# Simulating West African squall lines with the GCE-PLACE model: Influences of surface fluxes near the land-ocean transition

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## ABSTRACT

A three-dimensional version of the GCE (Goddard Cumulus Ensemble) cloud-resolving model is being used to simulate cloud formation and precipitating processes near the coast of West Africa, a region where surface-atmosphere interactions from continental and maritime environments are crucial for the development of storms. For this study, the GCE model is initiated with radiosonde and surface data collected near Dakar, Senegal during the 2006 NAMMA (NASA African Monsoon Multidisciplinary Analysis) field campaign. GCE is coupled with the PLACE (Parameterization for Land-Atmosphere-Cloud Exchange) land surface model to consider the influence of surface fluxes on MCS (mesoscale convective system) development, particularly as these storms travel from the land to the ocean. Model output is validated with vertical reflectivity profiles collected from the NASA NPOL radar. The case study presented here is a simulation of a squall line that crossed the West African coast on August 31st at 0830 UTC. This case was simulated twice: once using an all-land domain (i.e., savanna) and once using an all-ocean domain. Preliminary results suggest that the model is capable of reproducing the general characteristics of a West African squall line, but that output is highly sensitive to surface fluxes. Overall, GCE-PLACE did a better job of simulating the storms in the all-ocean run. Future work will involve testing GCE-PLACE using part-land, part-ocean domains that more realistically represent the West African coast.

## INTRODUCTION

Mesoscale convective storms (MCSs), and squall lines in particular, are a common and critical feature of the West African monsoon season (Hamilton and Archbold, 1945). An advanced understanding of West African MCSs is both scientifically and socially motivated. Most notably, these storms are responsible for the majority of the annual rainfall West Africa (Lebel et al., 2003). In addition, however, MCSs that survive as they pass through this region may develop into tropical depressions and storms over the Atlantic Ocean (Carlson, 1969).

Simulations of MCSs through their transition from continental West African into the Atlantic Ocean may lend insight into West African precipitation processes and tropical storm development. The Goddard Cumulus Ensemble (GCE) model (Tao and Simpson, 1993; Tao et al., 2003), for instance, is a widely used cloud-resolving model that has been successful in capturing the characteristics of MCSs in other tropical regions of the world (e.g., Brazil, Lang et al, 2007). Cloud resolving models, such as GCE, have been used to gather valuable information of MCSs that cannot be measured directly (e.g.,

latent heating and remotely-sensed precipitation, see Tao et al., 2003). Additionally, these models may be coupled with land-atmosphere models (i.e., PLACE, Parameterization for Land-Atmosphere-Cloud Exchange, see Wetzel and Boone, 1995) and used as a tool to investigate storm sensitivities to different surface conditions (e.g., soil moisture, coastline curvature, Baker et al., 2001; land cover, Mohr et al., 2003; soil moisture, Alonge and Mohr, 2007). Finally, developing models that can accurately reproduce these storms may improve our ability to predict extreme events resulting from these systems in the future.

Modeling West African MCSs as they move into the Atlantic Ocean may be particularly challenging, however, because the characteristics of these storms over the continent and the ocean are very different (Fuentes et al., 2007). Vertical profiles of reflectivity change significantly as they develop and transition through continental, coastal, and maritime regimes (see Figure 1). Much of this structural change may be due to a shift in surface energy fluxes, which are a critical source of heat, moisture and momentum to the atmosphere and, therefore, exert an important control on clouds and storm evolution (Strong et al., 2004).

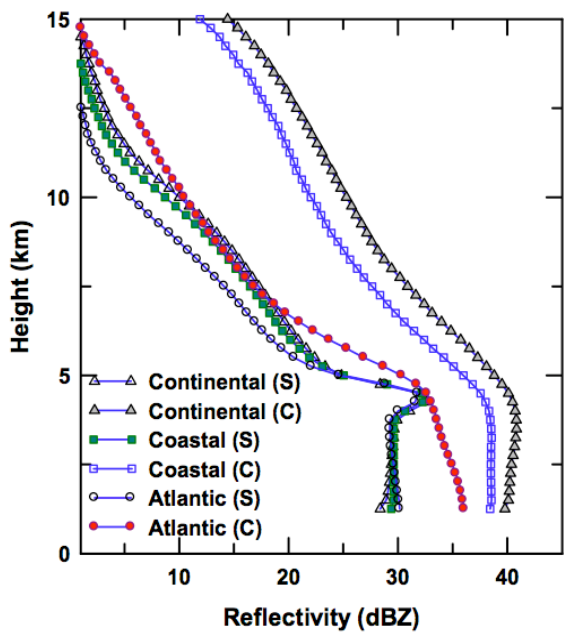



**Figure 1: Ensemble averaged reflectivity over continental West Africa to the Atlantic Ocean from June-Semptember (1998-2004) (Fuentes et al. 2007)**

The objective of this summer project was to begin testing the ability of the current GCE model to correctly represent the thermodynamic features of mesoscale convective storms as they transition from continental West Africa to a maritime environment. Because surface fluxes represent a crucial change encountered by MCSs as they change environments at the coast, this initial investigation considered the influence of these fluxes by coupling with PLACE. Specifically, the August 31, 2006 case study was simulated twice with GCE-PLACE: once with an all-land PLACE domain, and once with an all-ocean PLACE domain. The goal of this research was to determine not only how well GCE place was able to simulate this event, but to test the sensitivity of the modeled storm characteristics to land and ocean surface fluxes.

## METHODS

### *Field Site and Observations*

The NAMMA (NASA African Monsoon Multidisciplinary Analysis) mission took place in West Africa during August and September 2006, the peak of the West African Monsoon season. The main field site in Senegal was located in the village of Kawsara (14 39' 23" N, 17 05' 53" W, Alt: 74 m ASL), approximately 8 km east of the Atlantic Ocean and 32 km southeast of Dakar. The operations at Kawsara involved several instruments to observe atmospheric conditions, including a dual polarized S-band Doppler radar (NPOL, scans every 15 minutes), a 10-meter tall fully equipped flux tower, and over 70 radiosonde launches. Radiosondes were additionally launched from several other sites in West Africa, including Dakar. There was also an extensive rain gauge network spanning the range of NPOL.

### *Case Study: August 31*

The case that will be considered here is a squall line that crossed the West African coast on August 31st, around 07:30 UTC. This was a fast-moving squall line from the northeast with a strong leading edge and a trailing stratiform region. The storm was spatially extensive, covering almost the fully view of the radar (150 km radius) by 09:45 UTC (Figure 2).

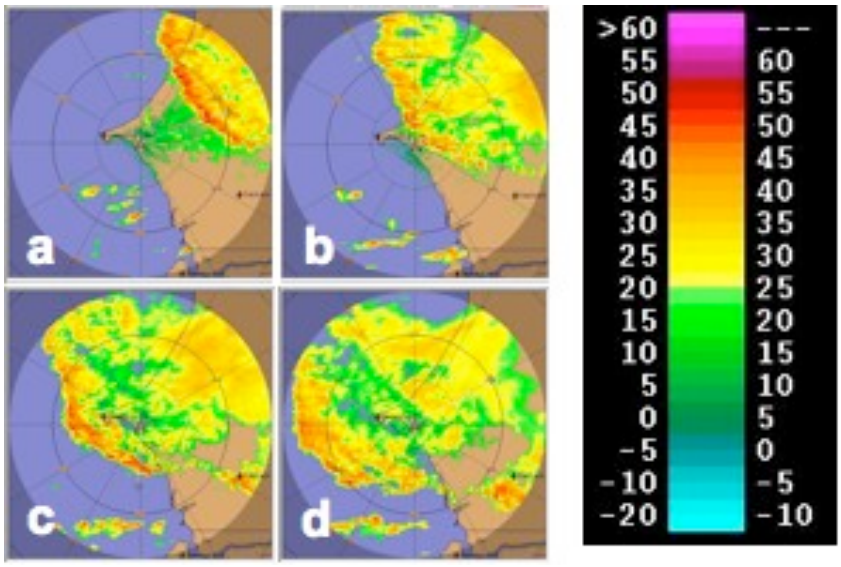



**Figure 2: Observed reflectivities (dBZ) from NPOL radar at a) 07:00 b) 08:00 c) 09:00 d) 09:45 UTC, 08/31/2007. Radiar radius is 150 km.**

The characteristics of the air mass prior, during, and after the passage of this storm were captured by radiosondes launched from Kawsara, Senegal (see Figure 3). Preceding the storm was a very warm and moist boundary layer, and westerly low level winds. As expected, during the storm there were strong wind shear and wind speeds.

After the storm, drier and cooler conditions prevailed, seen clearly by the profiles of equivalent potential temperature in Figure 3.

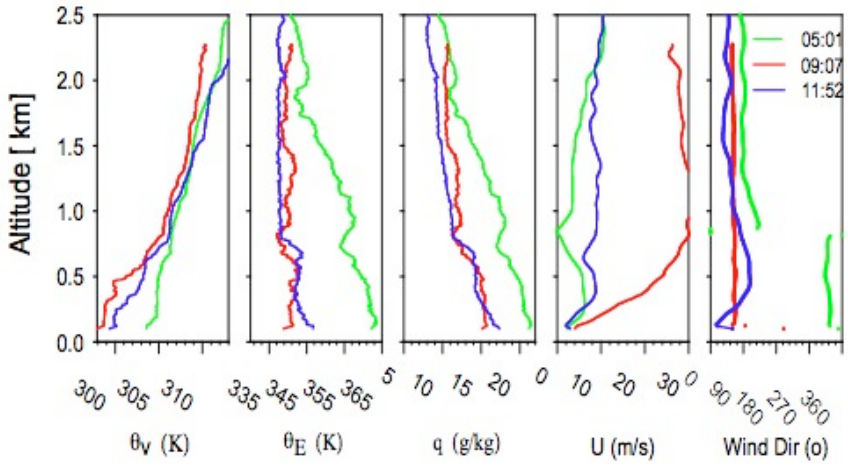



**Figure 3: Vertical profiles of (*left to right)* virtual potential temp, equivalent potential temp, specific humidity, wind speed, and wind direction representing pre- (05:01), mid- (09:07), and post-storm (11:52) conditions on 8/31/2007 at Kawsara, Senegal.**

***GCE-PLACE Model***

For this study, the August 31, 2006 case was modeled with the Goddard Cumulus Ensemble (GCE) model (Tao and Simpson 1993), coupled to the PLACE (Parameterization for Land-Atmosphere-Cloud Exchange) land-surface model (see Wetzel and Boone, 1995). The GCE is a cloud-resolving model (CRM) that has been developed over the course of more than 20 years at the NASA Goddard Space Flight Center. This model can be run in three-dimensions, typically using a 256 x 256 up to 1024 x 1024 horizontal grid points at a resolution of between 1-2 km (Tao 2006). For this study, the three-dimensional model was run for 12 hours with 512 x 128 grid points at 2 km spatial resolution. The boundary conditions were open in the x-direction and periodic in the y-direction. A graupel physics version of microphysics was employed.

The model was initiated with a sounding from August 30 (see Figure 4). A shaped cold pool (e.g. 5.25 degrees of steady cooling over ten minutes) was introduced in the eastern side of the domain after the model had been running for one hour. The purpose of this perturbation was to simulate evaporation of rainfall from the organized August 31 squall line that was entering the domain from the east at approximately this time.

To investigate the role of surface fluxes, GCE was coupled with the PLACE model. PLACE calculates surface fluxes based on land cover characteristics (e.g., soil moisture, vegetation type, etc.) and these values are outputted to GCE every three minutes. There are currently fourteen different vegetation classes to choose from. For our case we used two of these classes for two different model runs: all savanna (with additional vegetation, to represent coastal Senegal during peak monsoon season) and all ocean.

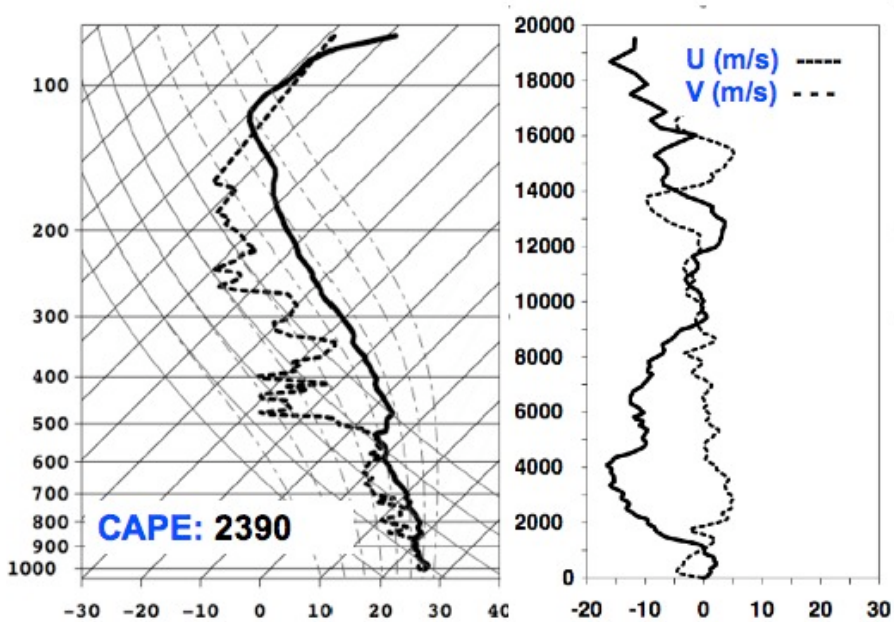



**Figure 4: 8/30/2006 05:30 LST sounding used for GCE initiation *(Left)* Temperature ($^{o}$C) and dew point temperature profiles ($^{o}$C) *(Right)* Wind speed (m/s) profiles**

## PRELIMINARY RESULTS

The land and ocean GCE-PLACE runs had significantly different characteristics, initially visible in the surface temperatures (Figure 5) and surface fluxes (Figure 6) outputted by GCE. The land-run was characterized by a strong diurnal pattern with surface temperatures at a minimum at the model start time (05:30) and peaking after about 7 hours of model simulation time (at about 12:30). Associated with these high daytime surface temperatures, the land surface had large latent and sensible heat fluxes that increased with time (corresponding to increasing land temperature). In contrast, the ocean surface temperatures fluctuated very little, and heat fluxes were smaller, but more consistent.

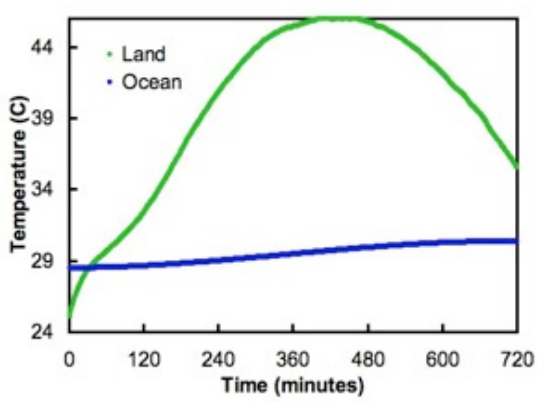
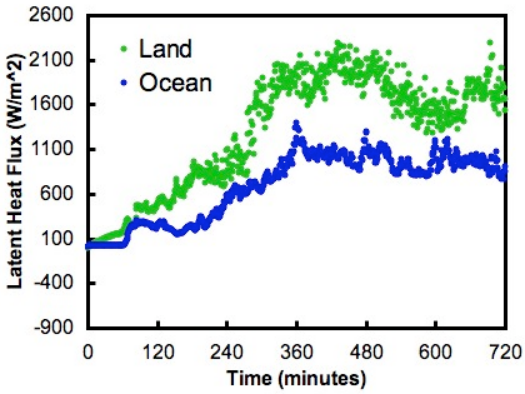



**Figure 5: Domain-maximum surface temperatures ($^{o}$C) for the land and ocean during the 12 hour GCE-PLACE simulations.**



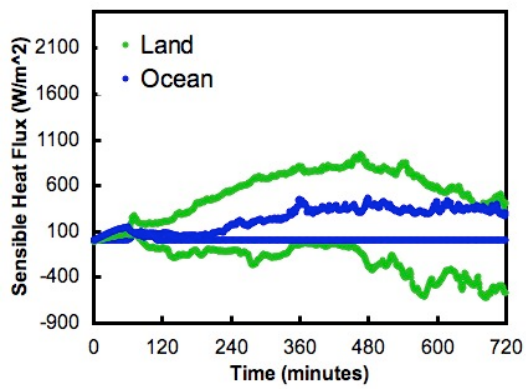




**Figure 6: *(left)* Domain-maximum latent heat fluxes (W/m^2) for the land and ocean during the 12-hour GCE-PLACE simulations.**

***(right)* Domain-maximum and minimum sensible heat fluxes (W/m^2) for the land and ocean during the 12-hour GCE-PLACE simulations.**

The storms simulated by the all-land and all-ocean GCE-PLACE runs also exhibited very different characteristics. Figure 7 shows the vertical profiles of reflectivity (dBZ) for the entire 12-hour model run for the all-ocean (a) and all-land (b) runs. The storm in the all-ocean run remained relatively intense at all levels throughout the simulation, though it began to decay slightly after about 8 hours. The all-land storm, however, was much weaker in the beginning, began to decay early in the simulation (i.e., particularly around 300 minutes), but regained some intensity near the end.

**GCE-PLACE: All-ocean**

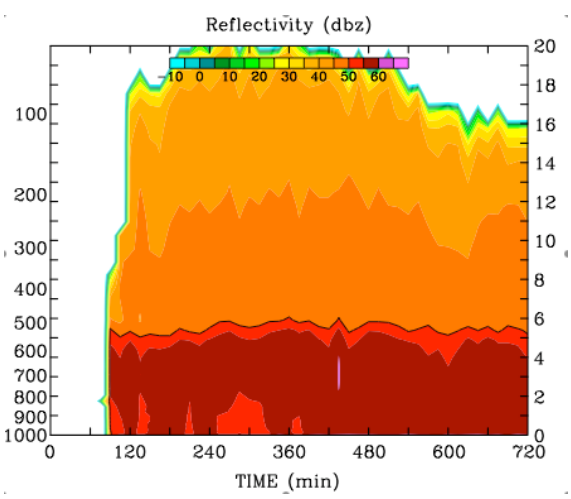
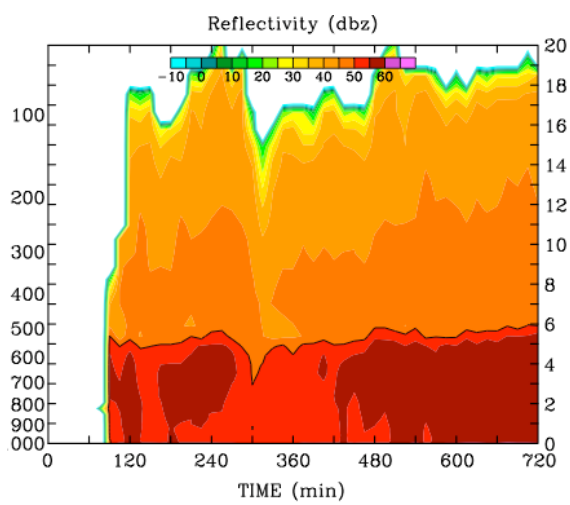



**Figure 7: (a) Vertical profiles of reflectivity (dBZ) during the 12 hour GCE-PLACE *all-ocean* run**

**GCE-PLACE: All-land**




(b) **Vertical profiles of reflectivity (dBZ) during the 12 hour GCE-PLACE *all-land* run**

The horizontal cross-sections of reflectivity from both the NPOL radar and GCE-PLACE output show how the model output compares to observed storm structure and

spatial extent (see Figure 8). In the case of the all-ocean GCE run, it is clear that the model is succeeding in producing a propagating squall line with a strong leading edge and trailing stratiform, as seen in the radar observations. Also, the spatial extent of the storm is comparable. The all-land run, however, does not match to radar observations quite as well.

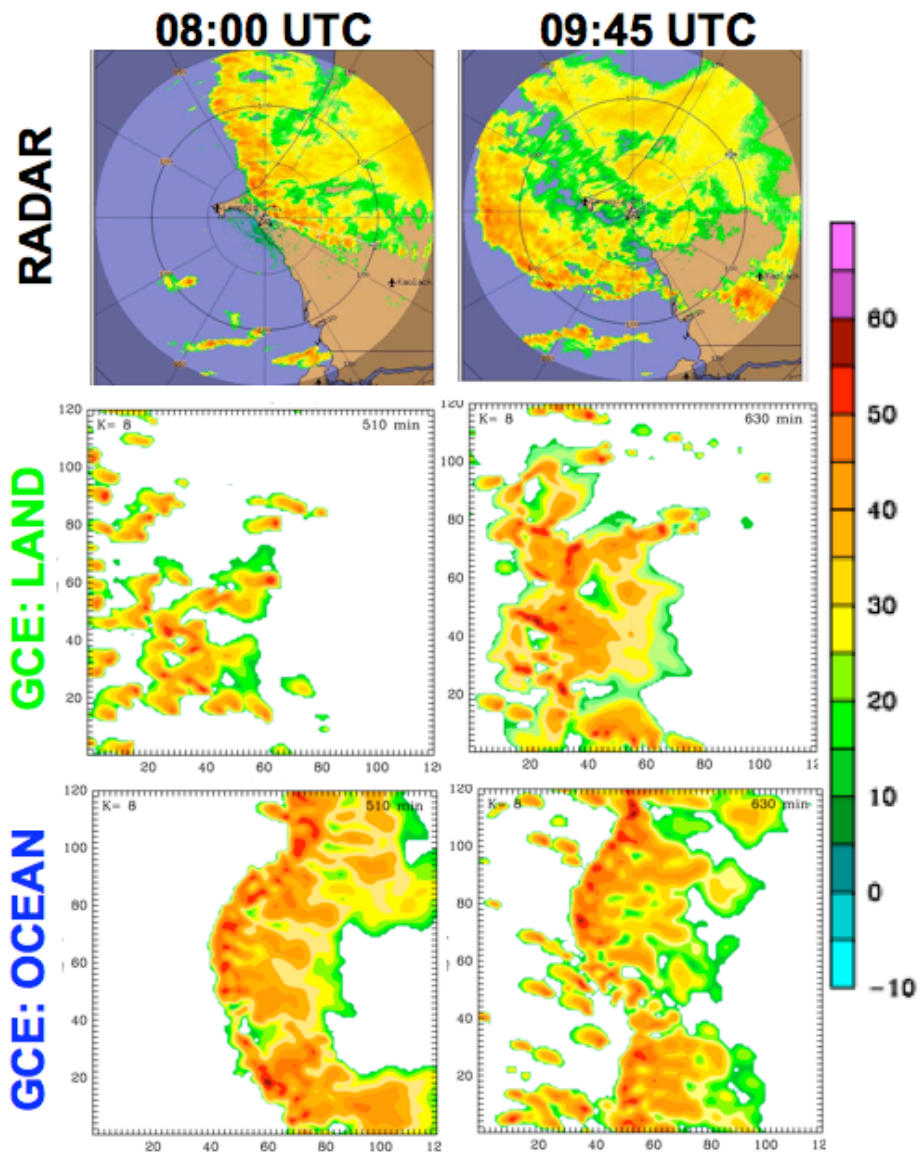



**Figure 8: Horizontal cross sections of reflectivity (dBZ) at 08:00 UTC (*left)* and 09:45 UTC *(right)* of *(top)* NPOL radar observations (*mid)* GCE all-land output *(bottom)* GCE all-ocean output. Radar radius is 150 km; GCE grid is 120 x 120 km.**

A more rigorous comparison of the radar observations and the model output can be made using CFADs (contoured-frequency with altitude diagrams) (Figure 9). CFADs for these data sets were produced using 30-minute bins (i.e., two data realizations) and a cutoff of 10 dBZ (i.e, reflectivities less than 10dBZ were not considered). In all of the CFADS, there is a shift towards lower reflectivities as the storm begins to decay from a

convective stage to a stratiform stage over the course of about two hours (i.e., comparing the left to the right side of Figure 9). These lower reflectivities are associated with more anvil. One other thing to note is that both model CFADs show higher probabilities of higher reflectivities than were observed. These overestimations are probably largely an artifact of the microphysical version that was used. As with the horizontal cross-sections, the CFAD from the GCE all-ocean run is much more similar to the radar CFAD than is the all-land CFAD.

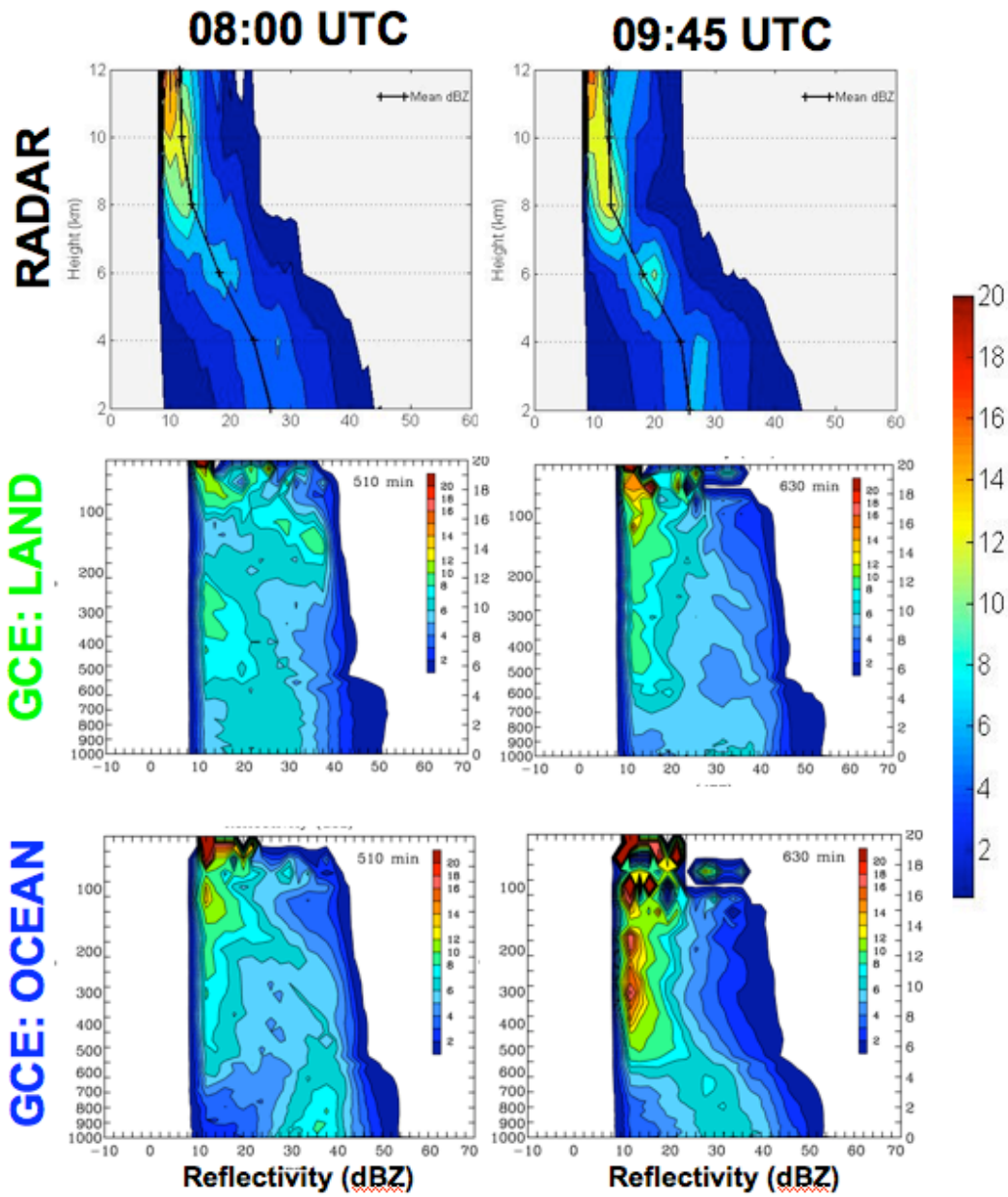



**Figure 9: Contoured-frequency with altitude diagrams showing domain-frequency of reflectivities in 30 minute bins at 08:00 UTC (*left)* and 09:45 UTC *(right)* from *(top)* NPOL radar observations (*mid)* GCE all-land output *(bottom)* GCE all-ocean output.**

## CONCLUSIONS

The preliminary results from the all-ocean and all-land GCE-PLACE runs demonstrate the important influence of surface fluxes on the characteristics of storms simulated by GCE. Since the model appears to be highly sensitive to the surface fluxes, it is critical that the appropriate land/water surfaces are included and correctly represented in future GCE simulations for West Africa. This research suggests that a West African morning storm with specific vertical profiles of temperature, humidity, wind speed, and wind direction may remain strong and organized over the ocean, but may decay over land. The constant supply of energy from the warm ocean, in addition to the shallower marine boundary layer, may encourage the growth and organization of an MCS. On the other hand, intense diurnal heating over land, a correspondingly high continental boundary layer, and a more limited moisture supply may make it difficult for an entirely continental storm to persist in this region after an initial perturbation.

## FUTURE WORK

The results discussed above suggest that the GCE-PLACE model can be used to study West African MCSs, with a particular focus on the importance of surface fluxes during the transition from a continental to maritime environment. Several upgrades will be made to the model immediately: using an upgraded version of the microphysics (e.g., including features such as no dry growth of graupel, a humidity correction for the Bergeron process, and lowered 40 dBZ echo penetrations), increasing the vertical resolution, increasing the domain size, and correctly orienting the cold pool.

In the long-term, mixed land-surface runs (e.g., half-land, half-ocean), that more realistically represent the domain, will be run. Soundings from other areas in the domain (e.g., an ocean sounding from Praia, Cape Verde) can be used to initialize the model. Ideally, multiple soundings will be used to create a weighted grid, rather than initializing with a uniform grid derived from a single radiosonde. Additionally, GCE will be run independently of PLACE, using observed fluxes, to investigate how closely PLACE-derived fluxes match observed values. Finally, in all simulations, there must be a more rigorous comparison of GCE-PLACE output with observations from both NPOL and TOGA radar.

This research and model validation will ultimately be used to make modifications to the GCE. It is anticipated that these modifications will significantly improve the ability of the GCE model to simulate West African MCSs. With a more accurate model, it will be possible to use the model to retrieve better information about precipitation processes from satellite missions such as TRMM (the Tropical Rainfall Measurement Mission). In regions of the world where field research is limited, such as West Africa, the benefits of being able to extract good information from satellites are particularly noteworthy. Also, we will have more power to realistically predict the evolution of MCSs, which may be particularly useful in cases where these storms can develop into extreme events.

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