Evaluation of Tropical Cloud Simulations between CMIP6 Models and Satellite Observations

CyberTraining: Big Data + High-Performance Computing + Atmospheric Sciences

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Abstract

In this project, we look at the Global Climate Models (GCM) of CMIP6 (6th generation of Coupled Model Intercomparison Project). We analyze the cloud parameterizations of three CMIP6 models, namely, NASA-GISS-E2.1-G, NCAR-CESM2 and NOAA-GFDL-CM4, and compare the model outputs against observational data from two satellites, namely, GOCCP-CALIPSO and CERES. A common issue related to cloud parameterization when studying earlier versions of GCMs is called "Too few too bright" problem, which is related to tropical low-level clouds. In this report, we compare the percentage low, medium and high level clouds and short-wave radiative flux in Earth's tropical region. Our analysis suggests that the CMIP6-era models no longer have the 'too bright' problem, however, the 'too few' problem still prevails.

Key words. CMIP6, global climate models, cloud radiative effects, cloud parameterization, low-level clouds, COSP, CALIPSO

1 Introduction

This report presents a detailed analysis and evaluation of three Global Climate Models (GCM) in 6th generation of Coupled Model Intercomparison Project (CMIP) where we study the low-level clouds in the tropical region. Climate model development and tuning is an intense task which is based on fundamental laws of nature, i.e. energy, mass, and momentum conservation. The three principal steps involved in developing a climate model are as follows:

1. Expressing physical laws in mathematical terms by using the understanding of theoretical and observational work.

2. Implementing the mathematical expressions on computers using some form of grid (latitude-longitude-height grid).

3. Parameterizing the processes which cannot be represented explicitly, because either their complexity is too high or the mathematical expressions used in the model is not covering spatial or temporal resolution to represent the desired scale.

Our study will mainly contribute to understand the developments required in the atmospheric parameterization which involves atmospheric convection and clouds, cloud microphysical properties, aerosol processes and cloud-aerosol interactions etc. In our project, we study multiple models from 6th phase of Coupled Model Intercomparison Project (CMIP6).

The structure of the report is as follows: Section 2: Background briefly explains clouds, effect of clouds on Earth's radiation balance, CMIP project, satellite observations and Cloud Feedback

Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP) simulator. Furthermore, the common problems in GCMs related to cloud simulations and our focus of the study is also included in the same chapter followed by hypotheses and objectives. Section 3: Dataset explains different datasets we used for this analysis including both model and observation categories with instructions of how to download the data. Next, section 4: Methodology gives step by step description alongside with a flow-chart of the method we followed. Section 5: Results and Analysis comprises of figures with detailed explanations followed by the final chapter, Section 6: Conclusion where we summarize the findings of our project.

2 Background

2.1 Clouds

Clouds are an important component of the Earth's energy balance, weather and climate. Their distribution cover roughly 60 percent of the globe. Clouds regulate Earth's average temperature by regulating its energy balance; cooling through reflecting incoming solar radiation (shortwave radiation) back to space and warming through absorbing or trapping Earth emitted radiation (long wave radiation). They are required for precipitation to occur and, hence are an essential part of the hydrological cycle. Cloud system also contributes to transport Sun's energy across the planet. Due to these reasons, even a smaller change in the abundance and the location of clouds affect changes in climate.

2.1.1 Cloud formation and cloud types

Clouds are composed of tiny particles of water and/or ice that originated from water vapor available through evaporation and aerosols of natural or anthropogenic origin. Clouds are formed when rising air expands and cools until it is sufficiently supersaturated to activate some of the available condensation or freezing nuclei, i.e. conversion of aerosol particles into cloud droplets and ice crystals [1].

The evolution of a cloud is governed by the balance between a number of dynamical, radiative and microphysical processes. Depending on the thermodynamic phase, clouds can be classified as liquid water clouds (including super-cooled liquid water), ice clouds and mixed phase clouds (both ice and water). The microphysical formation mechanisms of clouds vary with its thermodynamic phase; droplet collision and coalescence for liquid clouds, riming and Wegener–Bergeron–Findeisen processes for mixed-phase clouds and crystal aggregation for ice clouds. Clouds are composed of liquid at temperatures above 0^0C, ice below about -38^0C, and both phases at intermediate temperatures [1].

Clouds can also be classified according to the cloud top height; above 440 hPa pressure level are high clouds, below the 680 hPa level are low clouds, and that in between are mid-level clouds [1]. Most high clouds occur near the equator and over tropical continents. Mid-level clouds are more prominent in the Intertropical Convergence Zone (ITCZ). Low clouds occur over all oceans but are more prominent over cooler subtropical oceans and in polar regions, but are less common over land. Across most parts of the globe these cloud layers are overlapped and that makes them less reliable to be detected separately. This in return affects the calculation of cloud radiative effects [2].

Depending on the cloud height and characteristics such as cloud phase in the atmosphere, clouds can influence the energy balance in different ways. Clouds reflect a significant portion of the incoming solar radiation (cloud albedo effect) [3], there by cooling Earth's surface. On the other hand clouds absorb and re-emit the thermal infrared radiation emitted by Earth's surface, by reducing the amount of thermal radiation escaping towards the space (cloud greenhouse effect) [4]. This cause warming of the underlying Earth's surface and atmosphere. Under clear sky conditions, solar radiation is reflected by underlying surfaces (land, ocean or vegetation) and aerosols and absorbed by atmospheric trace gases and absorbing aerosols. Therefore in comparison to clear sky conditions, cloudy skies have the potential of either to warm or cool the Earth's surface [5].

2.2 Effect of clouds on Earth's radiation balance

The cloud height affects the amount of outgoing heat radiation a cloud is capable of trapping (Fig.2.2). A cloud that is at a higher altitude in the atmosphere emits less heat to the space than an identical cloud at a lower altitude. Low level clouds are relatively warmer than upper level clouds and hence their emission takes place at warmer temperatures closer to that of the Earth's surface. Therefore they have a little impact on emitted thermal radiation which translates to more emission to the space [1].

The cloud thickness (or optical thickness) affects the ability of a cloud to reflect incoming solar radiation (Fig.2.2). Thick clouds are capable of intercepting more radiation hence they have a larger albedo or more reflection capability [1]. Thin clouds are sparse and have lower albedo. Usually the high level clouds are thinner compared to low level clouds. Therefore the contribution of low level clouds towards the reflection of incoming solar radiation is larger. With less reflection and more absorption, the overall effect of the high thin clouds is to warm the Earth's surface where as the overall effect of low clouds is to cool the Earth's surface.

Deep convective clouds that spreads vertically to an extent around 10 km have cloud tops that are high and cold. Due to these high cold cloud tops, these clouds radiate very less thermal energy to space. As they also are very thick, they reflect much of the solar radiation back to space [1]. As a consequence, the cloud greenhouse and albedo effects almost balance for deep convective clouds thereby making their overall effect neutral.

The net effect of clouds towards Earth's temperature depends on the cloud cover, their thickness and altitude, the size of the condensed particles, and the amount of water and ice it contains [5].

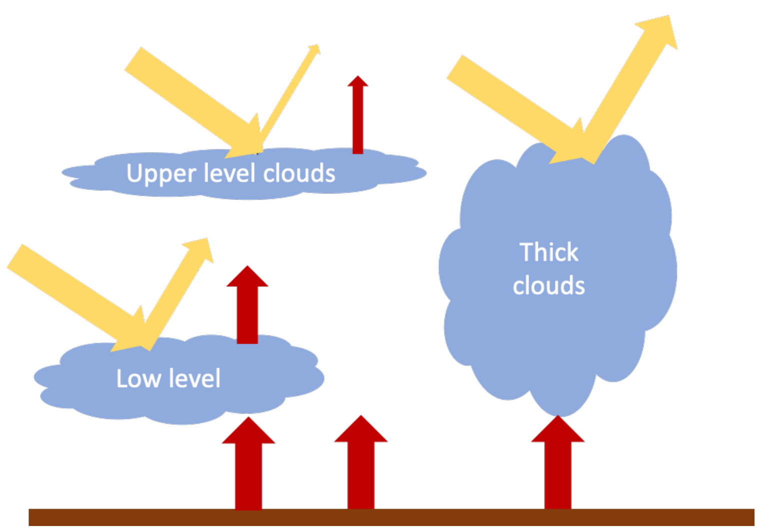


Figure 2.1: Cloud albedo and greenhouse effects. (Yellow arrows: Incoming shortwave solar radiation, Red arrows: Outgoing long wave thermal radiation). The width of the arrow represents the magnitude of the radiation flux.

2.2.1 Radiation energy balance

The Earth's energy balance refers to the balance between the incoming solar energy and outgoing energy from the Earth, i.e., radiative equilibrium. By balancing the energy, the Earth maintains a stable average temperature which results in a stable climate. This energy balance depends on factors such as atmospheric greenhouse gases, aerosol types and abundance, surface albedo and cloud cover.

Changes in the surface temperature due to the changes of the Earth's energy balance do not occur until a new equilibrium state is established between radiative forcing mechanisms and the climate response. Radiative forcing are the changes to Earth's radiative equilibrium, that cause temperatures to change over a subtantial period of time. They are either of natural or anthropogenic origin. Positive radiative forcing takes place when the Earth receives more incoming energy from sunlight than it radiates to space and vice versa. Radiative forcing are also capable of triggering feedbacks that in return intensify or weaken the original forcing [6].

Earth's net radiation, or net flux, is the balance between incoming and outgoing energy at the top of the atmosphere which is capable of influencing the climate.

$$F^{net} = F^{\downarrow} - F^{\uparrow} \tag{2.1}$$

where $F^{\downarrow}$ is the downward total flux and $F^{\uparrow}$ is the total upward flux. Each total flux is a combination of short wave (SW) flux F_{SW} and long wave (LW) flux F_{LW}. Then the net flux can be written as,

$$\begin{aligned} F^{net} &= (F^{\downarrow}_{SW} + F^{\downarrow}_{LW}) - (F^{\uparrow}_{SW} + F^{\uparrow}_{LW}) \\ F^{net} &= F^{net}_{SW} + F^{net}_{LW} \end{aligned} \tag{2.2}$$

2.2.2 Cloud radiative effect (CRE)

The difference between net fluxes measured for average (overcast or cloudy) atmospheric conditions and clear sky conditions for the same region and time period is known as the cloud radiative effect (CRE). It is directly dependent on the amount of clouds present or cloud fraction per given area. CRE is partitioned into longwave (CRE_{LW}) and shortwave (CRE_{SW}) forcing terms. The combined effect typically results in a negative net forcing at the top of the atmosphere. The short wave cloud radiative forcing, CRE_{SW} can be defined as follows [7].

$$\begin{aligned} CRE_{SW} &= F_{SW\,cloudy} - F_{SW\,clear} \\ CRE_{SW} &= (F^{\downarrow}_{SW\,cloudy} - F^{\uparrow}_{SW\,cloudy}) - (F^{\downarrow}_{SW\,clear} - F^{\uparrow}_{SW\,clear}) \\ CRE_{SW} &= F^{\uparrow}_{SW\,clear} - F^{\uparrow}_{SW\,cloudy} \end{aligned} \tag{2.3}$$

where $F^{\downarrow}_{SW\,cloudy}$ and $F^{\downarrow}_{SW\,clear}$ are similar for both cases. The short wave cloud radiative forcing, CRE_{LW} can also be expressed similarly, where $F^{\downarrow}_{LW}$ for both clear and cloudy cases are non-existent.

$$CRE_{LW} = F^{\uparrow}_{LW\,clear} - F^{\uparrow}_{LW\,cloudy} \tag{2.4}$$

With more solar radiation being reflected back to space under cloudy conditions, CRE_{SW} is usually negative. On the other hand, CRE_{LW} is usually positive as less radiation is allowed to escape in to space under cloudy conditions. The amount of high level cloud fraction is less significant for CRE_{SW} as it becomes less negative under the presence of high level clouds compared to low level clouds.

The annual global CRE_{SW} is approximately -53 W/m^2 where as that of CRE_{LW} is approximately 30 W/m^2. The net global annual mean CRE is approximately -21 W/m^2. Thus the clouds have a net cooling effect on the current climate [7].

2.3 CMIP Project

To make climate predictions on seasonal to decadal and over coming century and beyond, the primary tools that are available to use are Global Climate Models (GCMs) and the investigations in these models are done by evaluating the response of the climate system to different types of forcing. The types of GCMs range from simple energy balance models to complex Earth System Models (ESMs) whereas the choice depends on the scientific question that needs to be addressed. The 'standard' climate models assessed in Intergovernmental Panel on Climate Change (IPCC)'s Fourth Assessment Report (AR4) were Atmosphere-Ocean General Circulation Models (AOGCMs) and the primary function of these models is to understand the dynamics of atmosphere, land, ocean and sea ice and make future predictions based on greenhouse gases (GHGs) and aerosol forcing. ESMs on the other hand are based on AOGCMs and expanded in to include other biogeochemical cycles such as carbon, sulphur or ozone [8]. There is another type which falls in between AOGCMs and ESMs which is named as Earth System Models of Intermediate Complexity (EMIC) which attempts to include relevant components from ESMs but at a lower resolution than both AOGCMs and ESMs [9]. EMICs usually are used to understand specific type of scientific questions. Regional Climate Models (RCMs) are another type, which carries the components of atmosphere and land without interactive ocean and sea ice of AOGCMs and are focused to do simulations on specific geographical regions to infer more detailed information [10]. Irrespective of the type of the model, to ensure the performances are on an acceptable level, it is important to assess their performances individually and collectively. In our project, the models we assess mainly falls under AOGCMs and our focus is mainly on the atmosphere component.

CMIP is a project which coordinates the design and distribution of GCM simulations of past, current, and future climate. The project is handled by World Climate Research Programme (WCRP)'s Working Group of Coupled Modelling (WGCM) and multiple modeling teams worldwide have contributed to CMIP since 1995. The main goal of CMIP is to advance scientific understanding of the Earth system which helps to better understand past, present, and future climate changes which results from natural and unforced variability or in response to changes in radiative forcing. One of the main goals of CMIP is to make the multi-model outputs publicly available in a standardized format which a wider climate community and users could make use of for different analysis. The Earth System Grid Federation (ESGF) data replication centres have facilitated the collection, archival, and access of the models output in a standardized and specified format. CMIP simulations get regularly assessed by IPCC Climate Assessments Reports and other national assessments whereas it is developed in phases where CMIP5 has been completed and CMIP6 is in the development stage.

Structure of CMIP has the following three main elements:

1. Handful of common experiments which is called Diagnostic, Evaluation and Characterization of Klima (DECK) and historical experiments which runs from 1850 to near present which will help maintaining the continuity across different phases of the project.

2. Common standards, infrastructure and documentation that will facilitate distribution of model outputs.

3. Ensemble of CMIP endorsed Model Intercoparison Projects (MIPs) which will build on DECK and historical simulations. These MIPs are specific to specific phase of CMIP and the ones we use in this study are from phase 6.

CMIP6 addresses the following three main questions:

1. How forcing would affect Earth system?

2. Where the systematic model biases are originated from and their consequences?
3. With given uncertainties, variabilities, and predictabilities of the scenarios, how can we assess future climate?

As mentioned above, there are handful of DECK experiments which helps to provide continuity across different CMIP phases, to evolve as little as possible over time, to be well established and to be used as a common ground between different simulations performed by different modelling groups, and to be relatively independent from the objectives of the considered CMIP phase. DECK comprises of four baseline experiments:

1. Historical Atmospheric Model Intercomparison Project (*amip*) simulation
2. Pre-industrial control simulation (*piControl* or *esm-piControl*)
3. Simulation forced by an abrupt quadrupling of CO2 (*abrupt-4CO2*)
4. Simulation forced by a 1%yr1 CO2 increase (*1pctCO2*)

CMIP also comprises of a historical simulation (*historical* or *esm-hist*) which covers the period from 1850 to the present. In our study we use data from *amip* and *historical* runs to be analyzed in detail. In AMIP simulations, the sea surface temperature (SST) and sea ice concentration (SIC) are prescribed based on observations. This allows the analysis and evaluation to be done on the atmospheric and land components of the climate system when they are constrained by the observed ocean conditions. On the other hand CMIP historical runs provide abilities to simulate climates including past trends which facilitates the analysis to determine whether climate model's forcing and sensitivities agree with the observational records [11].

Our analysis is mainly focused on cloud simulations of CMIP6 generation models, hence different data related to cloud properties are being used here.

2.4 Satellite Observations

Satellite observations which operates continually provides global coverage of information on the Earth and its subsystems which are atmosphere, oceans, continental surfaces, cryosphere, and biosphere. Satellites can see all the interesting cloud characteristics which includes up-welling and down-welling solar radiation data at top of the atmosphere for cloudy and clear sky conditions with cloud fraction data from multiple satellites will be used in this study.

2.5 COSP simulator

Comparing clouds simulated by GCMs directly with the clouds derived from the satellite observations from earth is not correct, because the definition of clouds depends on sensitivity of the instrument and the vertical overlap of the cloud layers. To make the comparison more meaningful, some GCMs use a community software named Cloud Feedback Model Intercomparison Project (CFMIP) Observation Simulator Package (COSP) which provides a diagnosis of what different satellites would observe if they were flying above an atmosphere which is generated by GCMs. Simulator list of COSP consists of CALIPSO, CloudSat, ISCCP, MISR, MODIS, PARASOL, RTTOV, and Combined (CALIPSO and CloudSat). For our analysis, we mainly focus on using COSP-CALIPSO data from different CMIP6 models.

By using mean vertical temperature profiles, humidity, hydrometeor of clouds and precipitation mixing ratios, cloud optical thickness, emissivity, and surface temperature outputs from model in terms of grid-box averages, COSP produces output comparable to satellite data. This is done in three main steps [12].

1. Each grid-box is first broken into sub-columns which represents a smaller area than a grid box which is in proportion to satellite pixel. This step is done to minimize the gap between the scale of GCM grid-box with the satellite pixel.

2. Each vertical profile of individual sub-column then passes through all the instrument simulators which will output the signals and/or retrievals from the respective simulators.

3. Finally, all the outputs are combined to build diagnostics which are directly comparable with the satellite observations.

2.6 Problems in cloud simulation

The existing GCMs are not accurate enough that the simulation of clouds and their feedbacks in the models remains challenging, increasing the model uncertainties, which is evident from the comparison of model estimated CRE with satellited observed CRE. Some of the common biases in climate models causing these deficiencies in terms of cloud simulation are, underestimation of total cloud, overestimation of optically thick cloud, and underestimation of mid level cloud. All these biases together lead to two common issues in GCM cloud simulations, which are listed below. In this study, we only focus on the first problem.

1. **Too few-too bright problem**
   This is related to tropical low level clouds and refers to the insufficient formation of low cloud fraction or few low level clouds in the tropical or subtropical ocean, especially over the eastern of major ocean basins (e.g., SE Pacific, NE pacific, SE Atlantic, SE Indian ocean). On the other hand, thicker clouds are simulated in those regions in the attempt of balancing the radiation in GCM, which translates in to higher cloud reflection, hence too bright clouds.

2. **Absorbed solar radiation bias in Southern ocean**

   This refers to the significant underestimation of the cloud fraction in the southern ocean region (˜40S-70S), leading to excessive absorbed solar radiation in the model (reflection is too weak, and absorption is too strong)

2.7 Hypotheses and Objectives

Hypothesis: Radiation bias between CMIP6 models and observations (Models not reflecting enough compared to observations) in the tropical region is mainly due to the deficiency in low level clouds of models in that region.

The objective of this project is, therefore, to evaluate the cloud simulations in the CMIP6-era GCMs. In particular, we will investigate:

1. Does the “too few too bright” problem still exist in the CMIP6-era models?

2. What are the improvements in CMIP6 models as compared to CMIP5-era models?

3 Dataset

This study has been conducted on two satellite observational datasets and three simulated Global Cloud Models GCMs datasets.

3.1 CMIP6 Models

The three uncoupled CMIP6 models considered in this study are NCAR-CESM2, NASA-GISS and NOAA-GFDL. All the datasets have been publicly accessed and downloaded using wget scripts published by the Earth System Grid Federation (ESGF) data archives. Instructions to download these scripts are available at https://github.com/big-data-lab-umbc/cybertraining/tree/master/year-3-projects/team-3/Data/Simulation. A tabulated description of grid levels, data variants, time periods and frequency is given in Table 3.1 and 3.2.

3.1.1 NASA GISS-E2.1-G

NASA Goddard Institute of Space Studies' GISS-E2.1-G model dataset is an improved and updated version of GISS-E2-R, which was used in CMIP5. This model uses the ModelE atmospheric code on a lat-lon grid, with 40 vertical layers. It has a model top at 0.1 hPa and is coupled to the GISS ocean model (11.25L40). The model was run by the Goddard Institute for Space Studies, New York, NY 10025, USA (NASA-GISS) in native nominal resolutions: aerosol: 250 km, atmos: 250 km, atmosChem: 250 km, land: 250 km, ocean: 100 km, seaIce: 250 km [13].

3.1.2 NCAR CESM2

Community Earth System Model (CESM) is a fully-coupled, global climate model that provides state-of-the-art computer simulations of the Earth's past, present, and future climate states. The CESM project is supported primarily by the National Science Foundation (NSF). Administration of the CESM is maintained by the Climate and Global Dynamics Laboratory (CGD) at the National Center for Atmospheric Research (NCAR) [14].

3.1.3 NOAA GFDL-CM4

NOAA's Geophysical Fluid Dynamics Laboratory Coupled Physical Model (GFDL-CM4) consists of AM4.0 atmosphere at approximately 1° resolution with 33 levels and sufficient chemistry to simulate aerosols (including aerosol indirect effect) from precursor emissions, OM4 MOM6-based ocean at 0.25° resolution with 75 levels using hybrid pressure/isopycnal vertical coordinate. The model produces a very good simulation of the present-day climatology and ENSO variability. NOAA's Geophysical Fluid Dynamics Laboratory provides state-of-the-art coupled global Earth system models - a suite of societally relevant information and decision support products from weather to climate time scales, and on geographic scales, from local to global [15].

3.2 Observational Data

The two satellites considered in this study for observational data are CERES and CALIPSO-GOCCP. These data were publicly accessed and downloaded via respective websites, for which the links and the instructions are mentioned at https://github.com/big-data-lab-umbc/cybertraining/tree/master/year-3-projects/team-3/Data/Observational

3.2.1 CERES

The CERES-EBAF product provides 1-degree regional, zonal and global monthly mean Top-of-Atmosphere (TOA) and surface (SFC) longwave (LW), shortwave (SW), and net (NET) fluxes under clear and all-sky conditions. The net TOA radiative fluxes of the CERES data set used in this study is derived from Level 4 Energy Balance And Filled (EBAF) products [16].

Table 3.1: CMIP6 models and GOCCP dataset description for downloading data from ESGF archives

Variable Name					Grid				Time Period			
CMIP6	**GOCCP**	**Variant**	**Frequency**	**Table ID**	**GOCCP**	**GISS**	**NOAA**	**CESM**	**GOCCP**	**GISS**	**NOAA**	**CESM**
cllcalipso	cllcalipso	r1i1p1f1	mon	CFmon	90x180	gn 90x144	gr1 180x288	gn 192x288	200606 to 201803	197901-198812, 198901-199812, 199901-200812, 200901-201412	200301-200812, 200901-201412	195001-201412
clmcalipso	clmcalipso	r1i1p1f1	mon	CFmon	90x180	gn 90x144	gr1 180x288	gn 192x288	200606 to 201803	197901-198812, 198901-199812, 199901-200812, 200901-201412	200301-200812, 200901-201412	195001-201412
clhcalipso	clhcalipso	r1i1p1f1	mon	CFmon	90x180	gn 90x144	gr1 180x288	gn 192x288	200606 to 201803	197901-198812, 198901-199812, 199901-200812, 200901-201412	200301-200812, 200901-201412	195001-201412
cltcalipso	cltcalipso	r1i1p1f1	mon	CFmon	90x180	gn 90x144	gr1 180x288	gn 192x288	200606 to 201803	197901-198812, 198901-199812, 199901-200812, 200901-201412	200301-200812, 200901-201412	195001-201412

Table 3.2: CMIP6 models and CERES dataset description for downloading data from ESGF archives

Variable Name					Grid				Time Period			
CMIP6	**CERES**	**Variant**	**Frequency**	**Table ID**	**CERES**	**GISS**	**NOAA**	**CESM**	**CERES**	**GISS**	**NOAA**	**CESM**
rsdt	solar_mon	r1i1p1f1	mon	Amon	180x360	gn 144x90	gr1 360x288	gn 192x288	200003 - 201701	185001-190012, 190101-195012, 195101-200012, 200101-201412	200301-200812, 200901-201412	195001-201412
rsut	toa_sw_all_mon	r1i1p1f1	mon	Amon	180x360	gn 144x90	gr1 360x288	gn 192x288	200003 - 201701	185001-190012, 190101-195012, 195101-200012, 200101-201412	200301-200812, 200901-201412	195001-201412
rsutcs	toa_sw_clr_mon	r1i1p1f1	mon	Amon	180x360	gn 144x90	gr1 360x288	gn 192x288	200003 - 201701	185001-190012, 190101-195012, 195101-200012, 200101-201412	200301-200812, 200901-201412	195001-201412

3.2.2 CALIPSO-GOCCP

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) which is a joint satellite mission between NASA and the French Agency CNES was launched on April 28, 2006. The main focus of this mission is to study the impact of clouds and aerosols on the Earth's radiation budget and climate. CALIPSO which comprises of the Cloud-Aerosol LIdar with Orthogonal Polarization (CALIOP), the Imaging Infrared Radiometer (IIR), and the Wide Field Camera (WFC) flies in formation with five other satellites in the international "A-Train" constellation for coincident Earth observations. In this study, GCM oriented CALIPSO dataset is being used which is based on CALIOP level 1B lidar Scattering Ratio profiles [17].

4 Methodology

We design an algorithm to load the different types of cloud data files from CESM, NOAA, GISS modeling files, as well as the satellite observation data GOCCP-CALIPSO and CERES, to compute its difference and make interpolation, as illustrated in Figure 4.1. We design a generic data loader that can read all the data types and can also be extended to other data types. The workflow starts checking what the data file it reads, and passes it to the corresponding data handling module, in which it will read the data from the disk, load its spatial and temporal information such as latitude, longitude, time, as well as the variables that will be analyzed such as low level cloud, mid level cloud, high level cloud, total level cloud. It then draws the cloud fraction data in a two dimensional figure and we can do some visualization comparison. Next, we interpolate all models and observations into 180x360 grid, and compute and draw the difference plots.

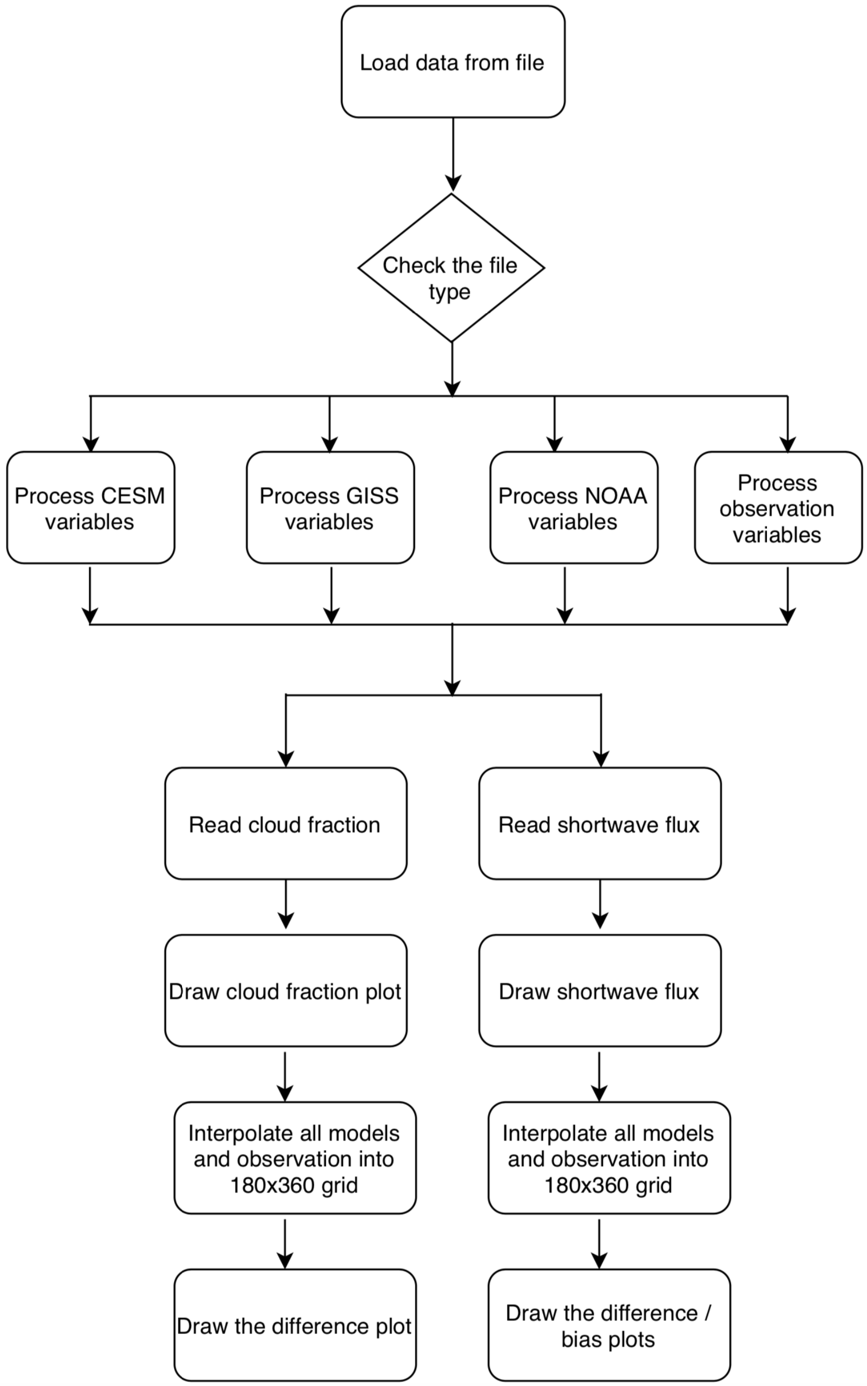


Figure 4.1: Method Diagram of Data Loading and Processing

Since the data loading and processing module is generic and flexible, we use the same flow to load the shortwave flux data from CESM, NOAA, GISS modeling files and two satellite observation data GOCCP-CALIPSO and CERES and generate the Shortwave radiation flux for Clear Sky and All Sky, and Shortwave bias plots for Clear Sky and All Sky.

To analyze the cloud radioactive effect in Tropical region, we load and compute the minimum values of medium and high level clouds, pick and load the non-overlapping low level clouds, pick and load CRE of non-overlapping low level clouds, and plot the probability density function of non-overlapped low-cloud covers as well as plotting shortwave cloud radioactive effect variation with low cloud cover.

5 Results and Analysis

As the starting point of our study, the global radiation energy balance of three CMIP6 models, namely, NCAR-CESM, NASA-GISS and NOAA-GFDL were compared with the observations from GOCCP-CALIPSO and CERES datasets for a time period of eight years i-e from May 2006 to December 2014.

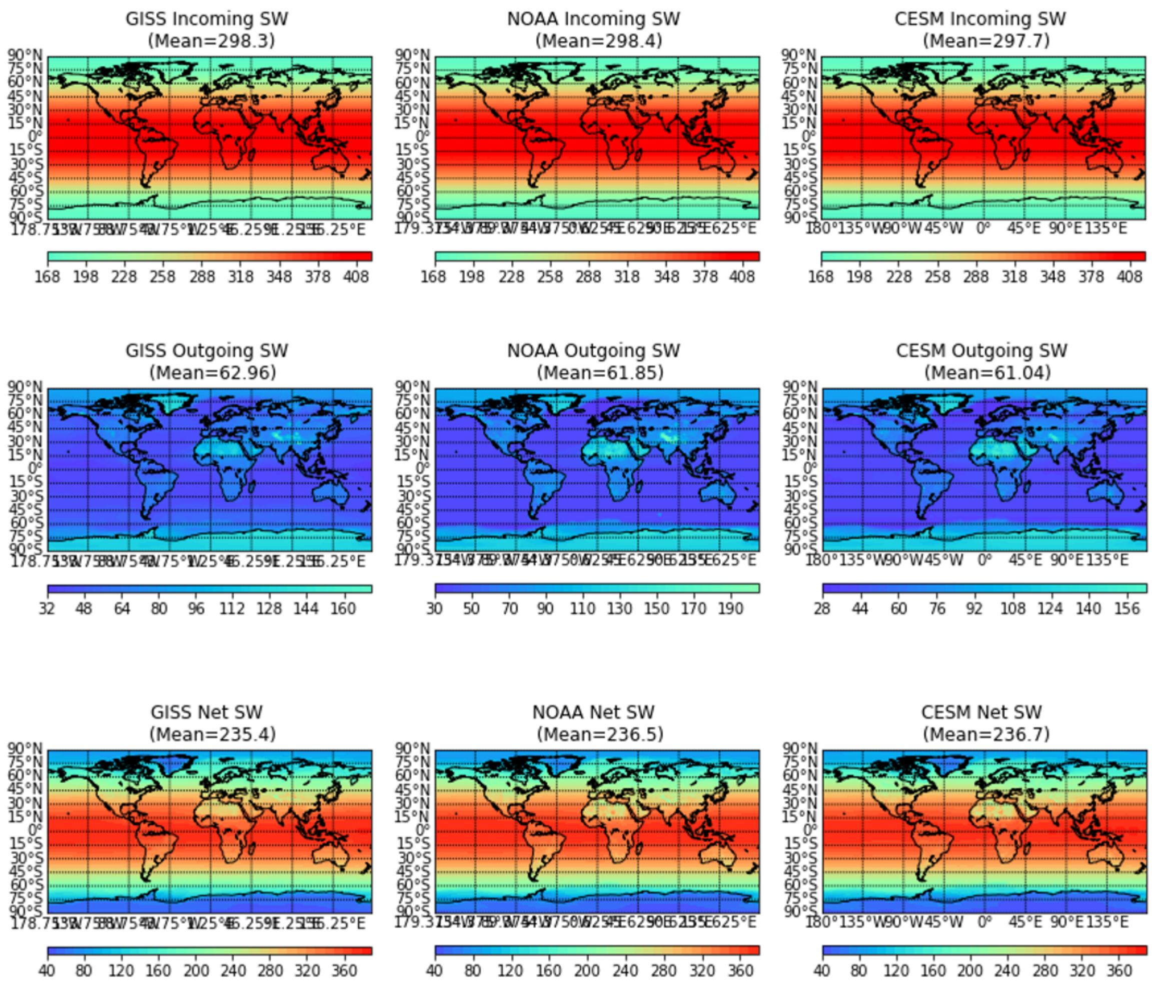


Figure 5.1: Shortwave radiation flux for Clear Sky

As it can be seen through the mean values shown in Figure 5.1 and Figure 5.2, the global value for net shortwave (SW) radiation is almost the same between the models and observations in

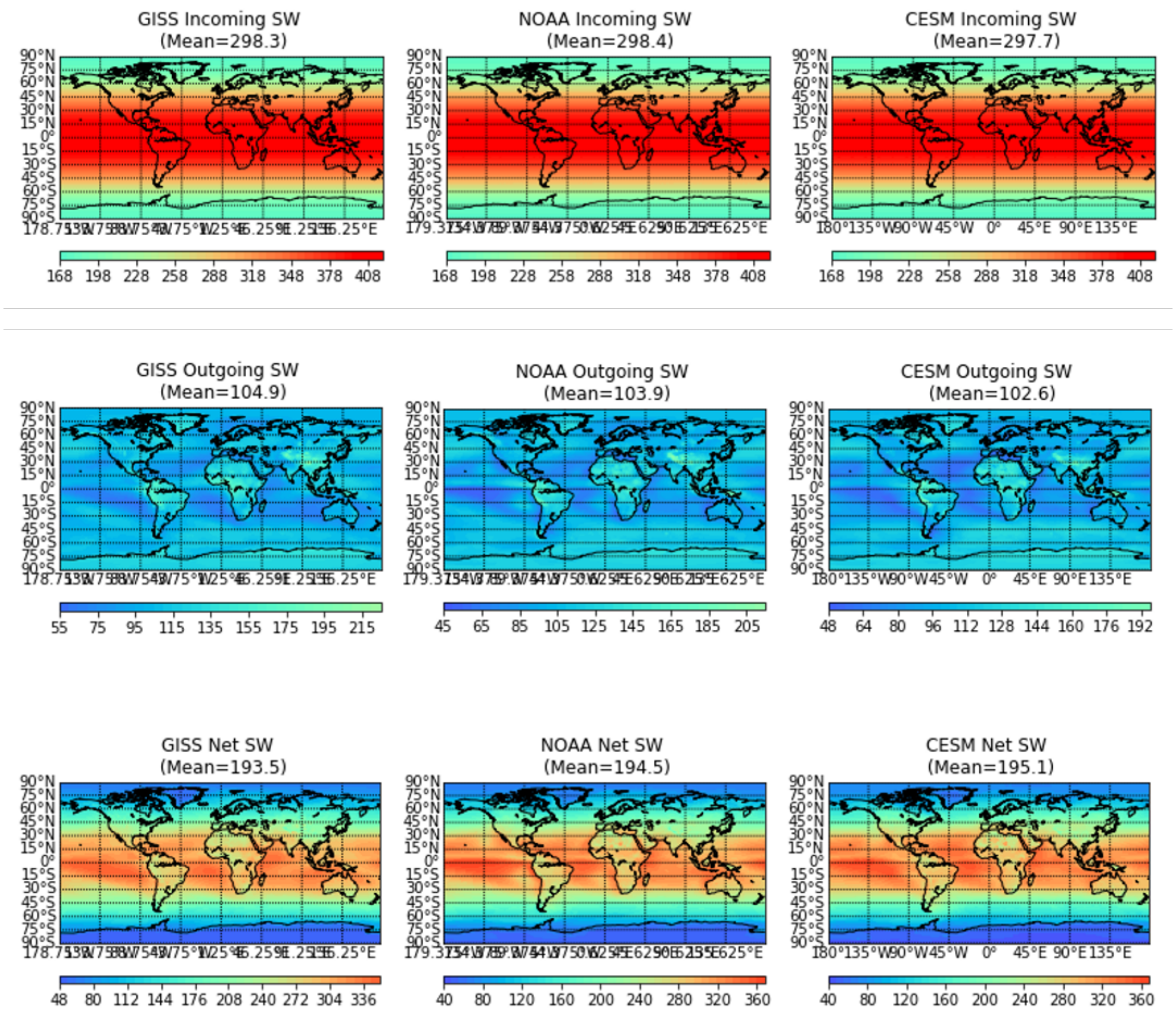


Figure 5.2: Shortwave radiation flux for All/Cloudy Sky

both clear and cloudy sky cases. However, when observing the net SW radiation bias plots, 'clear sky' cases show very small biases overall while there are significant positive and negative biases in different regions in 'all sky' cases which collectively contribute to the almost zero bias in the global average values. This drives our focus to study the contribution of clouds to these biases, because in the first order the change from 'clear sky' to 'all sky' is the addition of clouds. Our study is mainly focused on the tropical region, which shows a significant positive bias in the 'all sky' cases for all the models considered. Positive net SW bias implies, models not reflecting enough SW radiation back to the atmosphere, which in first order could be hypothesize as 'not having enough clouds' in those regions.

As it can be identified in the total cloud bias plots in Figure 5.5, the regions with a negative total cloud bias (i.e. models not generating enough clouds), are directly correlated with positive net SW bias regions. For example, South East Pacific (West of South America), South East Atlantic (West of Africa) and North East Pacific (West of North America). This supports our hypothesis of

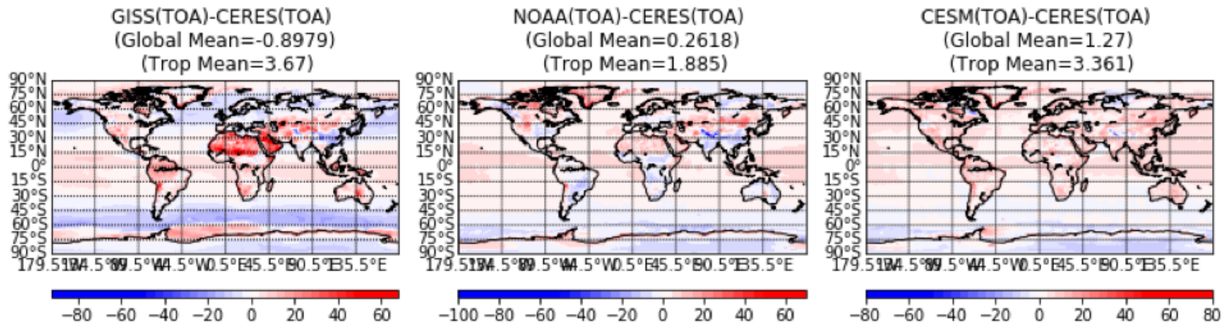


Figure 5.3: Shortwave bias plots for Clear Sky

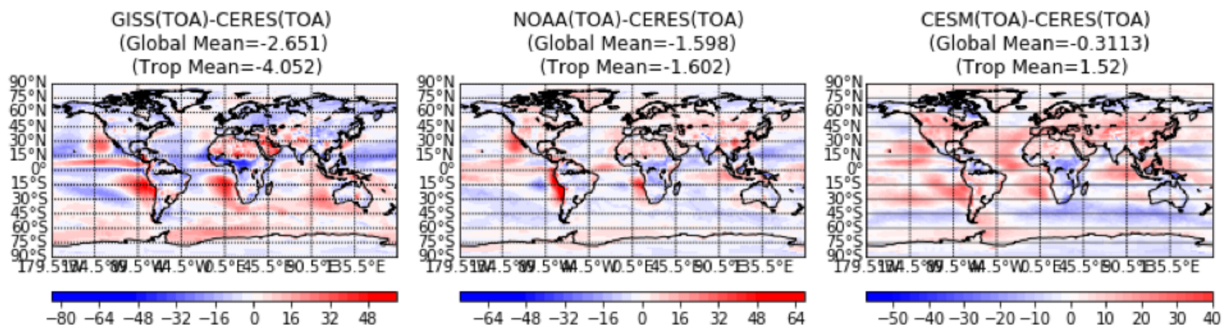


Figure 5.4: Shortwave bias plots for All Sky

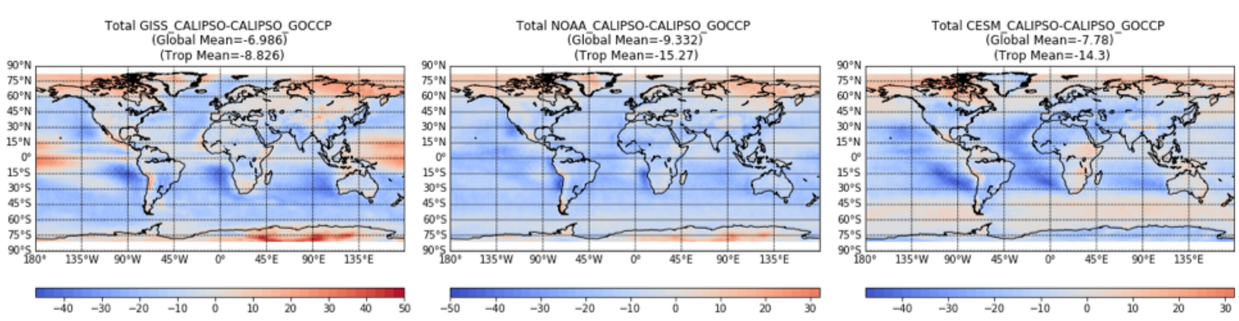


Figure 5.5: Total Cloud Fraction Bias in NASA-GISS, NOAA-GFDL and NCAR-CESM Models (2006-2014)

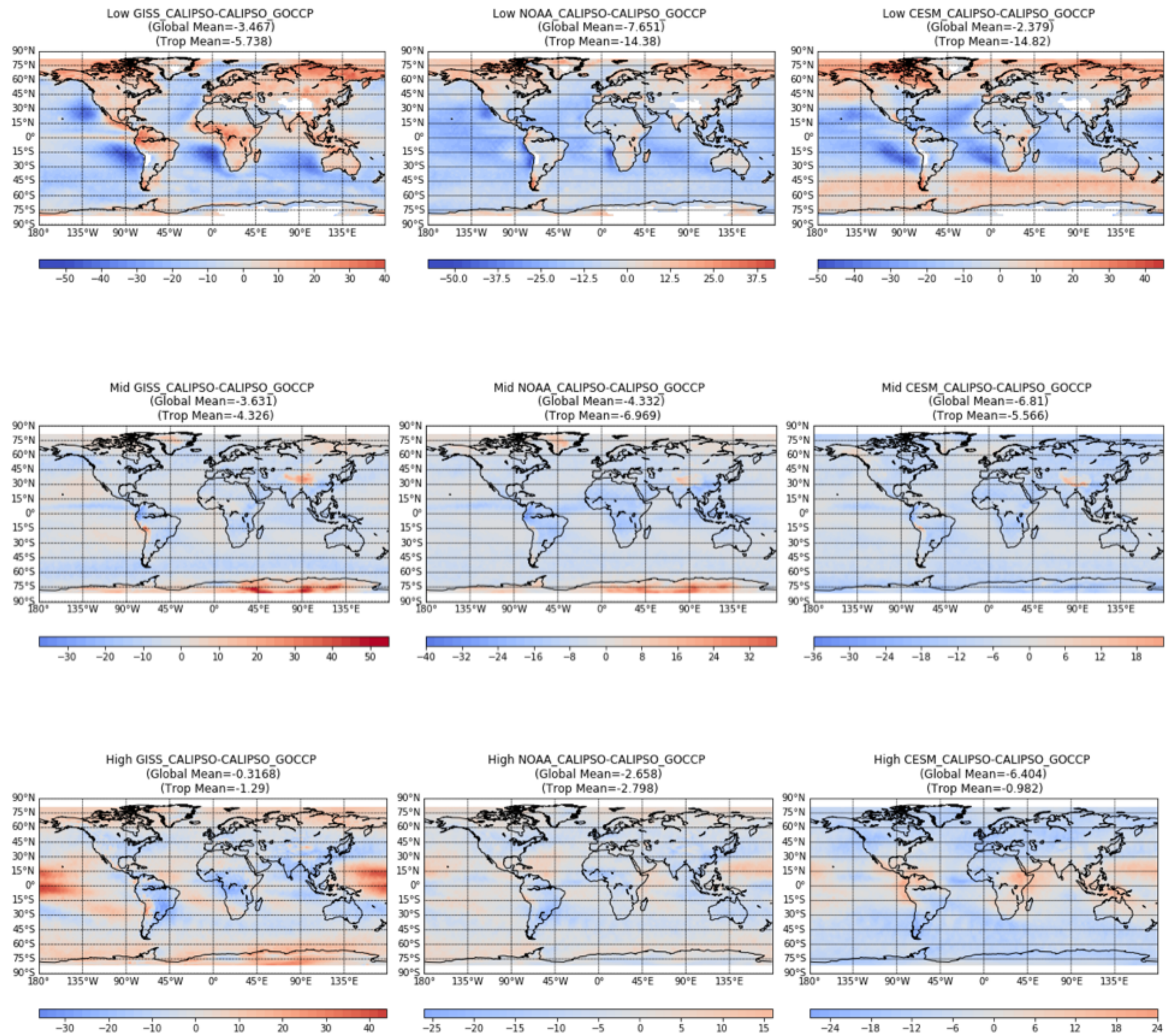
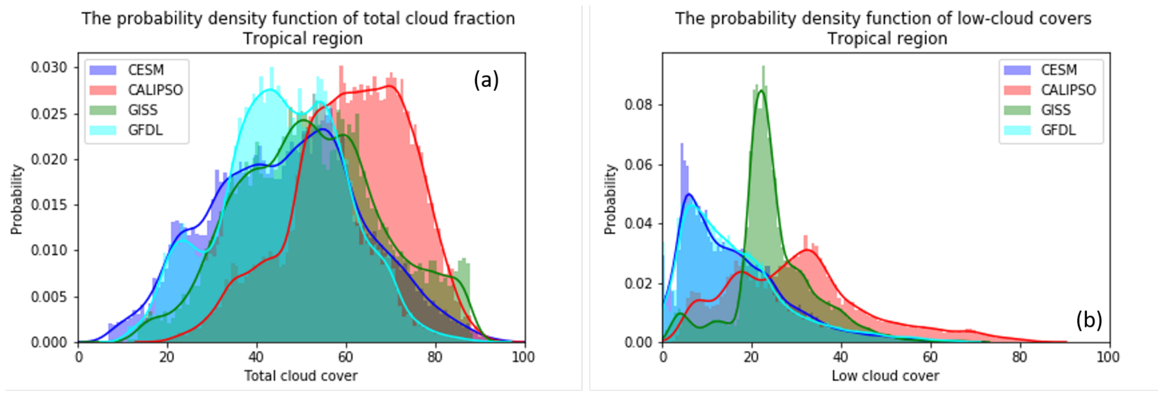


Figure 5.6: Low, Mid and High Cloud Fraction Bias in NASA-GISS, NOAA-GFDL and NCAR-CESM Models (2006 - 2014)

"Radiation bias between CMIP6 models and observations (Models not reflecting enough compared to observations) in the tropical region is mainly due to the deficiency in clouds of models in that region." To further analyze this, and to relate it to long lasting "too few – too bright" problem in GCMs, the cloud biases were broken down in to low, mid, and high levels as shown in Figure 5.6.

When observing the bias plots, it is evident that the negative bias in the total cloud fraction plots are mainly contributed by the low-level cloud biases, which supports the previous understanding of "too few" problem of low level cloud generation in GCMs. To further analyze this, the following plots of probability density function (pdf) of low-level clouds in the tropical region were created.

Figure 5.7 shows pdfs of all three models are positively skewed and the distribution of low-



tropical total giss = 52.38%
tropical total gfdl = 45.94%
tropical total cesm = 46.91%
tropical total calipso = 61.21%

tropical low giss = 24.92%
tropical low gfdl = 16.23%
tropical low cesm = 15.82%
tropical low calipso = 30.61%

Figure 5.7: The probability density function of total cloud fraction in Tropical region

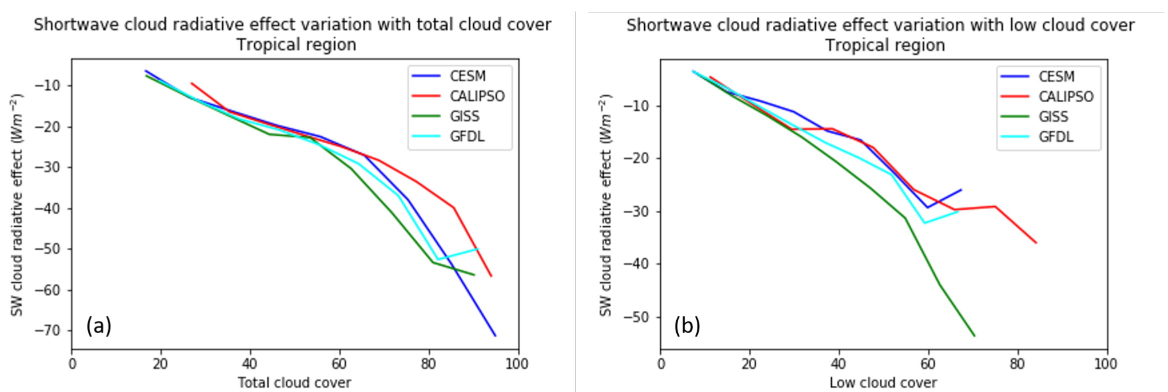


Figure 5.8: Shortwave cloud radiative effect for GISS, CESM, NOAA models vs CALIPSO observations

level clouds show the models generally over-estimate clouds with small cloud fractions. The area under the pdfs account for the low-level cloud cover in the tropical region which are 31%, 25%, 16% and 16% for CALIPSO observations, NOAA-GISS model, NCAR-CESM model and NASA-GFDL model, respectively. This concludes that models have more broken low-level clouds whereas observational low-level clouds are more over-cast. This contributes to the net SW bias we observed in Figure 5.4, where models reflect lower amount of SW radiation back in to the atmosphere, because of the fact that the generated low-level clouds in the models being more broken, which allows radiation to pass through them towards the Earth, instead of being reflected back. Pdf for the total cloud fraction over the tropical region was also created to fact check whether the area under the curves reflect the exact values for the tropical region.

To evaluate the “too bright” part of the long-lasting problem we are focused on, SW cloud radiative effect was plotted against low-level cloud cover in the tropical region.

Figure 5.8 (a) shows in the CRE for total CF, all the models agree with the CALIPSO observations up to around 60% of the CF. After that, models seem to have brighter clouds when total CF is considered. Figure 5.8 (b) - the variation of CRE for low-level CF, shows, all three models agree with the CALIPSO observations up to around 30% of CF and for CF larger than that, GISS seems to generate more brighter clouds while CESM and GFDL continues to match the brightness of CALIPSO low-level clouds.

6 Conclusion

In conclusion, the three GCMs evaluated, i.e., NASA-GISS-E2.1-G, NCAR-CESM2 and NOAA-GFDL-CM4 from CMIP6 have achieved a shortwave radiation balance in the global scale. However, tropical region manifest considerable biases in different regions compared to CERES observations. The regions which are not reflecting enough in the GCMs (Positive biases in Figure 5.4) are associated with cloud deficiencies in the model (Negative bias regions in Figure 5.5). Total cloud deficiencies in the considered CMIP6 models are mainly contributed by the under-estimation of low-level clouds (Figure 5.6). This supports the presence of "too few" problem of low-level clouds in the CMIP6 generation models. This is further explained with Figure 5.7 (b). However, when CREs of the models are compared against the observations (Figure 5.8 (b)), not enough evidence was present to show the presence of "too bright" problem in the tropical low-level clouds which previous generations of GCMs have identified [18]. In summary, our analysis suggests that the CMIP6-era models no longer have the 'too bright' problem, however, the 'too few' problem still prevails.

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