Convection and Cloud Mechanisms in GCMs

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ABSTRACT

Climate modeling allows researchers to discover the latest trends and concerns regarding climate change. Connections can be made between different variables and models, which can help enhance understanding of the models themselves and define relationships within the model. These low-resolution models are sensitive to cloud and convection parameters, which is the primary focus of this study. The Iowa State Global Climate Model (ISUGCM) is analyzed and compared with other observational and model datasets. The impact of these convection and cloud mechanisms on GCMs in general is of interest in this study. Several variables are explored, with significant differences identified for each variable. Observed longwave radiation flux was not found overall significantly different from the ISUGCM, while the other six variables were. Shortwave radiation is over-estimated at high values, and the overestimations of total cloud near the equator correlate with the underestimation of shortwave flux here. Convective precipitation rate is found to shift with the ITCZ from season to season, which agrees with general behavior of the ITCZ itself. Precipitable water and relative humidity overestimations justify the vigorous convection in the model. Surface temperature correlates well with past data in non-extreme latitudes, but could take issue with albedo in higher latitudes. These conclusions can provide a basis for additional understanding of the impact of changing convection and cloud parameters in a GCM model. Therefore, these results can be applied to additional future adjustments in the model.

1. Introduction

Climate modeling has enabled researchers around the world to expand our knowledge about climate change as well as predict the behavior of Earth’s atmosphere over time. It allows us to look at the world through infinite scenarios of future climate. Relating climate variables in certain regions of the world to studied phenomena brings to light possible key factors of differences between a model and observations. Global climate models (GCMs) generally have relatively low (coarse) resolution and under-achieve in the representation of sub-grid scale meteorological processes, making parametrization a necessity (Mangin 2013). As with all models, GCMs come with their own strengths and limitations.
GCMs are quite sensitive to cloud and convection parameters, along with interactions between the atmosphere and oceans. However, progress is now being made on both the sphere grid and the dynamical core with greater resolution (NASA 2016). The data in the models is averaged over a certain time scale. A shorter time interval for averaging will have an enhanced risk of differing considerably from observed variable anomalies, and longer model runs should be implemented (Wilby and Wigley 1997). Some versions of GCMs have taken this approach.

Another important aspect of GCMs is spatial resolution. This can be defined as the resolution of the atmosphere in the model, or how “fine” the plotted data looks. A vast majority of GCMs have spatial scales on the order of 100-300 km. Variables such as surface pressure can be easily smoothed out over larger areas, but convective variables such as precipitation is much more difficult because it occurs more locally (Exploring Climate Model Data). For the latter variable, interpolation of some kind is needed. Popular methods include downscaling and bias correction, which both help minimize the spatial resolution error between GCMs and observations (Exploring Climate Model Data). Another flaw in GCM models is the production of a double Inter-Tropical Convergence Zone (ITCZ). When both branches of the zone are portrayed as parallel to each other, overestimation of precipitation results (Mangin 2013).

Atmospheric convection is one of the driving factors of low-pressure systems on the synoptic scale of meteorology. These can take the form of the conceptual Norwegian Cyclone Model in mid-latitudes (30-50° N). The simulation of these mid-latitude systems is considered as a key strength of GCMs, while larger scales are also well-resolved (Bader 2008). There has been exploration from a distinct perspective of other possible mechanisms behind eastward propagation of these systems. It is shown that a slow-moving eastward disturbance can have strong low-level diabatic heating driving it, where heat energy content increases (Hayaski and Itoh 2017). Without this heat, the system would have a challenging time sustaining itself in terms of instability and producing precipitation. However, this forcing mechanism only brings dynamical evidence, with no focus on other convection variables such as radiation and moisture.

Climate models can mathematically and visually portray annual, well-known weather phenomena such as the Indian summer monsoon. Future trends in these events that have been investigated and analyzed should be revealed to the public. However, economic sectors such as agriculture and water management frequently need climate variables at a finer spatial resolution than these models can supply (von Storch, 1995b). It is found that these higher-resolution models have closer estimates to the observed amounts than lower-resolution GCMs (including the one used in this paper). The physical and dynamical mechanisms behind the higher-resolution models showing these more promising results have been investigated. Stationary eddy meridional velocity convergence (which can be interpreted as just convergence) is found to be a leading factor in these superior high-resolution model performances (Yao, J. et al.,
Although this is true, the lower the degree of resolution has been found to entail a higher precipitation estimate (as previously mentioned earlier with GCMs), which could occasionally be closer to the observed amount (Yao, J. et al., 2017). This inference relates to the double-ITCZ zone issue. However, these high-resolution models do come closer to the observations in aspects such as total energy budgets.

Other past studies have looked at several other aspects of convection in climate models. Convection can occur for a set of atmospheric conditions. For example, a moist lower tropospheric boundary layer is more suited for convection that a dry one, owing to the lack of entrainment (Zhang 2009). Without this entrainment, or mixing of dry air with moist air, vapor is better able to condense moisture into water droplets. With the convection, abundant moisture is a key condition for clouds and convective precipitation to form. To get moisture in the atmosphere, there must be plenty of water vapor as well. An example of a convection closure aspect is CAPE (convective available potential energy). The more unstable the atmosphere is, the more convection and CAPE that can form. To get convection, you also need heating from shortwave radiation. An important part of the Earth-atmosphere relationship is radiation. Two kinds of radiation dominate this relationship: shortwave and longwave radiation. Shortwave radiation is emitted by the Sun, while longwave radiation is emitted by Earth’s surface and clouds. The atmospheric radiation budget is dominated by these two variables. These radiation processes can be quite complicated, which has contributed to cloud uncertainty in models. The cloud mosaic scheme in the ISUGCM improves radiation estimates by assigning cloud types to individual sub-cells. This “second tier” of convective initiation consists of the Bechtold and heated condensation framework (HCF) triggers (Song and Zhang 2017). The second tier is what the ISUGCM focuses on (this will be discussed later).

In this paper, the focus is around convection and cloud mechanisms. These aspects will be looked at in detail. Specifically, what is the impact of these mechanisms on the ISUGCM and GCMs in general? Both the Indian summer monsoon region (denoted in this paper as the area off the west coast of India, where convection initiates) and the ITCZ are involved in this study. Areas of very high discrepancy are also identified. Adjustments are made for the annual north-south shift of the ITCZ, and the ITCZ extension will be further discussed. Data and model information are presented in Section 2, with analysis of the results in Section 3. To wrap up, conclusions are made about the study, along with some possible future work.

2. Data and Methods

2.1 Model Description

The data for this research was obtained from the Iowa State General Circulation Model (ISUGCM). The ISUGCM is a modified version of a parent GCM model ran at The National Center for Atmospheric Research (NCAR). Its horizontal resolution is 2.8° x 2.8°, which is the same resolution as the NCAR model. A key difference between the ISUGCM and the NCAR model involves a modified convection, cloud, and radiation scheme built around midlatitude convection.
behavior. Emphasis is placed on temperature and moisture advections, both key factors of atmospheric stability and instability (Zhang and McFarlane 1995). Compared to the NCAR model, convection in the ISUGCM was found to be more intense but less frequent. Because of this modification, convective (cloud, moisture, and precipitation) variables are directly impacted. The ISUGCM also has a cloud mosaic (pattern) scheme, where model grid points are divided into different sub-cells with one cloud classification (type) for each, accounting for differing radiative properties of clouds (Mangin 2013). In comparison with other GCMs of its kind, another notable difference is that the ISUGCM model surpasses other models of its kind in indicating the southeast Asian monsoon trough and convergence zone (Mangin 2013).

2.2 Data

ISUGCM data is taken during the period 1991-2010 in this study, with the convection and cloud formation influenced by many different climatological variables. In this study, radiation variables of interest include TOM (top of model) net longwave (longwave radiation) and shortwave (shortwave radiation) fluxes. Precipitation and moisture variables of interest include precipitable water (water vapor mass in a layer), precipitation rate, total cloud, and relative humidity. Temperature variables of interest include the surface temperature. In this model, temperature is already prescribed as sea surface temperature, not accounting for land features. For study regions, the data for this study is plotted globally. The data is plotted through both zonal averages and global spatial patterns. Each variable data set was analyzed with an independent t-test. For the analysis, all plots were looked at for noticeable trends and anomalies. The t-statistics were then used to look at significant difference over the entire dataset. Values greater in magnitude than 0.9750, significant differences exist between the two datasets. Possible reasons for these differences were then formed, as well as any inferences that stem from them.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Compared Dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOM Net LW Flux</td>
<td>ERBE</td>
</tr>
<tr>
<td>TOM Net SW Flux</td>
<td>ERBE</td>
</tr>
<tr>
<td>Precipitation Rate</td>
<td>GPCP</td>
</tr>
<tr>
<td>Precipitable Water</td>
<td>ECMWF</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>NCEP</td>
</tr>
<tr>
<td>Total Cloud Fraction</td>
<td>ISCCP</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td>ECMWF</td>
</tr>
</tbody>
</table>

Table 1: Corresponding datasets for each variable compared with ISUGCM model data. Abbreviations are as follows: ERBE (Earth Radiation Budget Experiment), GPCP (Global Precipitation Climatology Project), ECMWF (European Center for Medium Range Weather Forecasting), NCEP (National Centers for Environmental Prediction).

3. Results

3.1 Net Longwave Radiation Flux

The first radiation variable looked at is net longwave (LW) flux. Annually, the longwave flux difference between the ISUGCM and ERBE varies greatly across all latitudes. Two local flux maxima occur at around 20-30˚N and S, with the ISUGCM slightly
underestimating between these points (Figure 1). There is also a flux minimum around the equator, where the ISUGCM is found to have also underestimated ERBE. The two data sets generally compare well with each other, with great underestimation over the Pacific Ocean and overestimation over west Africa, both near the ITCZ (Figure A1). The Indian monsoon region is slightly underestimated as well.

**Figure 1:** Annual zonal difference in net longwave flux ($\frac{W}{m^2}$) for the period 1991-2010 between the ISUGCM and ERBE data.

During the summer months, two local flux maxima are seen at around 30°N and 20°S, and a flux minimum for both just north of the equator (Figure 2). The ISUGCM overestimated ERBE over a similar region to the annual averages (Figure A2). It underestimated ERBE south of the equator. However, the two compare well south of 20°S. The ISUGCM underestimates north of 50°N. There was a greater area of underestimation but greater magnitudes of overestimation, wherever they occurred.

**Figure 2:** A summer zonal difference in net longwave flux ($\frac{W}{m^2}$) for the period 1991-2010 between the ISUGCM and ERBE data. Relevant months include June, July, and August.

During the winter months, the ISUGCM and ERBE compare very well with each other from 60°N to about 20°N (Figure 3). There is a flux maximum for both at around 30°S and 15°N, and a flux minimum near the equator. ISUGCM underestimates ERBE from 20°N southward to the minimum, as well as south of 50°S. Areas of overestimation and underestimation are similar to the other two time averages (Figure 4). Based on the t-values, there is no overall significant difference between the ISUGCM and ERBE. Of note is the very low significance in winter. This is supported by the fact that the ISUGCM was found to have only a slightly higher mean LW flux annually, a slightly lower mean in the winter, and a slightly higher mean in the summer.
Figure 3: A winter zonal difference in net longwave flux (\(\frac{W}{m^2}\)) for the period 1991-2010 between the ISUGCM and ERBE data. Relevant months include December, January, and February.

Figure 4: A global spatial plot of winter net TOM longwave radiation flux difference between the ISUGCM and ERBE. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.
3.2 Net Shortwave Radiation Flux

The other radiation variable analyzed was net shortwave (SW) flux, or the amount of shortwave radiation in a sub-cell. The two models generally compare very well with one another throughout all latitudes (Figure 5). Two flux maxima are found at around 10ºN and 10ºS. The ISUGCM slightly underestimates these maxima. In the Pacific Ocean, underestimation is also present in this region (Figure 6). Overestimation can be seen off the west coasts of several continents.

Figure 5: An annual zonal difference in net shortwave flux ($\frac{W}{m^2}$) for the period 1991-2010 between the ISUGCM and ERBE data.

Figure 6: A global spatial plot of annual net TOM shortwave radiation flux difference between the ISUGCM and ERBE. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.
In the summer months, the ISUGCM and ERBE are basically the same south of 10˚S, with flux maxima around the equator and near 25˚N (Figure 7). ISUGCM overestimation is found between 25˚N and 50˚N, and high underestimation is found between 50˚N and 70˚N (extreme latitudes). Very high SW fluxes are seen off the west coast of U.S. and over the Mediterranean Sea (Figure A3). Greater ISUGCM underestimation appears in Alaska and Siberia, with great overestimation on the South and North American west coasts. Slight underestimation is present in the southern portion of the Indian monsoon region.

Figure 7: A summer zonal difference in net shortwave flux (W/m²) for the period 1991-2010 between the ISUGCM and ERBE data. Relevant months include June, July, and August.

In the winter months the ISUGCM and observations are quite similar north of 20˚N, with a flux maximum seen at around 35˚S (Figure 8). Slight model overestimation occurs in the entire area south of the maximum. ISUGCM overestimation decreases in the Northern Hemisphere and greater overestimation emerges on the south coast of Australia (Figure A4). The t-values of this variable indicate overall slightly significant differences in all three time intervals, with the least amount of difference in the summer. Compared to ERBE the ISUGCM has a slightly higher mean SW flux annually, a slightly higher mean in the winter, and slightly higher mean in the summer.

Figure 8: A winter zonal difference in net shortwave flux (W/m²) for the period 1991-2010 between the ISUGCM and ERBE data. Relevant months include December, January, and February.

3.3 Total Cloud

As stated, clouds have a direct impact on the global radiation budget. They can absorb, deflect, and emit radiation that crosses their path. Annually, the ISUGCM tends to
underestimate the ISCCP in mid-latitudes of both hemispheres and overestimates in extreme latitudes (Figure 9 and Figure A5). There is minimum discrepancy just north of the equator.

**Figure 9:** An annual zonal difference in total cloud (percentage of 100) for the period 1991-2010 between the ISUGCM and ISCCP data.

In the summer months, the ISUGCM greatly underestimates the cloud minima (found at 25°S and 30°N) in the mid-latitudes of both hemispheres (Figure 10). Overestimation of summer total cloud is again seen in the extreme latitudes of both hemispheres, as well as in Australia and near the central Pacific ITCZ zone (Figure 11). Greater underestimation occurs in central Asia and the U.S. west coast.

**Figure 10:** A summer zonal difference in total cloud (percentage of 100) for the period 1991-2010 between the ISUGCM and ISCCP data. Relevant months include June, July, and August.

For the winter months, the ISUGCM underestimates total cloud in a sizable portion of the Southern Hemisphere, with less discrepancy around the equator (Figure 12). Vast overestimation is seen in the extreme Southern Hemisphere, with minima at around 15°N and 30°S. Greater underestimation occurs east of Japan (Figure A6). The t-values for this variable indicate significant differences for all three time intervals. The ISUGCM was found to have a lower mean total cloud in all three data set categories (ANN, DJF, JJA).
Figure 11: A global spatial plot of summer total cloud difference between the ISUGCM and ISCCP. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.

Table 2: T-statistics for the three radiation variables. All values are rounded to four significant digits. The two datasets are: ERBE for LW and SW flux, and ISCCP for total cloud.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>LW Flux</th>
<th>SW Flux</th>
<th>Total Cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>0.8055</td>
<td>2.350</td>
<td>-22.70</td>
</tr>
<tr>
<td>Winter</td>
<td>0.0545</td>
<td>1.093</td>
<td>-18.70</td>
</tr>
<tr>
<td>Summer</td>
<td>0.6006</td>
<td>0.9829</td>
<td>-16.23</td>
</tr>
</tbody>
</table>

Figure 12: A winter zonal difference in total cloud (percentage of 100) for the period 1991-2010 between the ISUGCM and ISCCP data. Relevant months include December, January, and February.

3.4 Convective Precipitation Rate
Convective precipitation rate is just what it says: the rate at which precipitation formed by convection falls. For annual convective precipitation rate, the ISUGCM model overestimates the GPCP from 35°N to 30°S, with an overestimation maximum at around
5°N and minima at around 20°N and S (Figure 13). Overestimation is also seen along the ITCZ in the western Pacific Ocean (Figure A7).

**Figure 13:** An annual zonal difference in convective precipitation rate (mm/day) for the period 1991-2010 between the ISUGCM and GPCP data.

In the summer months, similar trends are found between the ISUGCM and GPCP, with the ISUGCM overestimating a precipitation maximum at around 5°N (Figure 14). Maximum underestimation is at 40°N and 60°S, and underestimation/overestimation areas increase in intensity when compared annually (Figure 15). Very high overestimation occurs near the Indian monsoon region.

![ISUGCM - GPCP](image)

**Figure 14:** A summer zonal difference in convective precipitation rate ($\frac{mm}{day}$) for the period 1991-2010 between the ISUGCM and GPCP data. Relevant months include June, July, and August.

In the winter months, similar trends are again seen between the ISUGCM and GPCP (Figure 16). The ISUGCM overestimates at a precipitation maximum at 10°S and underestimates in the mid-latitudes of both hemispheres. Max ISUGCM underestimation is found at around 45°S, while overestimation areas shift slightly south and increase in intensity compared with the annual and summer plots (Figure A8). T-values indicate significant differences between the ISUGCM and GPCP. The ISUGCM has a higher mean precipitation rate than the GPCP annually, in the winter, and in the summer.
Figure 15: A global spatial plot of summer convective precipitation rate difference between the ISUGCM and GPCP. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.

Figure 16: A winter zonal difference in convective precipitation rate \( \text{mm day}^{-1} \) for the period 1991-2010 between the ISUGCM and GPCP data. Relevant months include December, January, and February.

3.5 Precipitable Water

Annually, the ISUGCM slightly overestimates the ECMWF model throughout all latitudes, with a large decrease in overestimation south of 30ºS (Figure 17). Maximum ISUGCM overestimation occurs around the equator and at 25ºS, with a maximum at around 5ºS. The ISUGCM also underestimates precipitable water in western Africa and Southern Asia, but overestimates over the central Pacific Ocean and western South America (Figure A9).
In the summer months, a similar pattern is seen in comparison with the annual and winter datasets. However, the maximum is shifted north of the equator (this is also the region of most ISUGCM underestimation) (Figure 18). This underestimation is found in central and western Africa, South America, and the Indian monsoon region (Figure 19). Greatest overestimations are over the Pacific Ocean.
In the winter months, essentially the same pattern is seen to the annual precipitable water. Maxima are shifted slightly south, with maximum ISUGCM overestimation at this point as well (Figure 20). Almost no discrepancies show up in extreme latitudes of the Southern Hemisphere (Figure A10). From Table 3, unusually low t-values indicate that very significant precipitable water differences are present between the ISUGCM and ECMWF models, the largest being in the winter (this could be a source of error). The ISUGCM has a higher mean precipitable water than the ECMWF annually, in the winter, and summer.

Figure 19: A global spatial plot of summer precipitable water difference between the ISUGCM and ECMWF. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.

Figure 20: A winter zonal difference in precipitable water (mm) for the period 1991-2010 between the ISUGCM and ECMWF data. Relevant months include December, January, and February.
3.6 Relative Humidity

Relative humidity plays a role in atmospheric moisture as well. Annually, the ISUGCM has far greater values in extreme latitude lower levels in the Southern Hemisphere (Figure 21). The ECMWF has low RH values in this region, resulting in great discrepancy here. Lower values of RH are found aloft at mid-latitudes for both models, while the minimum and maximum are both greater for the ISUGCM.

**Figure 21:** An annual zonal difference of relative humidity (percentage of 100) for the period 1991-2010 between the ISUGCM and ECMWF data.

In the summer months, the maximum and minimum are still greater for the ISUGCM (Figure 22). The lowest RH values are aloft in the Southern Hemisphere mid-latitudes for both models, with ISUGCM underestimation near the tropics.

**Figure 22:** A summer zonal difference of relative humidity (percentage of 100) for the period 1991-2010 between the ISUGCM and ECMWF data. Relevant months include June, July, and August.

In the winter months, more high values for the ISUGCM appear in lower levels at extreme latitudes (Figure 23). T-values for all three time intervals suggest strong significant differences between the ISUGCM and ECMWF models, with winter having the largest of the three. The maximum and minimum are still greater for ISUGCM. The lowest RH values are aloft in the Northern Hemisphere mid-latitudes.
Figure 23: A winter zonal difference of relative humidity (percentage of 100) for the period 1991-2010 between the ISUGCM and ECMWF data. Relevant months include December, January, and February.

Table 3: T-statistics for the three moisture variables. All values are rounded to four significant digits. The three datasets are: GPCP for convective precipitation rate, and ECMWF for precipitable water and relative humidity.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Convective Precipitation Rate (mm/day)</th>
<th>Precipitable Water (mm)</th>
<th>Relative Humidity (fraction)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>-14.00</td>
<td>-403.2</td>
<td>-47.91</td>
</tr>
<tr>
<td>Winter</td>
<td>-12.25</td>
<td>-365.5</td>
<td>-55.87</td>
</tr>
<tr>
<td>Summer</td>
<td>-9.218</td>
<td>-427.8</td>
<td>-31.82</td>
</tr>
</tbody>
</table>

3.7 Sea Surface Temperature

Annually, almost no discrepancies appear between 60°N and S for the ISUGCM and NCEP (Figure 24). The ISUGCM model overestimates in the extreme latitudes in both hemispheres, with a maximum at around 5°N. There is high underestimation throughout most of Asia and Africa, but high overestimation in the extreme latitudes of both hemispheres and North America (Figure A11).

Figure 24: An annual zonal difference of surface temperature (Kelvins) for the period 1991-2010 between the ISUGCM and NCEP data.

For the summer months, the temperature maximum shifts north of the equator (Figure 25). The ISUGCM overestimates south of 60°S, with a steep decline in temperature in this region for both models. There is greater overestimation in the extreme southern latitudes, but less so in the extreme northern latitudes. Underestimation is more widespread in the Middle East, while overestimation is maximized in North America (Figure 26).
**Figure 25:** A summer zonal difference of surface temperature (Kelvins) for the period 1991-2010 between the ISUGCM and NCEP data. Relevant months include June, July, and August.

**Figure 26:** A global spatial plot of summer surface temperature difference between the ISUGCM and NCEP. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.
In the winter months, the temperature maximum is shifted south of the equator (Figure 27). The ISUGCM overestimates in the extreme Northern Hemisphere latitudes but underestimates in extreme Southern Hemisphere latitudes. T-values for surface temperature suggest significant differences, although not as much as the moisture variables, between the ISUGCM and NCEP data. The ISUGCM has a slightly higher mean for the annual, summer, and winter datasets.

**Table 4:** T-statistics for surface temperature. All values are rounded to four significant digits. The dataset is: NCEP for surface temperature.

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Surface Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual</td>
<td>6.103</td>
</tr>
<tr>
<td>Winter</td>
<td>5.122</td>
</tr>
<tr>
<td>Summer</td>
<td>4.599</td>
</tr>
</tbody>
</table>

**4. Discussion and Conclusions**

4.1 *Longwave Radiation*

The ISUGM had oscillations of net longwave flux overestimation and underestimation with latitude. However, there are obviously smaller-scale variations. Recalling the definition of longwave radiation, there are causes of general variation in the amount of emitted radiation from the surface. This includes the different properties of ocean water and land. Since water has a lower specific heat, it will warm up and cool off at a slower rate than land. The faster a surface can cool off, the more longwave radiation that escapes. But since convection requires surface heating, higher emitted longwave fluxes could imply more frequent convection, according to the Stefan-Boltzmann Law (as is seen in the ISUGCM). The regions of high ISUGCM overestimation are primarily in the mid-latitudes, where land makes up a sizeable portion of the region (especially in the Northern Hemisphere). For extreme latitudes, the ISUGCM overestimates longwave radiation compared to the winter Northern Hemisphere ERBE data and the summer Southern Hemisphere ERBE data. This suggests that the ISUGCM overexaggerates the fact that winter nights are long-lasting in extreme latitudes, where...
longwave radiation can easily escape and prevent the surface from heating up for a majority or an entire day. Overestimation over northern South America in the winter lines up with the ITCZ extension, where clouds can emit much of the longwave radiation back to the surface. However, Longwave radiation flux simulated by the model was found to generally correlate with the ERBE. The lack of overall significant difference suggests that longwave radiation is well-predicted by the ISUGCM.

4.2 Shortwave Radiation

The opposite concept is true of shortwave radiation. Emitted by the Sun, it takes on a role of heating Earth’s surface. This increases the surface temperature, which helps initiate convection at the surface. This process, if accompanied by convergence (like near the ITCZ), occurs at or near low-pressure systems in mid-latitudes. Since the ISUGCM has higher means for all three time averages, it has a net overestimation of the amount of incoming shortwave radiation at the top of the atmosphere. The ISUGCM predicts shortwave fluxes quite accurately in the Southern Hemisphere in summer and the Northern Hemisphere in winter. This infers that the model does a better job at shortwave flux prediction in the hemisphere receiving the least amount of shortwave radiation (during that hemisphere’s cold season). Extreme amounts of shortwave radiation seem to cause the ISUGCM to over-predict. However, annual under-estimation in the Pacific Ocean perhaps suggests that extensive precipitation (resulting from the expanded ITCZ branch) blocks shortwave radiation enough to have a noticeable impact on a monthly scale.

4.3 Total Cloud and the Mosaic Scheme

The compared dataset here, the ISCCP, has shown that more recent GCMs are unable to accurately produce cloud simulations. “Convective cloud”, or clouds that form by convection, is one cloud classification that a sub-cell can possess in the ISUGCM. Underestimation of total cloud in mid-latitudes can be attributed to the lack of accountability of small-scale cloud formation processes, such as orographic lift, that occur over land (this is a general flaw in GCMs). Overestimation of total cloud in the tropics correlates well with the underestimation of shortwave flux in this region, as more clouds block off more of the radiation. Even through model improvement, local processes cannot be perfectly replicated. In addition, this variable includes several kinds of cloud classifications. Thus, this is not an efficient variable for looking at strictly clouds formed by convection.

4.4 Precipitation and Convection

Overestimation of mean convective precipitation rate in the tropics (and cumulatively) is not at all surprising, considering the extension of the additional ITCZ branch found in most GCMs. In addition, it was previously mentioned that lower-resolution models like the ISUGCM tend to over-estimate precipitation, which holds true in this case. The ITCZ not only shifts northward and southward with the seasons, but it also matches/goes along with the shift of the precipitation maximum, thus confirming the fact that the ITCZ is truly the center of precipitation and convergence. Since the ITCZ is the center for such convergence, plentiful precipitation results. The “greener” regions that have more lush
growth near the equator (e.g. Central Africa) are a result of this. In the Indian monsoon region, high overestimation infers that the ISUGCM over-amplifies the summer trough that causes the monsoon. This is most seen if there’s a higher precipitation rate due to convection, which can come about through heating and rising motion, then the convection itself can said to be more vigorous in this region (as was found in the ISUGCM).

Precipitable water can also show the amount of moisture in the atmosphere, and is given by

\[ PW = \frac{1}{\rho g} \int_{p_1}^{p_2} q_v dp \]  

(1)

where \( q_v \) is the water vapor mixing ratio. A higher mixing ratio, lower air density, or larger vertical layer can all increase precipitable water. A higher precipitable water value in an air column can stem from mass convergence of water vapor into that column. The fact that overestimation occurs over a vast portion of all three plots signifies the overestimation of the amount of moisture in the atmosphere as well, with higher vapor mixing ratios over a constant layer. Since the ISUGCM accounts for moisture advections in terms of atmospheric instability (and thus convection), convection can be overestimated compared with other GCMs. Areas of overestimation over the Pacific Ocean accompany underestimations of longwave radiation over this same region through the high specific heat of the large body of water (the Pacific Ocean is the largest ocean on Earth). This provides a constant moisture source over the ocean, particularly near the ITCZ. However, the connection between these two variables has yet to be explained, as more moisture should entail more clouds and thus more emitted longwave flux to the surface.

4.5 Relative Humidity

Relative humidity is given by

\[ RH = \frac{e}{e_s} \]  

(2)

where “\( e \)” is the vapor pressure and “\( e_s \)” is the saturation vapor pressure. A higher relative humidity encloses the gap between saturation and actual state of the air. With this, there’s a higher chance for moisture convergence and convective precipitation clouds. As seen in the figures, ISUGCM overestimation persists throughout a majority of the annual and seasonal plots. This ties to the trends of precipitable water, which is also a moisture variable. If moisture advections are the deciding factor for initiation of convection (like in the ISUGCM), high relative humidity and precipitable water values will be emphasized.

4.6 Sea Surface Temperature

As with the other variables, surface temperature can fluctuate constantly at a given location. It can also fluctuate greatly between points (as seen with the \( t \)-values). Major causes of these variations include cloud cover, wind direction, and surface albedo (surface reflectivity). However, it is still uncertain why much of Asia is underestimated, as such a large region cannot have concrete reasons that apply over the entire area. But since the ISUGCM only incorporates sea surface air temperature, the model will perform much more accurately over oceans than land (as seen in the spatial plots). In extreme latitudes, overestimation
occurs in the cold season of both hemispheres. This may be partially due to the model not accounting for surface albedo, which would be impacted greatly by snow and ice over water. The temperature max, like convective precipitation rate, shifts with the seasons.

4.7 Model Limitations

As with all GCMs, limitations are present in the ISUGCM. For one, lower-resolution GCMs are known to have lower and more inaccurate precipitation estimates (Yao, J. et al., 2017). With GCMs, a significant flaw happens to be deficiencies in clouds that further lead to precipitation deficiencies (Mangin 2013). This can be confirmed by the significant negative t-values of total cloud and all three moisture variables. In addition, the resolution of the model is coarser than other higher-resolution models. This made small-area trends difficult to assess, with general conclusions instead having to be made.

4.8 Summary & Future Work

So overall, some mechanism differences such as total cloud were able to be explained and some, such as precipitable water over the central Pacific Ocean, were not. Some differences in data were evident, while others were not as evident. GCMs are not able to account for smaller-scale factors associated with variables such as total cloud. Along with the confirmation of the impact of sea surface temperature on land, some further research has to be done with how changing the parameters in the ISUGCM (or another GCM) would affect the zonal and global spatial plots themselves. Variable relationships and/or decisions can then perhaps be derived.

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Figure A1: A global spatial plot of annual net TOM longwave radiation flux difference between the ISUGCM and ERBE. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.

Figure A2: A global spatial plot of summer net TOM longwave radiation flux difference between the ISUGCM and ERBE. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.
Figure A3: A global spatial plot of summer net TOM shortwave radiation flux difference between the ISUGCM and ERBE. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.

Figure A4: A global spatial plot of winter net TOM shortwave radiation flux difference between the ISUGCM and ERBE. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.
**Figure A5:** A global spatial plot of annual total cloud difference between the ISUGCM and ISCCP. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.

**Figure A6:** A global spatial plot of winter total cloud difference between the ISUGCM and ISCCP. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.
Figure A7: A global spatial plot of annual convective precipitation rate difference between the ISUGCM and GPCP. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.

Figure A8: A global spatial plot of winter convective precipitation rate difference between the ISUGCM and GPCP. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.
Figure A9: A global spatial plot of annual precipitable water difference between the ISUGCM and ECMWF. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.

Figure A10: A global spatial plot of winter precipitable water difference between the ISUGCM and ECMWF. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.
Figure A11: A global spatial plot of annual surface temperature difference between the ISUGCM and NCEP. Warmer colors indicate overestimation and colder colors indicate underestimation. Vertical axis denotes latitude and horizontal axis denotes longitude.