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Effects of Ice Crystal Fall Speed on the Simulations of Convective Cloud Systems

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ABSTRACT

Cloud resolving models are considered one of the best tools that can simulate cloud systems and their growth over time. Within cloud systems, there are many different parameters involving moisture and ice that can have major effects on the overall system. Thus the ice crystal fall speed, is analyzed to see how it affects the cloud system. We hypothesize that cloud systems will increase in size and grow deeper when ice crystal fall speeds are slower, and inversely that cloud systems will decrease in size and become more shallow when ice crystal fall speeds are faster. Observed large-scale forcing was obtained using data from the DYNAMO (Dynamics of the Madden-Julien Oscillation) experiment over the Indian Ocean. A Clark-Hall cloud resolving model was then run with the forcing to compare the model simulation against observations. Two different cloud simulations were run with faster and slower ice fall speeds to compare to the original control test. Shortwave and longwave radiation and mixing ratio plots were used to analyze the size of the clouds in relation to ice crystal fall speeds. Results show that the cloud model was also able to simulate cloud systems and their characteristics without much bias. They also show that cloud systems are larger with slower ice fall speeds and smaller with faster ice fall speeds.

1. Introduction

Cloud systems play a major role in the weather and climate of a region. They affect everything from solar radiation to instability and precipitation. But, framing the role of cloud processes in forecast and research models has been one of the longest and hardest challenges to overcome (Grabowski et al., 1996). Many scientists tried to incorporate cloud systems into their research models, but the scale cloud dynamical processes are too small to be well modeled in numerical weather prediction models or general circulation models (Grabowski et al., 1996). Due to this reason, cloud resolving models (CRM) have risen to becoming very important to the study of convection and
clouds. CRMs are very important to many areas of modern meteorological research because they are run at such a small resolution, usually between 1 and 4 kilometers (Cheng and Cotton, 2004). Cloud resolving models can be applied to cloud related convection, as an aide to operational forecasting, and to compare how different models predict shallow and deep convection. As other forecasting models begin to have smaller grid spacing, CRMs will become more useful and more integrated because they work well at such high resolution. With this as a useful tool, scientists have begun to make conclusions that they thought were possible.

2. Background

Grabowski et al (1996) began studies that used a CRM to model cloud dynamics and their behavior in the atmosphere. Cloud resolving models work by simulating cloud formations and properties when given different observed variables using sets of equations. In this study, they used a cloud resolving model to simulate different tropical cloud systems two-dimensionally during a period of 7 days in September 1974 of the Global Atlantic Tropical Experiment (GATE). Observed data and conditions were input into the cloud model, and the cloud systems were simulated on a two-dimensional area of the central Atlantic between Africa and South America with 1km horizontal resolution (Grabowski et al. 1996). Large scale forcing terms as well as cloud parameters were simulated, and results showed may different types of cloud systems, including shallow and deep convective systems, as well as squall lines. Conclusions from their research showed that cloud resolving models work well in modeling the evolution of cloud systems, and that they could be applied for further studies of clouds.

Wu et al (1998) analyzed clouds systems once again, but they took their research one step further and looked at heat and radiative fluxes within cloud systems. They used the same setup and computer models that were used in Grabowski et al. (1996) (Wu et al., 1998). Observed data was taken during a thirty-nine-day period during a Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment (TOGA COARE) experiment. The cloud resolving model used this observed data to simulate cloud systems and many experimental variables, with precipitation, sensible heat flux, and radiative heat flux being more closely analyzed. Comparisons of the simulated cloud systems and parameters with the observed data showed once again that cloud resolving models are good models to use to predict cloud formations, and that they can be beneficial for other research topics such as mesoscale forecasting and improving numerical weather prediction models.

Wu et al (1999) from the National Center for Atmospheric Research (NCAR), took their previous cloud research another step further. They completed a second part of their 1998 research by analyzing cloud ice microphysics. They used the same data was used from their first study (Wu et al., 1998), but a CRM was used to analyze how cloud ice microphysics affected cloud systems and radiation. Previous studies mostly focused on cloud systems near the tropics, which start as mostly water vapor. Clouds in the mid-
latitudes usually start with some amount of ice crystals in them since the atmosphere is much colder. CRM simulations were run with the observed data, which focused on the relationship of cloud ice properties to the replicated precipitation, heat, and moisture fluxes, and most thermodynamic variables (Wu et al., 1999). Results from this study showed that shortwave fluxes and forcing within the cloud system are significantly changed due to the change in the absorption of radiation (Wu et al., 1999), which is directly related to cloud-ice properties. The cloud resolving model also performed even better with the ice crystal parameters included in the simulations, showing that with more data available for the CRM, the more accurate it can be.

Guy et al (2013) from Colorado State University analyzed the effectiveness of cloud resolving models by looking at how they handled two different MCS’s (mesoscale convective system) that formed off the coast of West Africa. Using the1-km resolution Goddard Cumulus Ensemble cloud resolving model, they compared the simulated systems to radar observations, using different diagrams and water and ice variables (Guy et al., 2013). Although the output of cloud resolving model simulations missed a smaller convective outburst, results showed that the cloud resolving model could simulate the same differences that were found in radar observations, further strengthening the knowledge that cloud resolving models are useful tools for cloud and climate research.

Verified through previous research, cloud resolving models have been shown to be the best tool available to simulate cloud growth and evolution, in addition to simulating their different large and micro scale properties. Due to the many physical processes that occur within a cloud system, very small changes in properties such as water vapor mixing ratio, ice crystal mixing ratio, condensation and collision processes, ice crystal processes, etc. can lead to major changes overall in the cloud. One of these important processes is the ice crystal fall speed. The ice crystal fall speed is the velocity at which an ice crystal will fall through the cloud. It can vary greatly due to different forces that affect the crystal, such as gravity, updrafts, and downdrafts. At such a small scale, it is very important to be able to successfully model parameters such as this because a slight change can cause drastic changes overall. A changing ice fall speed may have a large impact on cloud growth and development, so it must be researched further to see just how big this impact is. It is hypothesized that decreased fall speeds will result in larger and deeper cloud systems, while increasing ice crystal fall speeds will cause shallower and smaller cloud systems.

3. Experimental Methods

a. Experimental Setup

This research focuses on an area of the Indian Ocean that was analyzed during the 2011-2012 DYNAMO (Dynamics of the Madden-Julien Oscillation) field project. The dimensions of the model area are 200 km by 40 km vertically, with 52 levels gridded within the vertical profile.

b. Observational Data

Observational data for this study includes temperature, wind, radiation, ice and liquid
water content, among others. The data was taken at 15 second intervals during a 30-day period in October 2011. Radiation data, including short and longwave radiation, is taken from CERES SYN1deg satellite data. Short and longwave radiation is averaged over a 3 hourly period for both the top of the atmosphere and the surface.

c. Clark-Hall Cloud Resolving Model

This cloud resolving model is a two-dimensional computer model derived from the Clark-Hall Cloud Resolving Model (1991). It has been used throughout this research to simulate different cloud systems and their characteristics with 1km resolution. The model contains many different programs and subprograms, each of which relate to a specific part of the simulation. Each program is run together to output the simulated cloud system, with outputted data for characteristics including shortwave and longwave radiation, temperature, moisture, mixing ratios, wind, updraft, and downdraft mass fluxes and more.

d. Procedure and Analysis

The cloud resolving model was run initially with data representing a control run of an average ice fall speed. This simulated data was compared to the observational data to verify the precision of the model for the 30 day time period.

After ensuring the cloud resolving model would work correctly under the prescribed data conditions, the ice fall speed parameter was changed twice in the cloud resolving model code to represent a faster and slower ice fall speed within the cloud. The resulting simulated data for each fall speed was then outputted and analyzed using the same comparison FORTRAN codes and plots. Model comparison to actual observed data was particularly looked at, as well as radiation plots. Radiation is a major variable related to the size and depth of cloud systems, and this variable is a key indicator as to how the cloud system responded to changing ice fall speeds.

4. Results and Analysis

a. Observed Forcing

Over the course of the thirty-day period, many variables change that reflect the change in cloud and convection systems. At the beginning of the period temperature forcing (which is similar to advection) remains low with some small positive temperature forcing near the end of the first week (Figure 1). Towards the end of the period, strong negative temperature forcing in the middle to lower part of the atmosphere indicates support for deep and large scale clouds because of the latent heat release of the water vapor condensing, causing the air to be warmer outside of the system and cooler inside the cloud.

On average, observed moisture forcing shows cloud systems occurring later in the period. Negative moisture forcing during the first half of the period at low levels in the atmosphere shows that cloud development is limited due to continually decreasing amounts of water vapor moisture in the air (Figure 2). As the period progresses, strong moisture forcing of an increase of 2 g/kg to 3g/kg per day indicates supports large cloud formation because of large amounts of
available moisture for condensation into cloud droplets.

Over the course of the 30 day period, zonal winds switch directions from light westerlies during the first half of the period to moderate easterlies at the end (Figure 3). Compared to the moisture and temperature forcing in the atmosphere, wind shear will be stronger during this last half of the period due to a combination of strong westerlies and the increased moisture and stronger temperature advections that are occurring.

While sea surface temperatures remain nearly constant, heat fluxes vary during the period (Figure 4), sensible heat flux, or the change in heat due to conduction and convection in

FIG. 1. Thirty day temperature forcing data plotted from the surface to 16km up into the atmosphere. Green values represent positive temperature forcing and red values represent negative temperature forcing.

FIG. 2. Thirty day moisture forcing data plotted from the surface to 16km up into the atmosphere. Green values represent positive moisture forcing and red values represent negative moisture forcing.
the atmosphere, remains lower during the beginning of the month. It gradually increased towards the middle of the month and then increases greatly at the end, mostly due to larger temperature differences between the surface and upper levels of the atmosphere due to clouds and convection.

Latent heat flux varies more over the course of the month, with the largest fluxes
occurring near day 10 and at the end of the period (Figure 4). Latent heat is the heat absorbed during evaporation and released during condensation, reflecting that some shallow clouds formed early on with larger clouds and convection becoming more likely at the end of the period with large scale forcing and flux values of close to 130 W/m².

b. Comparison of model output and observed data

Before changing the ice fall speed data within the cloud resolving model, the original simulated data from the control run was analyzed against observed variable data to ensure that the cloud resolving model could depict the cloud system. After taking the thirty day mean of the variables of temperature and mixing ratio, the observed data was subtracted from the cloud resolving model output to see how close the model could simulate the system (Figure 5).

On average, the cloud resolving model could simulate the temperature and mixing ratio of the cloud system without much bias over the time period. The modeled temperature was generally cooler than the observed data by 0°C to 3°C, which is well within the standard deviation of the simulation. It was further off towards the middle of the atmosphere, but this is mostly because of larger differences in temperature due to convection and clouds. Modeled mixing ratio data was even closer, averaging between 0 g/kg and 2 g/kg less than expected. When the ice crystal fall speed parameter was changed within the model, model bias for both faster and slower ice fall speeds is also relatively small (Figures 6 and 7).

FIG. 5. Thirty day averages of cloud resolving model data compared to observed data. The vertical line is the average difference in temperature (a) and mixing ratio (b) during the period with standard deviation plotted horizontally across the line at each height level.
Overall, the cloud resolving model could generally depict the overall cloud systems that occurred during this thirty day period, showing that it would be able to produce valid results if the ice crystal fall speed

c. Comparison of Simulated Total Mixing Ratio

The total ice mixing ratio within the cloud is comprised of the ice mixing ratio, liquid water mixing ratio, and the water vapor mixing ratio. During the 30-day period, the
total mixing ratio also changes to reflect changes within the size of the cloud system. In addition to radiation, it is also a good indicator of cloud size and depth because higher mixing ratios lead to more ice and moisture, leading to larger and deeper clouds.

For the control simulation (Figure 8.a), the total mixing ratio is very low at the beginning of the period, showing that there is little moisture and resulting in little to no clouds. As the period progresses, the total mixing ratio begins to increase at a rapid rate. By the end of the period, the mixing ratio is very large and supports large scale cloud growth due to high amounts of moisture present for development.

To compare the faster and slower ice fall speed runs, the simulated total mixing ratios for both speeds was subtracted from the control run to see if there was an overall increase or decrease in total mixing ratio during the period. For the faster run (Figure 8.b), there is a larger difference in the mixing ratio than the control run, meaning that more ice and moisture fell out of the cloud. This would cause smaller and shallower cloud

![Image](image_url)

**FIG. 8.** Thirty day measurements of simulated cloud total mixing ratio in g/kg. The first plot (a) represents the control simulation, the second (b) shows the difference of the control and faster ice fall speed simulation, and the third (c) shows the difference of the control and slower ice fall speed simulation. For (b) and (c), red areas represent negative values and green areas represent positive values.
systems due to less moisture to support growth. For the slower ice fall speed (Figure 8.c), the difference between the control simulation is very small and it even is zero for part of the 30-day period. The total mixing ratio is thus very close to the control simulation, meaning that cloud development and growth is similar to the control run with larger and deeper cloud systems.

d. Model Simulated Mass Fluxes

Mass fluxes throughout the atmosphere during the month coincide with different cloud systems. Mass fluxes are the direction in which the main areas of cloud mass will move throughout the atmosphere. After the first week and at the end of the period, there are large values of upward mass flux, with values in the 8 to 12 range in the mid to upper levels (Figure 9). In addition, downdraft mass fluxes are close to three quarters to about half of these values at the same times (Figure 10). This leads to relatively stronger updrafts throughout the cloud system, supporting strengthening and further development of clouds and convection.

e. Comparison of Simulated Radiation

The amount of radiation at the top and the bottom of the atmosphere changes throughout the 30-day period to reflect changes in the cloud systems. Radiation is a good indicator of the depth and size of cloud systems since the particles within the cloud are very good scatters of radiation. The radiation is measured in several different ways at two different places. Shortwave radiation, or radiation from the sun, can either pass through the cloud and be received by the surface or be reflected into space. The same can occur with longwave radiation, which is radiation given off by the Earth’s surface. It can pass through the clouds and go to the top of the atmosphere or it can be reflected to the ground. Both types of radiation are measured at the top of the atmosphere and at the surface, with upward and downward

FIG. 9. Thirty day measurements of updraft cloud mass flux. Red areas represent sections of the atmosphere where the main section of the cloud containing its mass is moving upward towards higher heights.
measurements of each at both levels of the atmosphere. Shortwave radiation reflected to the atmosphere increases towards the end of the period, showing that there are thicker and larger clouds blocking the solar radiation. Longwave radiation follows the same principle and has more reflected back to the surface at the end of the period, indicative of more clouds blocking the radiation.

For the control data, the shortwave radiation reflected to the top of the atmosphere shows increased amounts of reflected radiation around the end of the first week, with the most reflected radiation occurring at the end of the period (Figure 11). Longwave radiation reflected to the surface (Figure 12) dips slightly towards the middle of the period, coinciding with an area of shallow to no cloud development. It does increase towards the end of the period, signaling stronger clouds that block the radiation from escaping. Shortwave radiation captured at the surface follows a typical diurnal cycle, but it also remains constant for most of the week before slowly lowering at the end of the period (Figure 13) This also supports large scale clouds and convection that are preventing solar radiation from passing through to the surface.

When the ice fall speed is changed to be faster, the radiation over the course of the month remains very similar, but it does show a change at the end of the period with respect to the constant run. The amount of shortwave radiation reflected upwards towards the top of the atmosphere decreases, and the amount of shortwave radiation received at the surface increases (Figure 14). This shows that the simulated cloud systems are weaker and shallower, since more radiation can pass through to the surface instead of being reflected. When the ice fall speed within the cloud resolving model is changed to be slower, the simulated cloud output is once again like the control run, but this time the results towards the end of the period are opposite of the faster ice fall speed. The shortwave radiation that passes through the cloud decreases, and the amount of solar shortwave radiation reflected up towards the top of the atmosphere increases (Figure 14). This supports a larger and deeper cloud system, because there must be more ice crystal particles within the cloud to scatter and reflect the shortwave radiation.

**FIG. 10.** Thirty day measurements of downdraft cloud mass flux. Green areas represent sections of the atmosphere where the main section of the cloud containing its mass is moving downward towards lower heights.
FIG. 11. Thirty day measurements of observed radiation in W/m². The first plot represents longwave radiation reflected up to the top of the atmosphere, the second shows shortwave emitted downwards from the top of the atmosphere, and the third represents shortwave.

FIG. 12. Thirty day measurements of observed radiation in W/m². The first plot represents longwave radiation reflected down to the surface, and the second shows longwave radiation emitted upwards from the surface.
FIG. 13. Thirty day measurements of observed radiation in W/m². The first plot represents shortwave radiation emitted down to the surface, and the second shows short wave radiation reflected up from the surface.

FIG. 14. Thirty day measurements of simulated control-faster(red) and control-slower(green) radiation in W/m². The first plot represents longwave radiation up to the atmosphere, and the second shows short wave radiation reflected up to the atmosphere.
5. Conclusion

Overall, the CRM is a very useful tool for this research. It could produce adequate simulations of cloud systems and multiple cloud parameters, showing that it is one of the best models that could be used to compare different cloud systems. As hypothesized, the ice crystal fall speed has a major impact on cloud development. As the ice crystal fall speed decreases, it results in larger and deeper cloud systems. As it increases, cloud systems become smaller and shallower. This is reflected in both the radiation and total mixing ratio simulations that were run to compare the ice fall speeds together.

Deeper cloud systems and increased cloud development is shown to be caused by slow ice fall speeds because they are moving slower through the cloud. Since they are falling slower, the ice crystals stay suspended within the cloud longer, which is shown through the increased reflected solar radiation and decreased shortwave radiation reaching the surface. These ice crystals can then help keep the cloud saturated and provide more moisture forcing for the cloud to grow and develop. As for faster ice fall speeds, the opposite holds true as they fall out of the cloud faster, so they do not stay within the cloud long enough to help aide in further cloud development.

The main takeaway from this research is the many benefits of CRMs that can be very useful for future studies. Since cloud resolving models are shown to be very successful in simulating cloud development, further research should be completed to try and incorporate a cloud resolving model such as the one used into different numerical weather prediction models. These models can take large scale forcing and simulate how clouds will develop with precision, so they must be included in other forecasting models. Cloud systems are the beginning point of all types of precipitation and weather that we experience, so adding cloud resolving components to current forecast models would only strengthen them to become more accurate for future forecasting.

6. Acknowledgements

I would like to thank Dr. Xiaqing Wu for all the guidance and support that he has offered me throughout the course of this study. I would also like to thank Cora Virgei for her help in learning the aspects of the cloud resolving model used to complete this research.

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