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Abstract

Studying the movement of water through the atmosphere has been an area of both interest and challenge. Climate models have been trying to recreate the dynamic processes of the atmospheric hydrologic cycle in attempt to better understand past, current, and future climate. However, this has proved to be quite difficult as the hydrologic cycle is not fully understood nor simple to simulate. It is shown though that climate models such as the Community Atmosphere Model are able to capture and recreate most of the patterns and paths of water as it moves through the atmosphere. Though, many of the long-standing biases in climate models are still found to be present in current versions of the model. This study will compare model output from the Community Atmosphere Version 5 with observational data. The variables that were compared were radiative surface temperature, evaporation minus precipitation, precipitation rate, precipitable water, total cloud fraction, and cloud liquid water path. The model tends to capture the zonal patterns of moisture across the Earth with only a few discrepancies near the mid-latitudes and with total cloud fraction. The model also tends to be accurate with the magnitude of the variables though there is a major discrepancy with cloud liquid water path. As a whole, the results suggest that current climate models are able to be an effective tool in trying to better understand both the hydrologic cycle and past climates.

1. Introduction

The movement of water in the atmosphere makes up the basis for weather in the atmosphere. Water plays many different roles from radiation balance to sustaining environments around the world with precipitation. Yet, representing this water in the atmosphere has long posed a challenge for scientists. This challenge is not limited to predicting the future of weather, it is still an issue that is present in determining past climates. In response to this challenge came the development of Global Climate Models (GCMs).

GCMs can simulate physical processes and variables in the atmosphere, on the ground, in the ocean, or some combination of the three (Conley 2012). By simulating data from known physical and dynamic processes, an attempt can be made from these models to recreate the past climates. However, it is these said dynamic and physical processes that are the source of error in trying to recreate the past. Most of these processes occur on a much smaller scale than GCMs tend to simulate (Hack et al. 2006). This leads to errors and biases in how these models attempt to represent the past climates.

One of the fundamental basis for representing the hydrologic cycle in the atmosphere is to accurately depict cloud amounts and cloud heights. This is not an easy task for the models as clouds have small physical processes and forcing mechanisms that lend to their development. This has caused the models to have significant error in reproducing the mean cloud cover across the globe (Dai 2006; Kay et al. 2012).

Clouds are not one dimensional. They can have varying heights and widths depending on the atmospheric conditions. They may also form at different heights in the atmosphere. All of these differences do have an impact on the influence of clouds on radiation and precipitation. GCMs therefore must accurately simulate both location and height of the clouds. One main struggle is to capture marine stratus or marine boundary layer clouds near the tropics and subtropics (Dai 2006; Kay et al. 2012). Many of the models tend to undershoot these clouds which leads to errors in the surface radiation budget and precipitation. Another struggle for these models is overshooting the high cloud amounts (Hack et al. 2006). This would in turn lead to error in radiation fluxes near the Top of the Atmosphere (TOA).

Simulating cloud location is an important aspect but also correctly estimating the available vapor in and around the clouds is just as vital. It has been found that the models have much more varying degrees of efficiency when it comes to accurately representing cloud liquid water with models from the Coupled Model Intercomparison Project (CMIP) tending to overestimate the mean Liquid Water Path (LWP) (Lauer, Hamilton 2013). This study did not try to correlate the result to precipitation but does show a bias of increased liquid water in clouds.

With the mix of clouds and liquid water, precipitation is now a factor in the hydrologic cycle. Since precipitation is the removal of water from the atmosphere, it plays a key role in the quantity of stored water in the atmosphere. Environments range in their conditions and how likely they are to see precipitation. This likelihood of precipitation also tends to change per season which leaves plenty of room for small errors. However, the models do seem adapt at reproducing the average spatial coverage of precipitation (Dai 2006).

The error for precipitation in models tends not to manifest itself in annual averages though any model does have some degree of error. Instead it is more regionalized like in the tropics where the Intertropical Convergence Zone (ITCZ) oscillates. It has been found in multiple models that a form of double ITCZ is produced from the simulations (Hack et al. 2006; Dai 2006). These studies also found that the tropics did tend to have erroneous regions of precipitation measurement. However, this depended on the model and acceptable error.

As mentioned earlier, the water cycle operates on both a larger and smaller scale. A GCM with a larger resolution will have a lesser chance of picking up these smaller differences than if it is more fine scale. Though it was found that for models like the Community Atmosphere Model (CAM) that resolution has little bearing on the results produced from the model (Bacmesiter et al. 2014). While certain features such as tropical cyclones are simulated with improved accuracy, the global climate scale was not significantly improved. Henceforth, an increased resolution is not important in determining the mean climate state.

2. Data and Methods

This study analyzed how accurately CAM 5 simulates different components of the atmospheric hydrologic cycle when compared to observational data.

a. Community Atmosphere Model

The CAM (Conley 2012) was developed by the National Center for Atmospheric Research (NCAR) and is the atmospheric component in the Community Earth System Model. The model is a three-dimensional climate model that is run with 26 vertical layers. Within the model are multiple programs and processes that run different equations to simulate many of the physical process for convection and moisture transport.

b. Observational Data

Observational data consists of precipitation rate from the Xie and Arkin study (XA), precipitable water and evaporation minus precipitation from the European Center for Mid-Range Weather Forecasts reanalysis (ECMWF), cloud liquid water path from NASA's Water Vapor Project (NVAP), total cloud fraction from the International Satellite Cloud Climatology Project (ISCCP), and radiative surface temperature from the National Center for Environmental Prediction (NCEP). The data is 12-month yearly averages that are averaged for the 10-year period from 1980-1989.

c. Procedure

The CAM was run with data from the beginning of the observational data period. Upon obtaining the simulated data from the model, the model's variable data was compared with the corresponding observational data. This was done using the NCAR diagnostic package for the CAM model. From this, zonal averages and global averages were calculated and compared annually (ANN), December through February (DJF), and June through August (JJA).

3. Results

a. Zonal Average Patterns

Temperature is useful in measuring potential forcing and storage of water in the atmosphere. Zonally averaged radiative surface temperature is simulated fairly accurately in comparison with observations in Fig. 1. The model manages to simulate the pattern from the equator to the North Pole in all the seasons with only slight underestimations from 50^{o}N to 90^{o}N. From the equator to the South Pole, the model also simulates the pattern up until 80^{o}S. Here the model does not simulate the slight increase in temperature poleward that inland Antarctica experiences during the region's winter months. Though it is worth noting that the model is closer in magnitude to observations across the Earth during the JJA period than it is during the DJF period.

The exchange of water into and out of the atmosphere is important for determining how much water is going into and out of the atmospheric hydrologic cycle. Fig. 2 illustrates this by comparing the zonally averaged evaporation minus precipitation for the CAM5 simulation and ECMWF observation. Annually, the model is accurate in simulating the zonal pattern across the planet. The model also is relatively accurate in representing the magnitude of evaporation though there is more discrepancy in and around the equator and tropics. This is especially true in the Southern Hemisphere where the model underestimates evaporation by nearly 50%. Another discrepancy is found in the sub-tropics and lower mid-latitudes of the Northern Hemisphere where the model shifts the pattern around 5° to 10° North during the JJA and DJF periods. The model also turns the two peaks in evaporation in this area during the winter months into one.

Looking more closely at the water leaving the atmosphere, Fig. 3 shows the zonally averaged precipitation rate. CAM5 when compared with the observations does a relatively good job of representing the patterns of annual rainfall short of the mid-latitudes in the Southern Hemisphere. Instead of decreasing the rainfall rate going poleward from around 40°S, the model continues to increase the rainfall rate to near 60°S before rapidly decreasing the rainfall rate to just before the pole. This leads the region to have overestimated precipitation in the mid-latitudes with underestimated precipitation in the pole. Given that this occurs in both

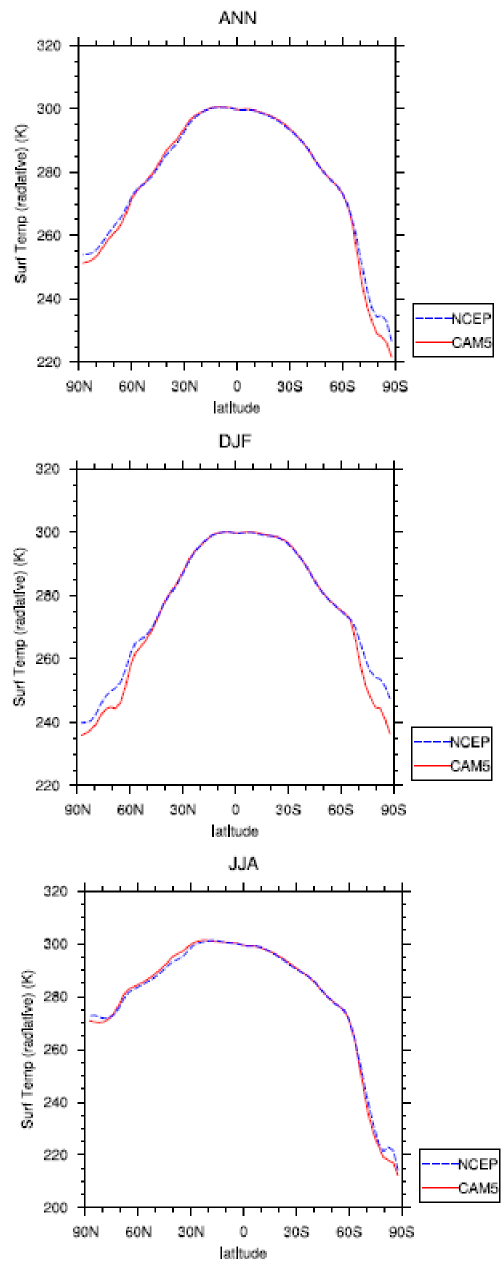

Figure 1: Zonally averaged surface temperature (determined radiatively in degrees K) simulated by CAM5 (Solid Red) and from NCEP observations (Dashed Blue) for ANN (top), DJF (middle), and JJA (bottom) periods.

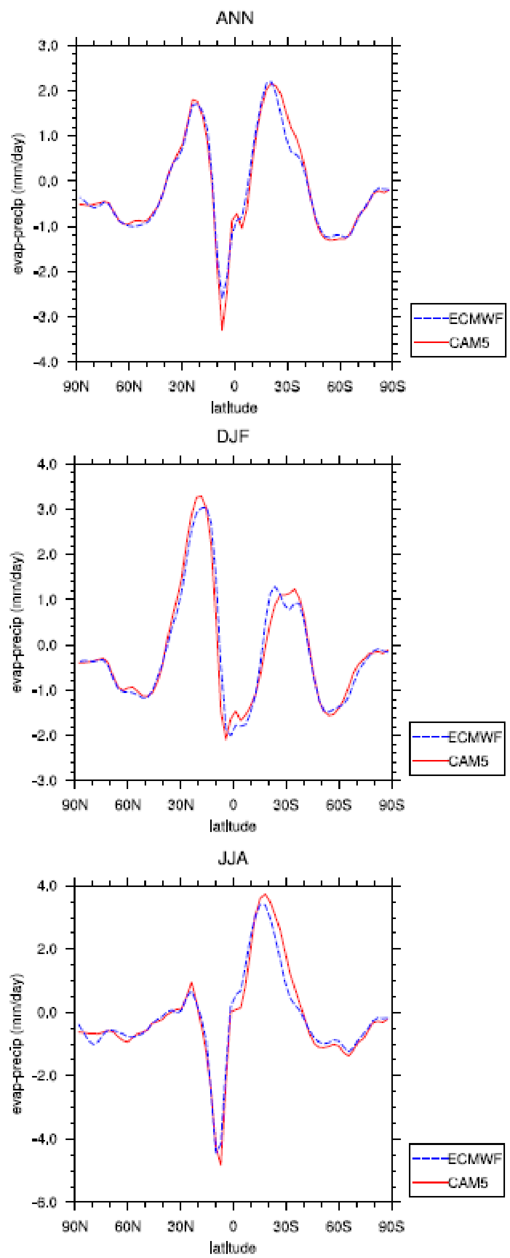

Figure 2: Zonally averaged evaporation – precipitation (in mm/day) as simulated by CAM5 (Solid Red) and for ECMWF observations (Dashed Blue) for ANN (top), DJF (middle), and JJA (bottom) periods.

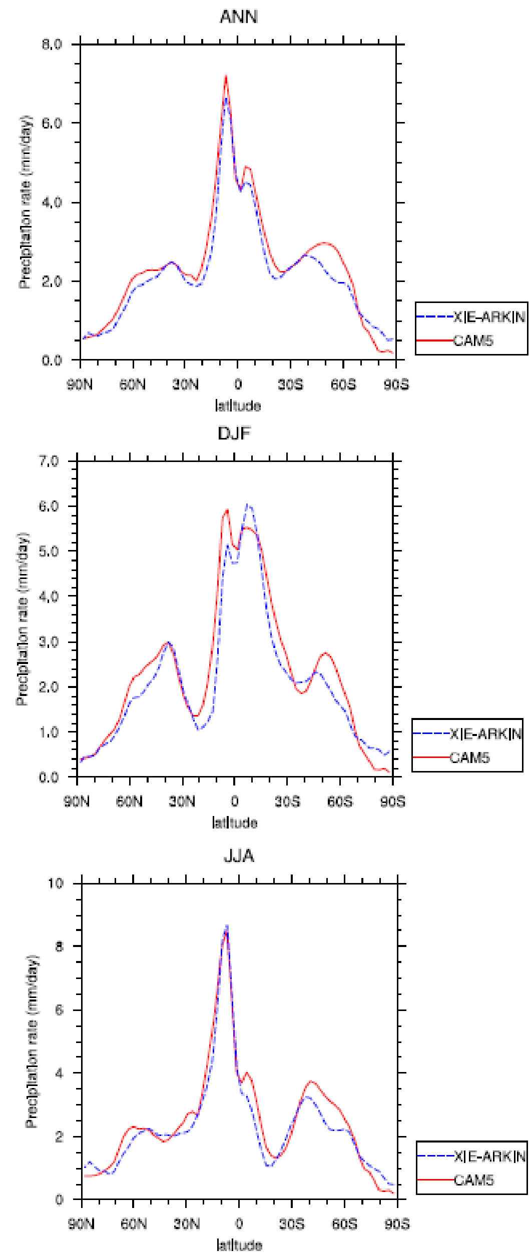

Figure 3: Zonally average precipitation rates (in mm/day) as simulated by CAM5 (Solid Red) and from XIE-ARKIN study observations (Blue Dashed) for ANN (top), DJF (middle), and JJA (bottom) periods.

seasonal plots as well, the model may have a bias in overestimating precipitation over open water given that most of the mid-latitudes in the Southern Hemisphere are ocean. Also worth noting is that the model continues to reproduce the double ITCZ during the Northern Hemisphere's winter (Hack et al. 2006). In terms of magnitude, the model both annually and seasonally tends to overestimate the precipitation rate but is often still relatively close to the observation.

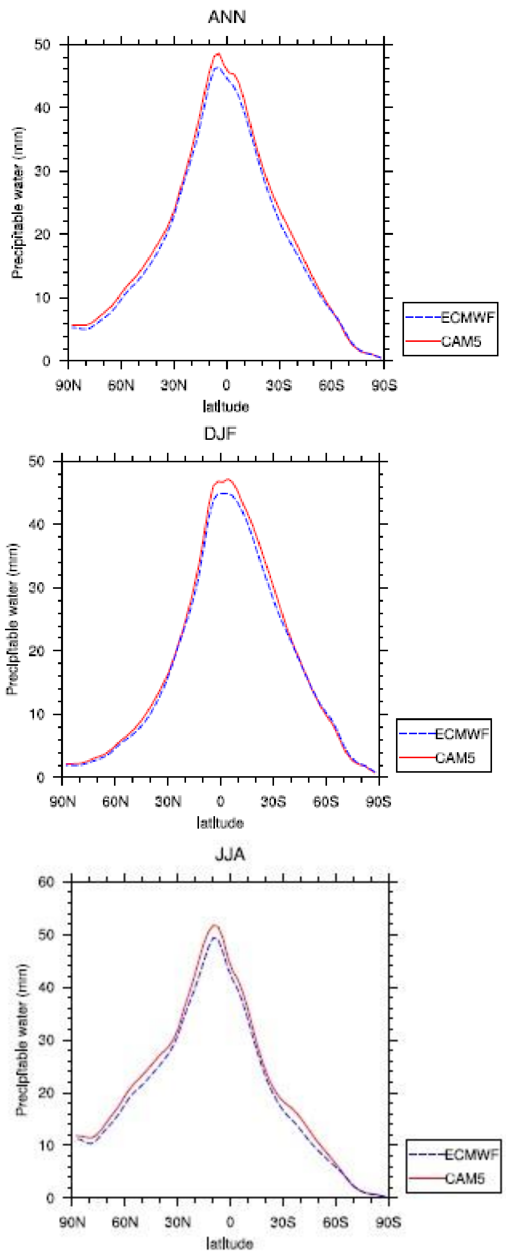

Figure 4. Zonally averaged precipitable water (in mm) as simulated by CAM5 (Solid Red) and from ECMWF observations (Dashed Blue) for ANN (top), DJF (middle), and JJA (bottom) periods.

While water often moves in and out of the atmosphere, some water vapor is left in storage. Fig. 4 shows this water storage by displaying the zonally averaged precipitable water. The model both seasonally and annually is nearly perfect in comparison with observation with the pattern of higher precipitable water near the equator with lower precipitable water near the poles. The models are even successful at depicting the

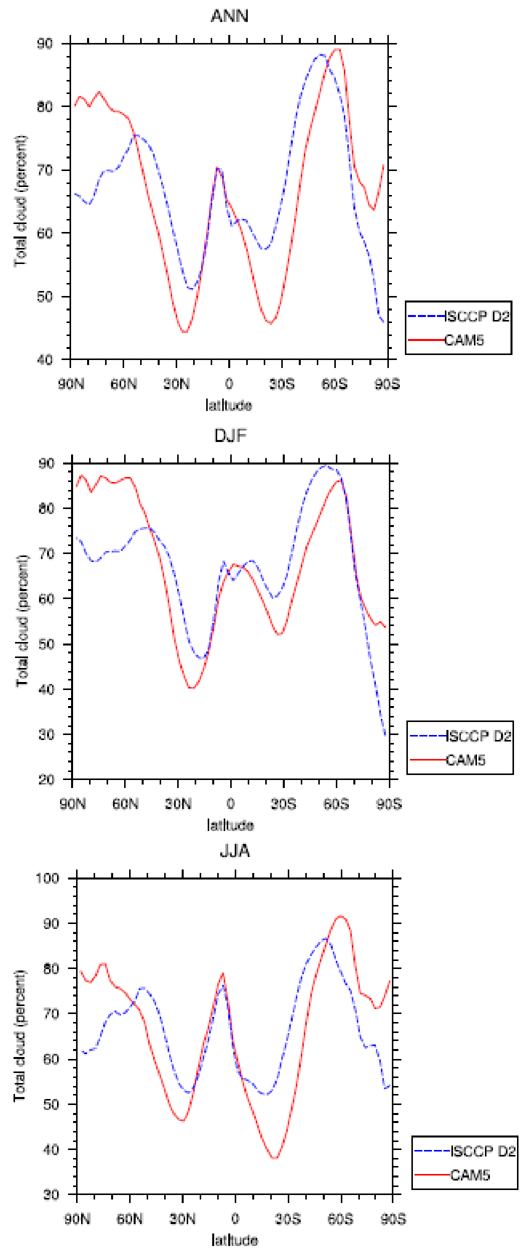

Figure 5: Zonally averaged total cloud fraction (percent) as simulated by CAM5 (Solid Red) and from ISCCP D2 observations (Dashed Blue) for ANN (top), DJF (middle), and JJA (bottom) periods.

change in precipitable water as the Northern Arctic Ocean freezes (decreasing precipitable water) during the DJF period and thaws (increasing evaporation and precipitable water) during the JJA period. This is further supported by the South Pole having less precipitable water than the North Pole (given Antarctica is almost all ice). Some discrepancy does exist with model overestimating precipitable water near the equator and during the JJA period. However, these differences are relatively small.

Not all available water in the atmosphere is condensed or precipitated out. Only some of the water in the atmosphere at any given time is either clouds or liquid. Fig. 5 looks at the zonally averaged total cloud fraction between the CAM5 simulation and ISSCP observations. In comparison with the observation, the model semi-accurately simulates the annual pattern of clouds from 50^{o}N to 80^{o}S. However, the pattern often lags behind the observations about 5^o to 10^o moving poleward. This seems to stem from the model exaggerating the peaks in magnitude. The model seems to struggle with reproducing the total cloud patterns in the poles as the model increases cloud percentage poleward instead of decreasing it as suggested by the observations. This is seen both seasonally and annually. Another discrepancy worth noting is that during the DJF period, the model has a peak magnitude at the equator where as the observations show distinct peaks in both hemisphere's tropics. This could suggest an issue with the model in capturing some of the seasonal variance associated with the ITCZ and the naturally warm waters associated with the Northern Hemisphere's tropics.

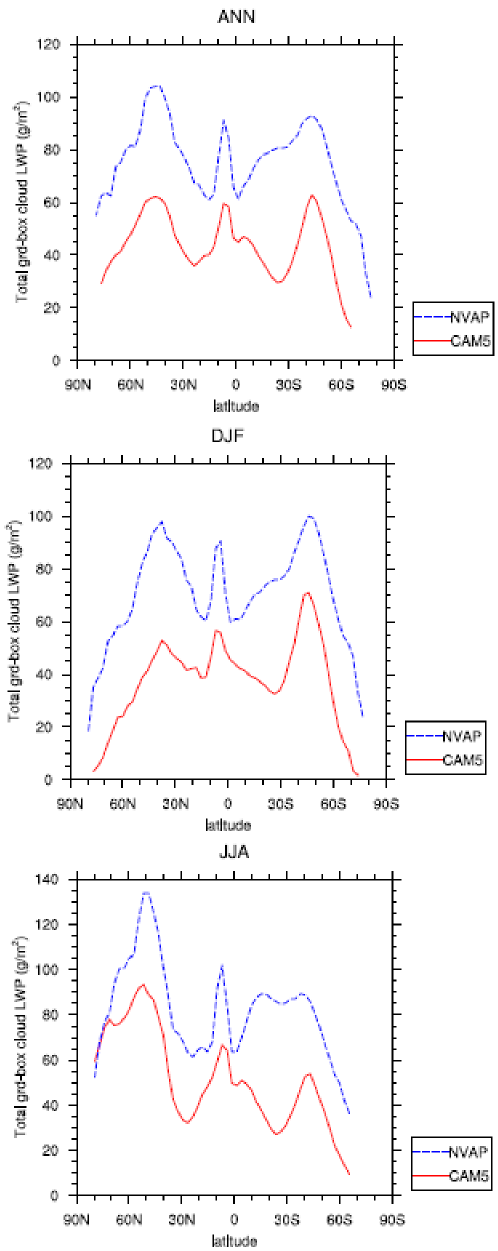

Figure 6. Zonally averaged cloud liquid water path (in g/m^2) as simulated by CAM5 (Solid Red) and from NVAP observations (Dashed Blue) for ANN (top), DJF (middle), and JJA (bottom) periods.

Clouds themselves do not contain all the available precipitable water in the atmosphere within them. Clouds have their own liquid water content which is measured by cloud liquid water path and compared in Fig. 6. The model semi-accurately reproduces the pattern in comparison with the observations but is different in the tropics and sub-tropics of the Southern Hemisphere. The model decreases the liquid water path towards the mid-latitudes instead of increasing as the model suggests. Looking at the seasonal averages, this occurs more during the DJF period when the ITCZ is present in this region. This could suggest that the model struggles to represent the water that is put into the atmosphere by the ITCZ when it is situated more over ocean (the Southern Hemisphere has more ocean in this region than the Northern Hemisphere). Another discrepancy for the model is that its magnitude both seasonally and annually is around 20 to 40 g/m^2 under the observed values. Given that the pattern is semi-followed, it is likely just an error in the equation. Though the model matches the observation around 75⁰N during the JJA period, this is likely due to the difference in pattern between the model and observations for this area.

b. Global Anomalies

Zonal averages are useful in displaying some of the model's strengths, weaknesses, and biases. Zonal averages are also useful for seeing how water is transported through the atmosphere given that the Earth tries to balance the Equator and Poles heat and moisture content. However, not all points along a latitude line have the same geologic structure or biome classification. Zonal averages can't completely represent area or regional events such as monsoons and climates such as deserts. Henceforth it is important to also analyze a model's accuracy in different areas around the world where climates and other conditions are not exactly the same.

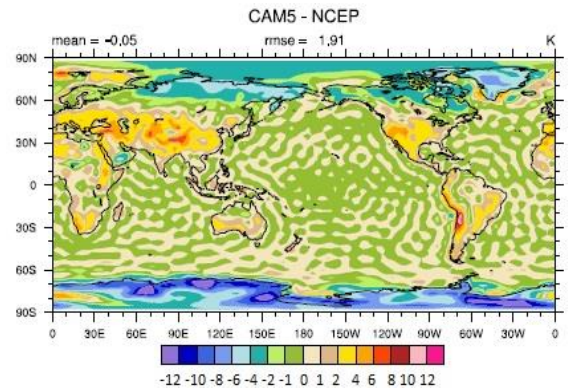

Figure 7: Annual global anomaly in radiative surface temperature (in K) for CAM5 simulated values minus NCEP observational values.

Looking at the annual average temperatures (Fig. 7), the model is fairly accurate across most of the globe. Most temperature anomalies are within 2 degrees Kelvin of the observational data. It should be noted that due to prescribed sea surface temperature, most of the oceans have little to no error to report short of the Arctic Ocean which will freeze during its respective winter time. The model does seem to have a tendency to underestimate the annual temperature in areas where ice is present (Antarctica, Greenland, Arctic Ocean, etc.). However, in mountainous regions such as the Himalayas, Rockies, and the Andes Mountains, the model tends to overestimate temperature.

In regards to annual evaporation minus precipitation (Fig. 8), the model is very accurate from the mid-latitudes poleward in both hemispheres. The model is also semi-accurate in the tropical regions though there are multiple local maximum and minimum across the equatorial region. Most of the

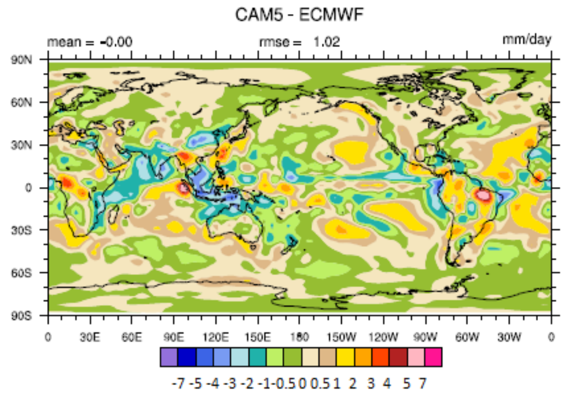

Figure 8: Annual global anomaly in evaporation minus precipitation (in mm/day) for CAM5 simulated values minus ECMWF observational values.

overestimates by the model occur over land where many underestimates occur over the ocean or Indonesian Islands.

In conjunction with Fig. 8, Fig. 9 shows the global annual average precipitation rate. Looking at both figures, the local high magnitude errors in precipitation rate mostly line up inversely

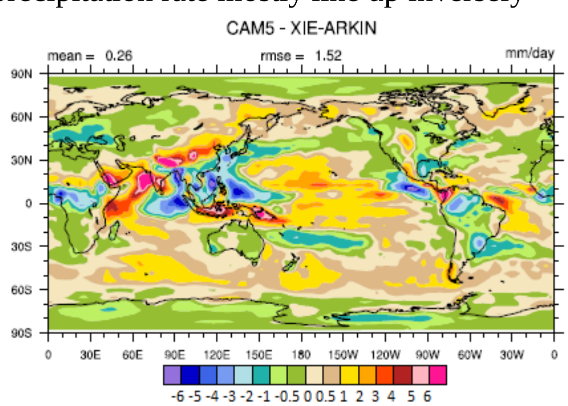

Figure 9: Annual global anomaly in precipitation rate (in mm/day) for CAM5 simulated values minus XIE-ARKIN study observational values.

with the high magnitude errors in E-P. This could suggest that the model is more accurate in representing evaporation than in precipitation. This is further supported by the magnitude of error being greater in precipitation rate than in E-P. Aside from the high magnitude errors in the tropics, the model handles precipitation rates fairly accurately. It is worth noting that precipitation rates do tend to be overestimated (even if slightly) over ocean water while precipitation rates are generally underestimated over land. The model does also tend to underestimate precipitation in regions that are predominately colder such as Antarctica and the Arctic Ocean.

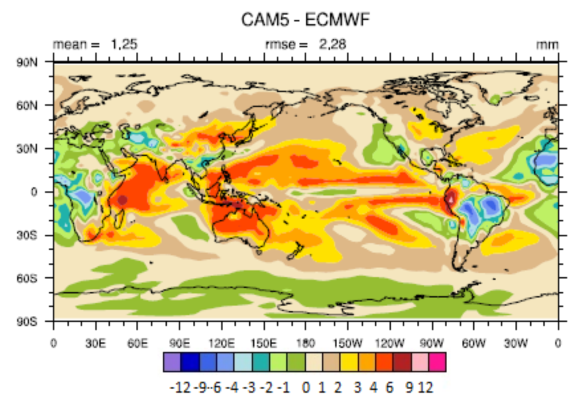

Figure 10: Annual global anomaly in precipitable water (in mm) for CAM5 simulated values minus ECMWF observational values

Looking now at annual precipitable water across the globe (Fig 10.), most of the results are similar to what was discussed above in the zonal averages. However, it is shown that most of the overestimation occurs over ocean (with the exception of Australia and the surrounding islands) and underestimation tends to occur over land. It is worth noting that most of the land/ocean borders that are underestimated do tend to be near an ocean current that is bringing cooler water from a more Arctic source.

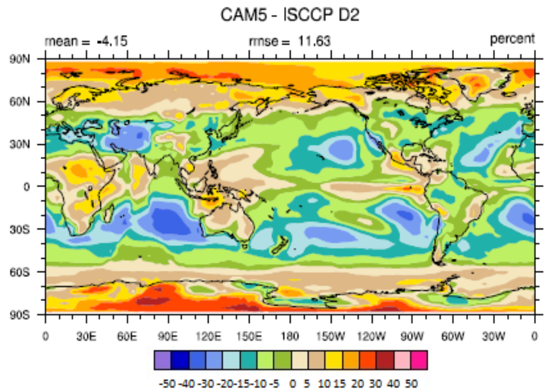

Figure 11: Annual global anomaly in total cloud fraction (in %) for CAM5 simulated values minus ISCCP D2 observational values.

Looking at annual total cloud fraction (Fig. 11), some of the results from the zonal averages are seen such as the overestimation in the polar regions. However, it can be seen that the oceans tend to be a source of higher magnitude errors as well, often underestimations in areas where colder ocean currents are moving next to land. This does not seem to be a product of colder water itself as 60°S is slightly overestimated and the Arctic Ocean has greater overestimation values than that. Land surface does tend to be more accurate than ocean surfaces not considering areas covered in ice.

Annual ocean only (excluding the Arctic Ocean) cloud liquid water path is shown in Fig. 12. The major feature looking across the oceans is that the model underestimates cloud liquid water path in open water. The area of the oceans that are closer to shore either saw a reduction in the magnitude in error or even lead the model to overestimate off the Northwest coast of

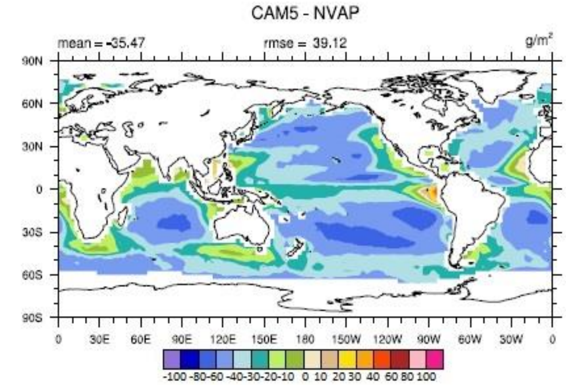

Figure 12: Annual global anomaly in cloud liquid water path (ocean only in g/m^2) for CAM5 simulated values minus NVAP observational values.

South America. Worth noting is that most of the higher magnitude underestimations, especially in the Pacific Ocean, tend to occur where ocean currents curve with the land features. They also line up with the higher underestimations in the total cloud fraction from Fig. 11.

4. Discussion

a. Equatorial and Tropical Region

In the area between 30°S and 30°N, the model handled the pattern of moisture very accurately short of the double ITCZ in precipitation during Northern Hemisphere winter. However, the model tends to move and store too much water in this region. Most of the moisture variables (precipitable water, E-P, precipitation rate) were overestimated with many of the greater magnitude errors occurring in the tropics. These greater errors also tend to appear in conjunction with more regional and seasonal events such as the movement of the ITCZ and the Indian Monsoon. Surface temperature are represented well both in pattern and magnitude with most errors being within 1-

degree Kelvin. Clouds are not represented as well as other variables in this region. The pattern is mostly simulated in the Northern tropics and near the equator albeit with significant underestimations both in cloud total and cloud liquid water path. The total cloud is semi-accurately simulated in the Southern tropics though the model does not accurately simulate the pattern moving towards the mid-latitudes.

b. Mid-Latitudinal Region

In the mid-latitudes, surface temperature is simulated fairly accurately. However, the Northern Hemisphere was more likely to be different from observations in large part because of the greater land mass area. Similar to the equatorial and tropical region, the model does tend to overestimate the precipitation variables in this region as well. The model is able to reproduce most of the patterns for water movement as well short of the Southern Hemisphere's precipitation rate which increases instead of decreasing poleward. Worth noting is that the evaporation minus precipitation for both hemispheres is mostly accurate both in magnitude and pattern. Henceforth the model is more rigorous in evaporation in this area to counter the overestimated precipitation. This is also seen by the slight increase in overestimation of precipitable water which means more water is being moved into the atmosphere than what was observed. Clouds are better represented in the mid-latitudes compared to the tropical regions as the total cloud pattern is simulated semi-accurately though the pattern does lag 5^{o} to 10^{o} poleward and is often underestimated till the relative maximum at 45^{o}S and 50^{o}N respectively. Cloud liquid water path is also simulated accurately with only and underestimated magnitude.

c. Polar Region

In the polar areas, surface temperatures simulated by the model were often lower than the observations and caused the poleward patterns to decrease faster than observed. Despite this, the model still simulated moisture variables nearly accurately or slightly overestimated compared to observation in the Northern Hemisphere. It is the Southern Hemisphere where not only temperature was underestimated, but precipitation also was underestimated compared to observation. The other precipitable water and evaporation minus precipitation were accurate in the Southern Hemisphere but this again suggests a compensation in evaporation. Total cloud fraction is not represented well at all in the polar region. The model both overestimates the magnitude of clouds and does not follow the poleward pattern in either hemisphere. In contrast, cloud liquid water path (especially annually averaged) seems to follow the pattern well for the polar areas that are simulated. The presence of ice seems to affect the model's ability to represent clouds given cold ocean water in the polar areas is simulated fairly well including cloud liquid water path where the ice masses are overestimated.

5. Conclusion

In conclusion CAM5 does a fairly good job at simulating the spatial pattern and movement of water through the atmosphere when compared with observations. Most of the moisture variables were represented fairly accurately with relatively small differences in magnitude when averaged zonally. Total cloud and cloud liquid water path were a little less accurate but still had a majority of their pattern simulated semi-accurately. Most of the difference in cloud pattern did result from higher magnitude errors in representing clouds.

While the model has a whole did well simulating the different components, some biases and reoccurring errors were present. Precipitation and precipitable water often were overestimated in areas with relatively warmer temperatures and over the oceans. This is likely caused by increased energy in these areas allowing for more evaporation and humid conditions from a steady source of surface water. With an abundance of moisture in the atmosphere, more rain is able to fall and likely to fall as the atmosphere can hold limited quantities of water depending on temperature.

Also worth noting is that total cloud responded inversely with precipitation in the model simulations. Instead of clouds increasing with precipitation overestimated, the total cloud cover decreased. This could suggest that the model is concentrating and increasing precipitation during rainfall events. This could explain why phenomena like the Indian Monsoon are overestimated if the event is being simulated with slightly more intense rainfall.

Finally, local topography and ground cover seemed to influence the model's interpretation of the different physical variables. Most mountain ranges tended to be local maximum in overestimation of the model's temperature data relative to the land surface surrounding them. Ice covered areas were often underestimated in moisture available to that area while still allowing for more condensation of the moisture that was simulated to be present.

Despite these biases, GCM's and specifically CAM5, are reliable tools for understanding the atmospheric hydrologic cycle and recreating past climates. There are still some errors and biases in the models, but understanding these discrepancies allow for a better understanding of what the model data is actually representing. So, while the field of past climate studies still has much more to understand and improve upon, climate models will prove to be very useful in furthering this research and understanding.

References

Bacmeister, J. T., Wehner, M. F., Neale, R. B., Gettelman, A., Hannay, C., Lauritzen, P. H., Caron, J. M., Truesdale, J. E., 2014: Exploratory High-Resolution Climate Simulations using the Community Atmosphere Model (CAM), *J. Climate*, **27**, 3073-3099, https://doi.org/10.1175/JCLI-D-13-00387.1.

Conley, A., 2012: Description of the NCAR Community Atmosphere Model (CAM 5.0). Accessed 9 September 2017, http://www.cesm.ucar.edu/models/cesm1.0/cam/docs/description/cam5_desc.pdf.

Dai, A., 2006: Precipitation Characteristics in Eighteen Coupled Climate Models, *J. Climate*, **19**, 4605-4630, https://doi.org/10.1175/JCLI3884.1

Hack, J. J., Caron, J. M., Yeager, S., Oleson, K. W., Holland, M. M., Truesdale, J. E., Rasch, P. J., 2006, Simulation of the Global Hydrological Cycle in the CCSM Community Atmosphere Model Version 3 (CAM3): Mean Features, *J. Climate*, **19**, 2199-2221, https://doi.org/10.1175/JCLI3755.1.

Kay, J. E., et al., 2012: Exposing Global Cloud Biases in the Community Atmosphere Model (CAM) Using Satellite Observations and Their Corresponding Instrument Simulators, *J. Climate*, **25**, 5190-5207, https://doi.org/10.1175/JCLI-D-11-00469.1.

Lauer, A., Hamilton, K., 2013: Simulating Clouds with Global Climate Models: A Comparison of CMIP5 Results with CMIP3 and Satellite Data, *J. Climate*, **26**, 3823-3845, https://doi.org/10.1175/JCLI-D-12-00451.1