm. The third peak is shifted more to the right and falls approximately into 66-80 mm in explicit convection while the first and second peak is similar to parameterized convection. This result also consistent with Figure 12 in preceding section, where there is higher column water vapour observed over India in explicit convection model compared to parameterized convection.

The results show that all three regions show changes in column water vapour frequency when the parameterization is turned off. We will study the relationship between the change of rainfall and column water vapour in the next section with two-dimensional histogram.

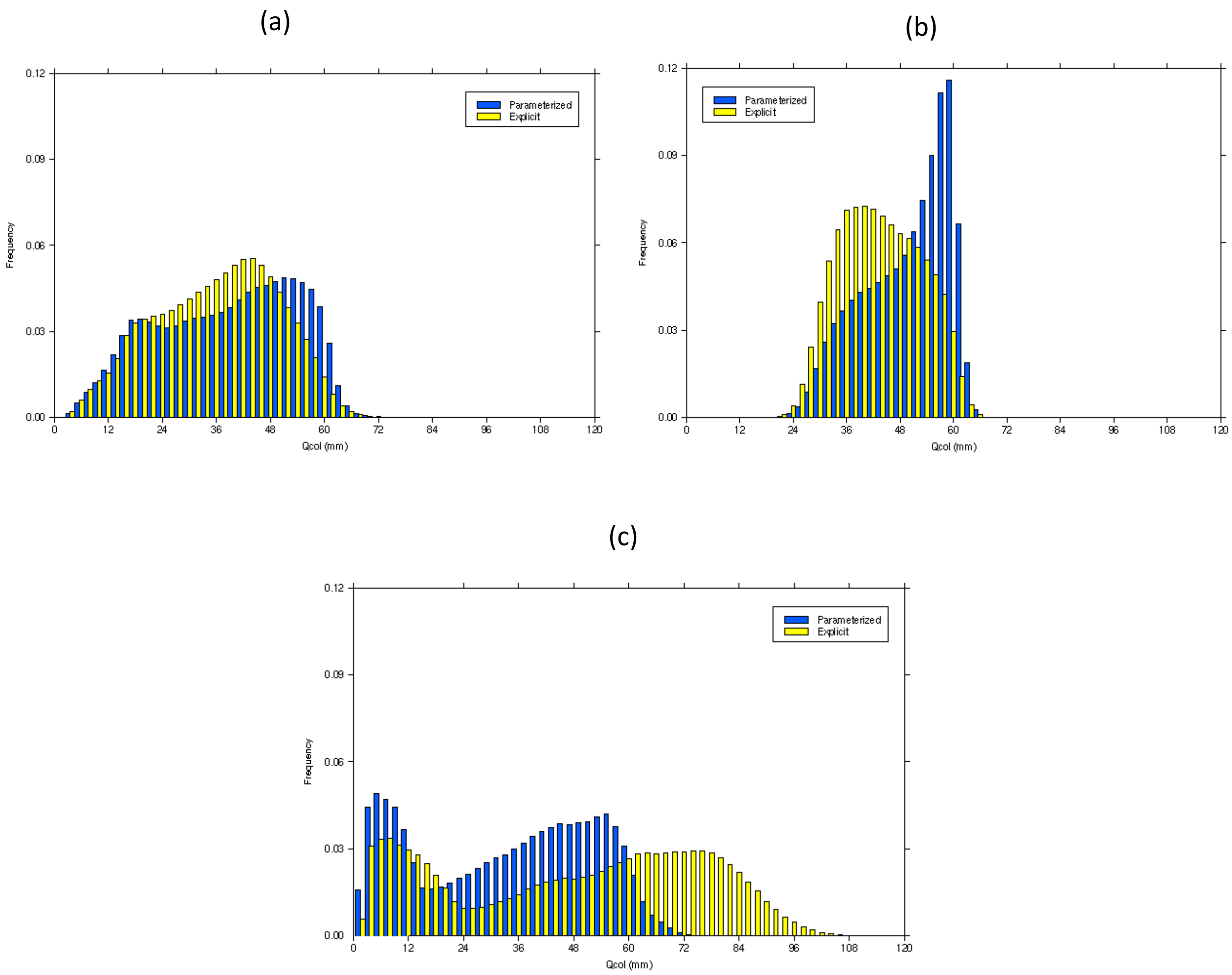


Figure 17: Histogram showing frequency of daily mean column water vapour in 2 mm wide bins for (a) warm pool, (b) Indian Ocean and (c) India region. Blue bars represent parameterized while yellow bars represent explicit convection respectively.

4.3 Two-dimensional histogram analysis for precipitation and column water vapour

We have seen the changes between summer rainfall and column water vapour in parameterized and explicit convection model in preceding section. In this section, we construct a two-dimensional histogram and calculate the average precipitation against water vapour for each three regions in order to further analyse the relationship between the two changes. The x-axis in the histogram (Figure 18) represents the bins for column water vapour for 0-120 mm with 2 mm wide bins while y-axis represent the precipitation rate which is in the range of 0-120 mm/day with 2 mm/day wide bins. We will classify the bins into three categories as we did in the previous sections which are lower, medium and higher rate bins. Note that each contour in the figures represents the frequency of that combination of daily precipitation and daily column water vapour at a grid point.

Figure 18a and 18b show the 2-dimensional histogram for warm pool region. The distribution rate of precipitation and column water vapour for parameterized convection model is shown in Figure 18a. We analysed that for parameterized convection, the lower rate of precipitation tends to concentrate in the lower and medium bins of column water vapour. However, less than 0.0005% of distribution for precipitation with medium rate is observed falls into the lower and medium bins of column water vapour. The result is similar for explicit convection model except that there is extension of precipitation with higher rate more than 120 mm/day but with small distribution which is not more than 0.0005% that falls into lower and medium column water vapour bins.

The changes between two parameters over Indian Ocean are shown in Figure 18c and 18d. Similar result with warm pool case is observed over Indian Ocean where the lower rate of precipitation is more concentrate in lower and medium rate of column water vapour in parameterized convection model. Very small distribution of precipitation with higher rate which is also not more than 0.0005% is observed in lower and medium column water vapour for Indian Ocean. No large changes observed in explicit case except the higher rate of precipitation is extend further more than 120 mm/day for lower and medium rate of column water vapour but with small distribution similar as shown by parameterized convection model.

Similar result as two other regions also obtained for India for both parameterized (Figure 18e) and explicit (Figure 18f) convection model. Note that the precipitation with lower rate is still observed to be more concentrate in lower and medium rate of column water vapour in parameterized with further extension of higher rate of precipitation which is more than 120 mm/day in the explicit case.

For all three regions, column water vapour rate is observed to be in the range of not more than 80 mm. The lower rate of precipitation tends to be more associated with lower and medium rate of column water vapour compared to precipitation with higher rate which is more than 80 mm/day. Both parameterized and explicit show quite similar result except in explicit the distribution for higher rate of precipitation that fall in the lower and medium column water vapour rate is overestimate which is more than 120 mm/day but only with small distribution which is not more than 0.0005%. We will further analyse the dependence of precipitation with column water vapour in the next section.

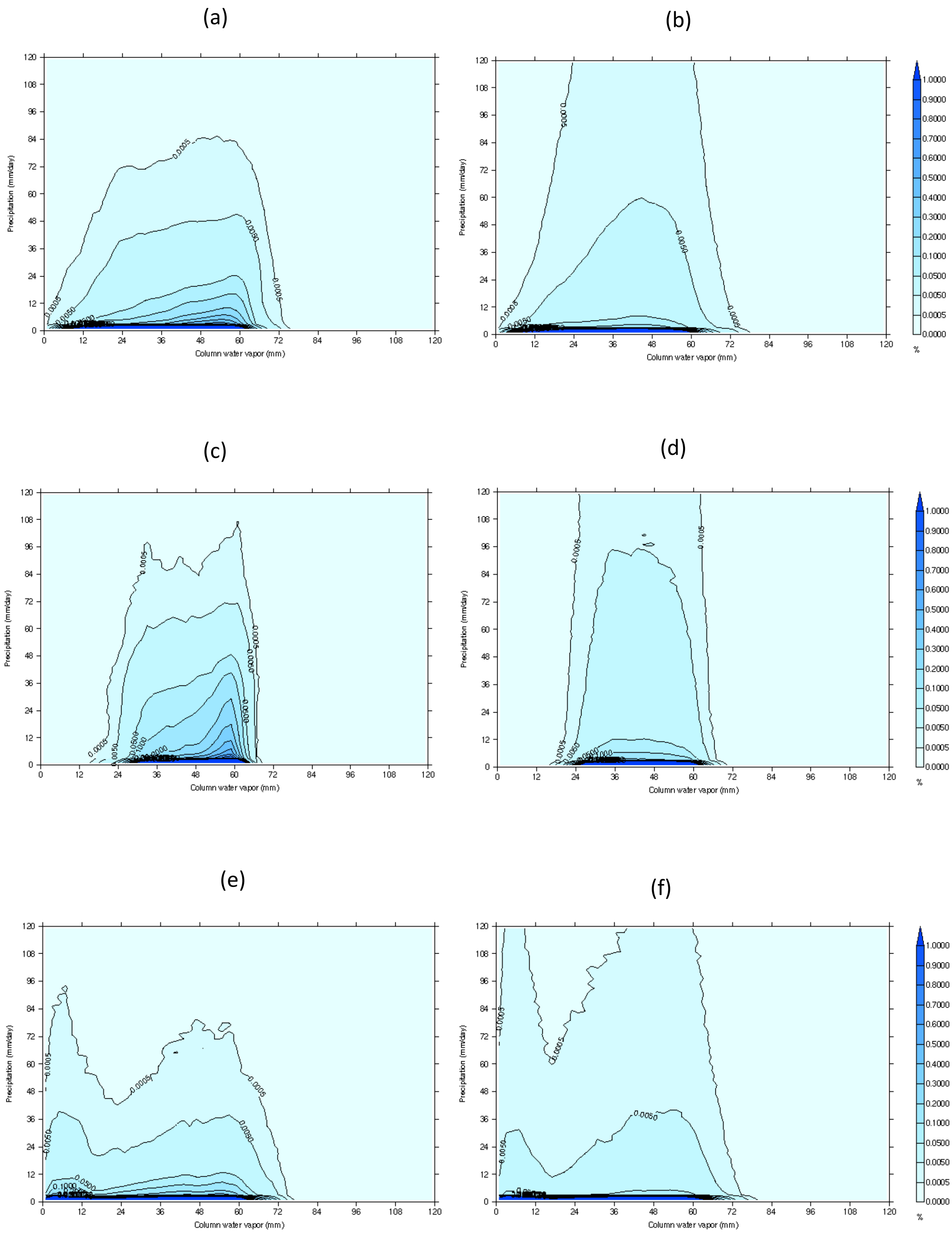


Figure 18: Two-dimensional histogram of daily JJAS precipitation (mm/day) against column water vapour (mm) with 2 mm/day and 2 mm wide bins for year 2008-2011. Left column is for parameterized convection over (a) warm pool, (c) Indian Ocean and (c) India regions while right column is for explicit convection over (b) warm pool, (d) Indian Ocean and (f) India regions respectively.

4.4 Averaged precipitation-column water vapour dependence

We have analysed and relate the changes between summer precipitation and column water vapour in previous section. In this section, we will see the relationship between precipitation and column water vapour in more detail. In order to see the relationship between the two parameters, we compute the precipitation averaged over all grid points in column water vapour bins. Figure 19 showed the relationship graph between averaged daily precipitation rate and daily column water vapour in parameterized and explicit convection model for year 2008-2011. The x-axis in the graph represents the column water vapour with 2 mm-wide while y-axis represents the average precipitation of grid point in those column water vapour bins. Figure 20 is another version of Figure 19 but plotted with narrower precipitation rate in order to observe more clearly the changes in precipitation between parameterized and explicit convection at lower precipitation rate.

Figure 19a show the relationship between precipitation and column water vapour over warm pool region. We observed that the column water vapour increases with increasing rainfall for parameterized convection. A sharp pickup of precipitation is observed approximately at 60 mm column water vapour. However, as the rainfall is increasing up to 108 mm/day, we observed a drastic drop in precipitation at approximately 80 mm column water vapour. Similar condition is observed for explicit convection where the column water vapour increases with increasing in rainfall except the precipitation start to pick up at approximately at 56 mm column water vapour which is less than parameterized. In explicit convection, the precipitation increase further more than 120 mm/day compared to parameterized. Up until 500 mm/day the rainfall starts to decrease approximately at 80 mm column water vapour.

Relationship between precipitation and column water vapour is further analysed for Indian Ocean in Figure 19b. We observed that for parameterized convection model, the sharp picks up is observed at 60 mm column water vapour and rainfall starts to increase up until 56 mm/day before it decreases at 66 mm column water vapour. However, for explicit convection model, the rainfall shows drastic increasing at 54 mm column water vapour which is less than what we observed in parameterized convection. The explicit convection also show the rainfall increase up to 560 mm/day more than the rate observed in parameterized convection before it drops at approximately 68 mm column water vapour.

Figure 19c show the relationship between the two parameters for India region. In parameterized convection, the rainfall shows an abrupt increase at 70 mm column water vapour. The rainfall is observed increasing up to 108 mm/day before it drops at approximately 74 mm column water vapour. However, explicit convection also shows a sharp pick up of rainfall at 70 mm column water vapour but as the rainfall is observed to increasing further up until 490 mm/day which is larger rate compared to parameterized convection. The rainfall for explicit drop at 80 mm column water vapour more than observed in parameterized convection.

According to previous studies as discussed in Chapter 2, increase in column water vapour associated with increasing in rainfall (Holloway and Neelin, 2009, Bretherthon *et al*. 2004). Our results are consistent with Holloway and Neelin (2009) and Neelin *et al*. (2009) where they found that the rainfall increases rapidly with moisture close to a critical value approximately at 60 mm, a rate where there is a sharp pick up of rainfall we observed in the relationship graph. However, Muller *et al*. (2004) and Neelin *et al.* (2009) further agreed that the rainfall will decreases at a very high humidity and this also consistent with our results where we observed that at a higher rate of column water vapour, the rainfall starts to decrease and the similar results obtained in all three regions.

We can see the change of the critical value is observed to be less in explicit convection compared to parameterized convection for warm pool Indian Ocean region. However, both parameterized and explicit convection show the same critical value for India region. The explicit convection show a higher rainfall rate compare to parameterized convection in all three regions and this result shows that without convective parameterization the precipitation much more sensitive to moisture. However, we observed that in Figure 20, at lower rate column water vapour, the explicit convection precipitation rate is increasing and decreasing relative to the precipitation rate in parameterized convection and the fluctuation trend is more obvious over India region compare to other two regions.

(a)

(b)

(c)

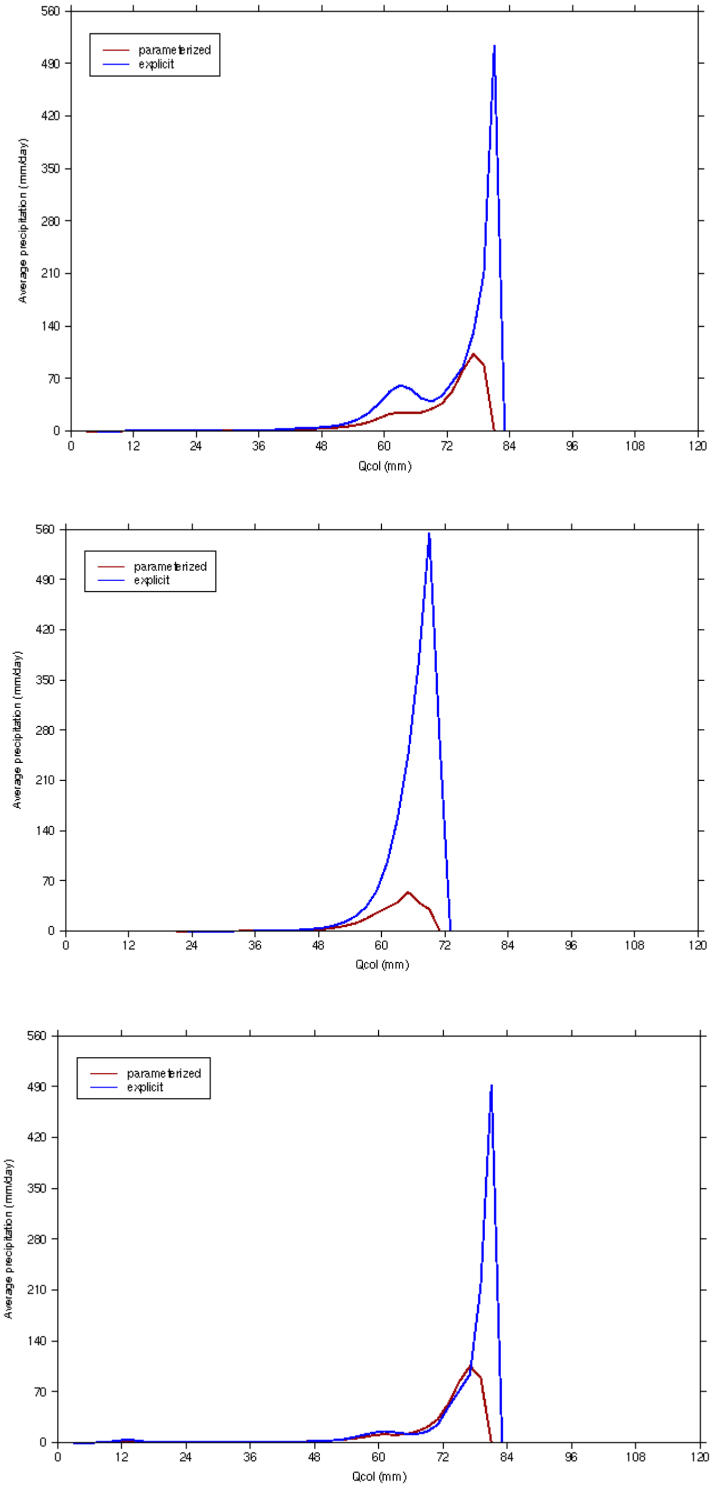


Figure 19: Average daily JJAS precipitation (mm/day) with column water vapour (mm) for year 2008-2011 over (a) warm pool, (b) Indian Ocean and (c) India for both parameterized and explicit convection. Red line represents parameterized convection while blue line represents explicit convection.

(a)

(b)

(c)

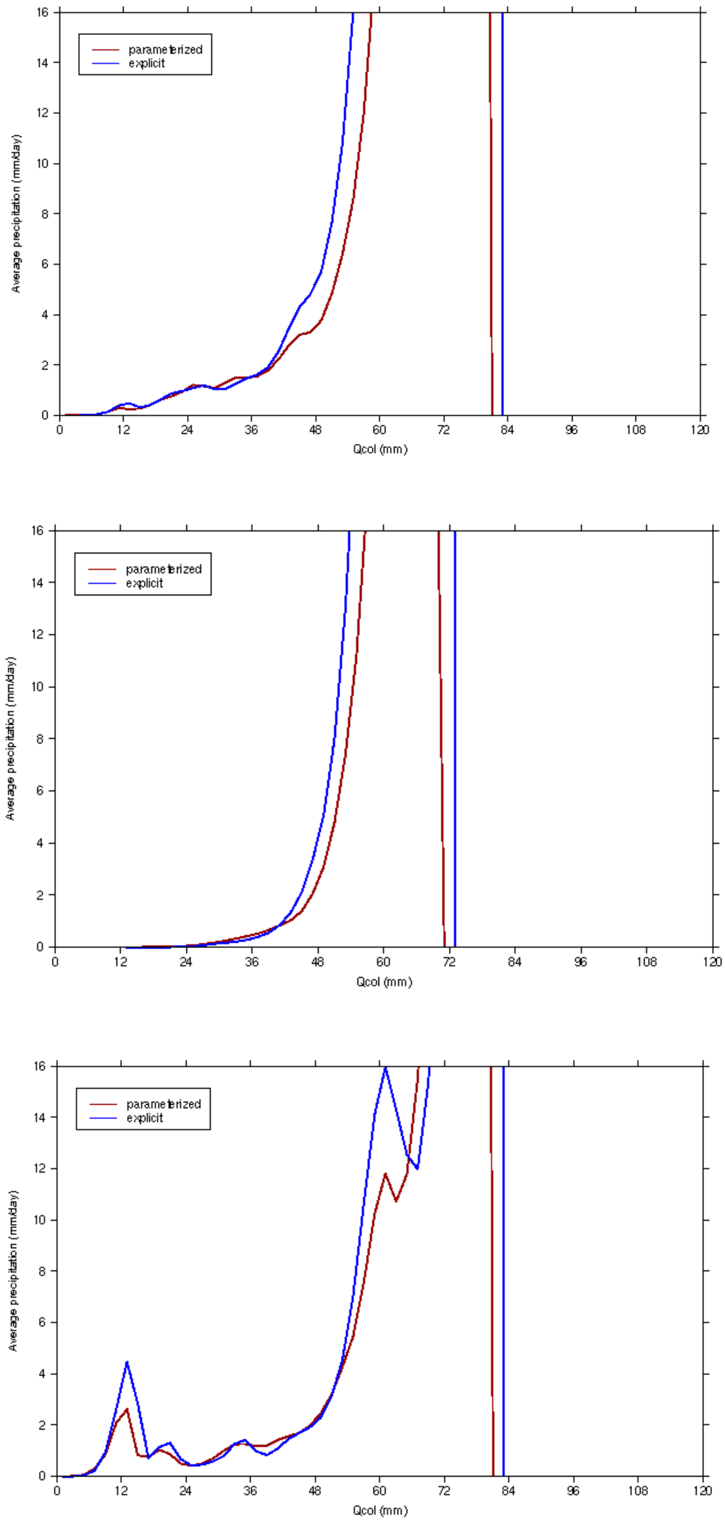


Figure 20: This figure is another version (with narrower precipitation rate) of Figure 19 show the average daily JJAS precipitation (mm/day) with column water vapour (mm) for year 2008-2011 over (a) warm pool, (b) Indian Ocean and (c) India for both parameterized and explicit convection. Red line represents parameterized convection while blue line represents explicit convection.

CHAPTER 5: CONCLUSION AND FUTURE PROSPECTS

5.1 Conclusion

Data over three regions namely warm pool, Indian Ocean and India with three different parameters: precipitation, column water vapour and winds were examined in order to study the changes between parameterized and explicit convection for years 2008-2011. In the first section of the analysis, the changes between parameterized and explicit are clear in precipitation and column water vapour. As the parameterization is turned off, a northward shift is observed in ITCZ but with less moisture throughout the tropics. It also found that the rainfall is increasing with increase in column water vapour over Pacific Ocean, Atlantic Ocean and Indian Ocean in parameterized convection model. However, the column water vapour seems to decreases with increasing in rainfall over the same aforementioned regions in explicit convection model. This result also shows that the changes are more affected over near equator rather than off equator. This is true throughout all four years examined but with different magnitude respectively. This result concluded that the intensity and location of precipitation distribution is changing as the parameterization turned off. The intensity of water vapour also changing as well as the location of its distribution which is too different compared to the model with parameterization thus result the bias particularly over Indian Ocean.

Furthermore, there are not much different of winds pattern over Indian Ocean. The zone of converging winds in the model is at similar latitudes with the reanalysis ERA-winds. However, northwesterly winds were observed over India region in both parameterized and explicit convection model while westerly winds were observed over that region in the reanalysis ERA-winds. This result concluded that turning off parameterization makes the wind pattern over India region more vulnerable to the changes compared to other regions.

The result also shows that in parameterized convection model the winds are stronger over equatorial Indian Ocean, Pacific Ocean and Atlantic Ocean compared to explicit convection model. The zone of converging wind for parameterized convection model is consistent with the ITCZ simulated by parameterized convection model in rainfall analysis. The ITCZ shifting is also consistent with the wind convergence zone simulated by explicit convection and similar result but different strength also observed in all years examined.

The difference between parameterized and explicit convection was further examined by studying the regional average JJAS precipitation over warm pool, Indian Ocean and India region. There are increasing in average precipitation observed as the parameterization is turned off for warm pool region and decreases over Indian Ocean region. However, each month show different changes in precipitation over India region when the parameterization is turned off. The results show that each region shows different changes in precipitation in explicit convection model.

The relationship between precipitation and column water vapour is firstly examined by studying the frequency distribution of precipitation over the three regions. The results show that the explicit convection model tends to distribute higher frequency in medium and higher rate bins than parameterized convection model. There are largely different in contribution of each rainfall rate to overall mean rainfall between parameterized and explicit convection model where the rainfall is evenly distributed over bin rates when the parameterization is turned off. The similar result obtained in all three regions examined.

The changes between precipitation and column water vapour was further analysed in two-dimensional histogram where the result shows that for all three regions, the lower rate of precipitation tends to be more associated with lower and medium rate of column water vapour compared to precipitation with higher rate which is more than 80 mm/day. Both parameterized and explicit show quite similar result except in explicit convection the distribution for higher rate of precipitation that fall in the lower and medium column water vapour rate is overestimate which is more than 120 mm/day but only with small distribution which is not more than 0.0005%.

In the final section, we analysed relationship between precipitation and column water vapour and found that our results are consistent with previous studies where the rainfall increases rapidly with moisture close to a critical value approximately at 60 mm and at a higher rate of column water vapour, the rainfall starts to decrease. The same result obtained for all three regions. However, when the parameterization is turned off, we observed a change in the critical value where it observed to be less in explicit convection compared to parameterized convection for warm pool and Indian Ocean region but both parameterized and explicit convection show the same critical value for India region. The explicit convection has higher rainfall rates at higher column water vapour compared to parameterized in all three regions and this result concluded that without convective parameterization the precipitation much more sensitive to moisture.

Overall, when the parameterization is turned off, many changes were observed and it show that the model is sensitive to turning off the convection scheme. The relationship between precipitation and moisture shows that precipitation for explicit convection has a higher dependence on moisture when compared to parameterized convection. The explicit convection simulated a direct prediction of the precipitation and is more appropriate if running with model with finer resolution than the resolution that used in this study.

5.2 FUTURE PROSPECTS

Future work could be carried out by comparing the difference between parameterized and explicit changes with observation and Tropical Rainfall Measuring Mission (TRMM) in order to obtain more realistic simulation of the monsoon. Further research should be done by comparing the changes between summer and winter monsoon and investigate the movement of ITCZ if it shifts in opposite direction. It will also be worth exploring the reason that caused the changes in ITCZ when the convection scheme is turned off. The relationship between precipitation and moisture can be further analyse by proving whether changing in spatial distribution of rainfall is associated with changing in moisture.

This investigation is hopefully can be helpful in improving monsoon prediction and more study is needed in the near future in order to reduce the effects and maximize the benefits of monsoon on vulnerable countries.

REFERENCES

Books

Das, P.K., 1972: *The Monsoons*. Edward Arnold (Publishers) Ltd, 162pp

Das, P.K., 1986: Monsoons. *Fifth IMO Lecture,* World Meteorological Organization**, No.613,** 155pp

Gadjil, S., and K.R. Kumar, 2006: The Asian monsoon – agriculture and economy. *The Asian Monsoon*, B.Wang, Praxis Publishing Ltd., 651-682

Murakami, T., 1987: Orography and monsoons. *Monsoons*, J.S. Fein, and P.L. Stephens, John Wiley &Sons, 331-364

Ramage, C.S., 1971: *Monsoon meteorology*. Academic Press, 296pp

Shukla,J., 1987: Long-range forecasting monsoons. *Monsoons*, J.S.Fein, and P.L.Stephens, John Wiley & Sons, 523-547

Slingo, J., 2003: Overview. Monsoon. *Encyclopedia of Atmospheric Science*, Holton, J.R., J.A. Curry, J.A. Pyle, Academic Press, **Vol.3**, 1365-1369

Webster, P.J., 1987: The Elementery Monsoon. *Monsoons*, J.S. Fein, and P.L. Stephens, John Wiley & Sons, 3-32

Webster, P.J., and Fasullo, J., 2003: Dynamical theory. Monsoon. *Encyclopedia of Atmospheric Science*, Holton, J.R., J.A. Curry, J.A. Pyle, Academic Press, **Vol.3**, 1370-1385

Yanai, M., and G-X. Wu, 2006: Effects of Tibetan Plateau. *The Asian Monsoon*. B. Wang, Praxis Publishing, 131-201

Journal and articles

Bollasina, M.A., and Y.Ming, 2013: The general circulation model precipitation bias over the southwestern equatorial Indian Ocean and its implications for simulating the South Asian monsoon. *Climate Dynamics*, **40** (3-4), 823-838

Boss, R. W, and J.V. Hurley, 2013: Thermodynamic bias in the multimodel mean boreal summer monsoon, *J.Climate*, **26**, 2279-2287

Bretherton, C.S., M.E. Peters, and L.E. Back, 2004: Relationships between water vapour path and precipitation over the tropical oceans, *J. Climate*, **17**, 1517-1528

De Rooy, W.C., P. Bechtold, K. Fröhlich, C. Hohenegger, H. Jonker, D. Mironov, A.P. Siebesma, J. Teixera, and J-I. Yano, 2013: Entrainment and detrainment in cumulus convection: an overview. *Q.J.R. Meteorol. Soc*., **139**,1-19

Del Genio, A.D., 2012: Representing the sensitivity of convective cloud systems to tropospheric humidity in general circulation models, *Surv. Geophys*, **33**, 637-656

Derbyshire, S.H., I. Beau, P. Bechtold, J-Y. Grandpeix, J-M. Piriou, J.L. Redelsperger, and P.M.M. Soares, 2004: Sensitivity of moist convection to environmental humidity, *Q.J.R. Meteorol. Soc*., **130**, 3055-3079

Gadjil, S., and S. Sajani, 1998: Monsoon precipitation in the AMIP runs. *Climate Dynamics*, **14**, 659-689

Holloway, C.E., and J.D. Neelin, 2009: Moisture vertical structure, column water vapour and tropical deep convection, *J. Atmos. Sci*, **66**, 1665-1683

Holloway, C.E., S.J. Woolnough, G.M.S. Lister, 2012: Precipitation distributions for explicit versus parameterized convection in a large-domain high resolution tropical case study, *Q.J.R. Meteorol. Soc.*, **138**, 1692-1708

Jakob, C., 2010: Accelerating progress in global atmospheric model development through improved parameterizations: challenges, opportunities, and strategies. *Bull. Amer. Meteor.Soc*., **91**, 869-875

Lal,M., U. Cubasch, J.Perlwitz, and J. Waszkewitz, 1997: Simulation of the Indian monsoon climatology in ECHAM3 climate model: sensitivity to horizontal resolution, *International Journal of Climatology*, **17** (8), 847-858

Li,C., and M.Yanai, 1996: The onset and interannual variability of the Asian summer monsoon in relation to land-sea thermal contrast, *J.Climate*, **9**, 358-375

Martin, G.M., 1999: The simulations of the Asian summer monsoon, and its sensitivity to horizontal resolution in the UK Meteorological Office unified model, *Q.J.R. Meteorol. Soc*, **125**, 1499-1525

Mukhopadhayay, P., S.Taraphdar, B.N. Goswami, and K. Krishnakumar, 2010: Indian summer monsoon precipitation climatology in a high-resolution regional climate model: impacts of convective parameterizations on systematic biases. *Wea. Forecasting*, **25**, 369-387

Muller, C.J., L.E. Back, P.A., O. Gorman, and K.A.Emanuel, 2009: A model for the relationship between tropical precipitation and column water vapour. *Geophys. Res. Lett*., **36**, L16804

Neelin, J.D., O.Preters, and K.Hales, 2009: The transition to strong convection, *J.Atmos.Sci*., **66**, 2367- n 2384

Randall, D., M. Khairoutdinov, A. Arakawa, and W.Grabowski, 2003: Breaking the cloud parameterization dreadlock. *Bull.Amer.Meteor.Soc*., **84**, 1547-1564

Ratnam, J.V., and K.K. Kumar, 2005: Sensitivity of the simulated monsoons of 1987 and 1988 to convective parameterization schemes in MM5, *J. Climate*, **18**, 2724-2743

Sperber, K.R., H. Annamalai, I-S. Kong, A. Kitoh, A. Moise, A. Turner, B. Wang, and T. Zhou, 2012: The Asian summer monsoon: an intercomparison of CMIP5 vs. CMIP3 simulations of the late 20th century, Climate Dynamics, doi:10.1007/s00382-012-1607-6

Walters, D.N, K. D. Williams, I. A. Boutle, A. C. Bushell, J. M. Edwards, P. R. Field, A. P. Lock, C. J. Morcrette, R. A. Stratton, J. M. Wilkinson, M. R. Willett, N. Bellouin, A. Bodas-Salcedo, M. E. Brooks, D. Copsey, P. D. Earnshaw, S. C. Hardiman, C. M. Harris, R. C. Levine, C. MacLachlan, J. C. Manners, G. M. Martin, S. F. Milton, M. D. Palmer, M. J. Roberts, J. M. Rodr´ıguez, W. J. Tennant, and P. L. Vidale, 2013: The Met Office unified model global 4.0 and JULES global land 4.0 configurations, *Geosci. Model Dev. Discuss.*, **6**, 2813–2881

Yavinchan, S., R.H.B. Exell, and D. Sukawat, 2011: Convective parameterization in a model for the prediction of heavy rain in southern Thailand. *J. Meteor.Soc. of Jpn*, **89A**, 201-224

Yihua,W., S.Raman,U.C. Mohanty, and R.V. Madala, 2002: Sensitivity of monsoon circulation and precipitation over India to model horizontal resolution and orographic effects, *Meteorol.Appl*., **9**, 345-356

Zachary, A.E., and D.A. Randall, 1999: Sensitivity of the simulated Asian summer monsoon to parameterized physical processes. *J.Geo.Research*, **104** (D10), 12177-12191

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