P2.4

REMOTE SENSING OF MICROPHYSICAL PARTICLES IN HURRICANES FROM AIRCRAFT OBSERVATIONS

Cerese M. Albers and Dr. Gail Skofronick-Jackson

Florida State University, Tallahassee, FL and NASA Goddard Space Flight Center Code 970 Remote Sensing Branch, Greenbelt, MD

I. Abstract

In an effort to better understand the number concentration characteristics and particle size distributions of frozen hydrometeors in hurricanes, brightness temperatures were compared with observations of Hurricane Erin (2001) from CAMEX-4 radiometers on the ER-2 aircraft. Frozen hydrometeors and hurricane particle microphysics play a large role in the development and strength of tropical cyclones through the convective processes in the rain bands present. Previous studies have proven that it is difficult to select proper ice particle parameterizations and that in situ measurements and additional studies are key to defining appropriate parameterizations.

The observations from the Fourth Convection and Moisture Experiment (CAMEX-4) and ER-2 Doppler reflectivities were co-located with brightness temperatures from the High Altitude MIMC Sounding Radiometer (HAMSR) and the Advanced Precipitation Microwave Radiometer (see figure 2). In order to obtain atmospheric profile information for radiative transfer calculations along the flight line of interest, supporting temperature, relative humidity, and wind speeds were obtained from a Mesoscale Model-5 (MM5) simulation of Hurricane Erin. Of 250 slices of simulated data in each direction, one ideal slice needed to be selected for use with the observed flight line. The observations had a definitive eye, several convective rain bands, and anvil ice clouds. The slice of data that proved to be ideal was number 123 in the i-direction, and is taken at the latitudes between 32.0 to 33.2 degrees north, and the longitude of -64.7879 degrees. The maximum altitude of the data slice was 15 km, and the simulated temperature, relative humidity, density of cloud ice, density of graupel, density of cloud water, density of rain water, and density of snow profiles were extracted.

Bilinear interpolation was used to convert the model data in 250 points with a resolution of 2km to 200 points with a resolution of 2.5km in order to match the observed data for purposes of comparison.

This observed data will be helpful in understanding whether the model slice is appropriate and if the accompanying parameterization is useful for these types of hydrometeors. There is a correlation between high frequencies (>= 85 GHz) and the accurate detection of frozen particles' radiative signatures in storms. Higher frequencies are particularly sensitive to the frozen hydrometeors, and finding a multi-frequency retrieval algorithm for ice particle characteristics is the goal.

*Corresponding author address: Cerese M. Albers, 1242 Minerva Ave. West Islip, NY 11795
(631) 398-4112; email: calbers@huey.met.fsu.edu

II. Introduction

Scientists often seek to refine their observations to obtain more precise measurements of their desired distributions. In a time when the remote sensing of microphysical particles from aircraft and satellite has become increasingly important this is certainly a priority. The applications of this important and relatively new field include better prediction of storm development and severity. By studying in situ satellite and aircraft measurements, analyzing them, and comparing them at different frequencies to known radar data, we seek to find the optimal operational frequencies at which the best data of different hydrometeors can be obtained. While much is known about rainfall distributions and optimum frequencies for detection in hurricanes and tropical convective storms, much remains to be discovered about the frozen particle distributions in them.

A recent attempt to discover the best manner in which to proceed with observing the ice particles was conducted as part of the Fourth Convection and Moisture Experiment (CAMEX-4 experiment).

The objectives proposed by the CAMEX-4 experiment were to investigate a combined analysis of both active radar and wideband passive microwave brightness temperature measurements (from 10 to 183 GHz) measured from heavily precipitating storm clouds around hurricanes acquired from the ER-2 (see the flight path in figure 1). Other CAMEX-4 sensors provided a rich set of collaborating data with concurrent DC-8, in situ particle probe measurements, and ground based observations. This study and analysis enhanced the understanding of cloud dynamics, electrification, and microphysics, providing insight for cloud resolving models, and improving rain rate estimations. The specific objectives of the research were: (1) To estimate the vertical distribution of microphysical cloud parameters (e.g., content, size distribution, shape and phase of the cloud particles and hydrometeors) in precipitating clouds by minimizing the difference between forward active and passive calculations based on the estimated profile observations from primarily the CoSMIR, AMPR, NAST-MTS, and EDOP instruments on the ER-2 aircraft. (2) To investigate active and high frequency (greater than 90 GHz) passive microwave observations in order to better define the high altitude ice microphysics and its relationship to cloud electrification. (3) To determine the impact of low versus high frequency microwave measurements on retrievals, Skofronick-Jackson (2000).

Observations from the ER-2 Doppler (EDOP) reflectivities co-located with brightness temperatures from the High Altitude MIMC Sounding Radiometer (HAMSR) and the Advanced Precipitation Microwave Radiometer (AMPR) were used to create horizontal plots of relative humidity along the flight path at 6 different altitudes as derived from a combination of 3 CAMEX-4 ER-2 dropsondes and MM5 model results from a Hurricane Andrew case study. It was found that the previous form of the Eddington Forward Radiative transfer (FRT) model succeeded relatively well in modeling liquid hydrometeors, but it did not do as well modeling the ice phase microphysics (high frequencies, i.e. the 183+/- 10 GHz channel). As a result, we persist in our quest to discover which frequencies and equipment give us the best and most accurate interpretation of the location, size distribution and type of frozen hydrometeors that exist in hurricanes, blizzards and tropical convective storms. This particular research makes use of a specific radiative transfer model named the Eddington Radiative Transfer Model, which we will use our computed model data will validate.

III. The Eddington Radiative Transfer Model

The Eddington Radiative Transfer Model is a method of modeling radiative intensity in the atmosphere as would be observed by a radiometer. The radiometer measures brightness temperatures and is attached to an aircraft, an ER-2 in this case. Brightness temperatures are a measure of the electromagnetic radiation intensity. Radiation intensity is converted to a brightness temperature using Planck's function. Sources of radiation intensity include the cosmic background radiation, surface temperature emissivity, and emission from rain and cloud drops. In order to numerically compute the brightness temperature as would be observed by a radiometer above the clouds, the atmosphere is divided up into planar stratified layers (see figures 18 and 19). The amount of scattered radiation for a given layer (if the incident radiation intensity is known) is a function of the rain and ice particles within that layer. These particles scatter, absorb, and emit radiation, and multiple scattering can also occur. Please refer to figure 17 for an illustration of this process and how the Eddington approximation lends itself to this detection.

IV. Case Study: Hurricane Erin

One particular event that was studied in this summer's research was Hurricane Erin, which began as a tropical depression on 7 September 2001 and rapidly intensified into a well-developed hurricane by 8 September 2001, maintaining its intensity off the east coast of the United States on 10 September 2001. When Erin's intensification finally waned, it was 0000 UTC 15 September 2001, and it transitioned from a tropical storm into an extratropical system. The case study of this storm provides us with a unique opportunity to study the well-organized structure and distribution of the hydrometeors present in the storm and to experiment with figuring out which parameters and frequencies serve to give us the best view of our desired particles.

Taking data from the flights made through the hurricane by the ER-2 plane, we can make slices that give us information about the precipitation profile. This was accomplished utilizing IDL, the Interactive Data Language program. By creating routines that cut the data into slices, exploration of 250 slices in both the i and j directions was possible. Then the parameters for which type of hydrometeor was to be examined were included. The output data was then assigned a location from which these thousands of slices could be viewed and compared. The optimal slices consisted of those which included a clear view of the precipitation in Hurricane Erin's eye, strong regions of convection and anvil ice. The plots were accomplished using a scale of reflectivity which plotted the longitude or latitude on the abscissa versus the altitude of the precipitation detected in the slice on the ordinate in kilometers. The set height of the slices was predetermined to be up to about 16 kilometers. Once an optimal slice for the desired parameters was achieved (see Fig. 1) the data was analyzed. This can be found at the location "C:\Documents and Settings\Student\My Documents\Cerese 2004\Final Presentation Stuff\New Final Presentation Output." Overhead precipitation plots were utilized to find the best path through which a slice should be taken based on a well defined eye region, an indication of heavy precipitation and ice particle presence. The data that accompanied the slices was then reconfigured through the method of bilinear interpolation. This method allowed for the analysis of the slices with respect to their reflectivity and at a proper distance between the points (2 -> 2.5 km) on the plot.

An important consideration is that there are many different manners in which an ice particle can be modeled. In fact, Liu has discussed several different methods for the development of a system which exploits the best ways to get higher reflectivities out of the desired particles by modeling them according to density and ice to water to air mixed ratios, Liu (2004). Several types of snowflakes and ice particles were categorized. These categories include Rosettes, Type-A snowflakes, Type-B snowflakes, varying bullet-numbered Rosettes, and all are affected by a so-called Softness Parameter (SP) which varies between 0 for solid spheres and 1 for soft spheres. At 150 GHz the SP=0.2 for Type-A snowflakes, SP=0.3~0.4 for Type-B snowflakes, and SP=0.25~0.3 for 5-Bullet Rosettes. The Eddington Radiative Transfer model takes the specific softness parameter that we used for our ice particles, described as the Sehkon Srivastava type, and models solid ice particles with density of ice (0.917 g/cm^3), closest to a Type-A snowflake.

It is important therefore, to have data in terms of the observed data to make comparisons to. This was accomplished by the aforementioned bilinear interpolation, from which 200 slices were obtained. The slice corresponding to the original desired slice #123 was slice #99 in the newly reconfigured data set. The new wind profiles and the relative humidity profile and the temperature profiles were computed (see figures 6, 7, 8, and 9). The particle density distributions were computed at this slice with the new data set and were run for the densities of snow, graupel, cloud water, cloud ice, and rain . The resulting plots can be viewed below (see figures 10, 11, 12, 13, and 14) and are available in the files labeled "C:\Documents and Settings\Student\My Documents\Cerese 2004\Final Presentation Stuff\New Final Presentation Output" with the accompanying IDL routines that were used to compute them located in the same folder.

Validation of the results from our computed model data set is necessary to show through comparison to the previous summer student's work (Eric Holthaus), that significant improvement has been made through our new method. This is accomplished by comparing the frequency diagrams from the previous study's plotted observations of the brightness temperatures versus mine from this summer. Eric's data is shown in figure 16 and my data is shown in figure 17. The results of this comparison are analyzed in detail in the next section. Dashed lines indicate Sehkon Srivastava modeling. Dotted lines also indicate Sehkon Srivastava modeling but they make use of hurricane Andrew data and the dashed lines are using the hurricane Erin simulations. The solid line indicates actual observations taken during the physical hurricane Erin event.

V. Results

Typical results for an ordinary model would show that the model is useful for lower frequencies and observing rainfall, but poor for higher frequencies, which are used to study the ice we know so little about. A good result is if the new model proves to be more accurate than prior models for modeling the frozen hydrometeors.

The comparisons look better than the ones Eric did using the hurricane Andrew data to cover the holes in available data that he had. The improvement in the eye wall region is especially noticeable. The newly recomputed frequency charts look much better in the eye for certain frequencies as well (see figures 15 and 16). At the 55.5 GHz frequency, the brightness temperatures are not as close as the hurricane Andrew ones, but my mentor tells me this is because the high altitude temperatures had to be adjusted in the hurricane Andrew data to be colder, and it is likely that this will need to be done for hurricane Erin's data as well in the future. It is possible that the MM5 simulations which were studied for both hurricane Erin and hurricane Andrew have issues with the upper altitude temperature profiles in hurricanes. This frequency sees the very top of the atmosphere below the aircraft. It is opaque even to the ice layer. At low frequencies the eye seems to be modeled a little better with the new remodeled data, but appears offset because of co-location difficulties. There is slightly better modeling along the outer part of the storm (the outer rain bands) as well. This can be seen clearly by comparing figures 15 and 16. There is significant improvement in the 50.3 frequency as well, which sees all the way down to right above the surface of the ocean where and it senses temperature.

Important results from this summer's research include the ability to interpolate the data and to be able to go from the original 2 kilometer resolution to the 2.5 kilometer resolution. It proved to be successful (thus see figure 6). By viewing and comparing the two resolutions for the temperature profiles, it is shown that we were able to use IDL's bilinear interpolation method to obtain a data set that could be compared to the actual observations without compromising the integrity of the data set (using the functions called "congrid" and "fltarray"). We know that the physical hurricane Erin had a certain cloud structure, but the simulated Erin has a slightly different structure (see figure 4 of the model precipitation bands). This is why it was important to find the right slice for our work. The ability to search through 250 x 250 different potential slices to find one that matched the actual observed hurricane Erin reflectivity data set was crucial since we expected that the temperature and relative humidity profiles would match the actual observation better that way than if we just randomly selected a slice in the data set.

Another one of the important products of this summer's work is having the re-sampled data for multiple fields (including cloud ice, rain, graupel, snow, and cloud water). This allows us to compare the observed data to the simulations on the same footprint resolution. This is important because we want the microphysics to be in the same field of view for both data sets.

Earlier in the summer I took Fortran and Unix courses at the Goddard Space Flight Center's Learning Center located in building 1. This was necessary and was mandated by my mentor. The successful completion of these two courses became highly useful in the IDL routine manipulations that were performed to produce the plots and the data sets.

As an associated task, a literature survey was performed in order to determine the scope and availability of prior research for the in situ measurements of snow and ice in clouds. This is important because the cloud ice, rain, snow, cloud water, and graupel fields that were obtained by re-sampling the data were only the amount not the sizes of the particles and the literature survey gives us an idea of appropriate size distribution for these types of particles. There were studies of actual in situ observations which will become useful when combined with this summer's research. Eric's plotted differences show that the previous study did not produce the brightness temperatures that matched the observations on all areas of the slices (see figure 15). It is possible that no single size distribution is appropriate and that multiple size distributions corresponding to different anvil regions will prove necessary. This is what my summer's research was intended to fundamentally improve upon. A significant difference between his work and mine is that he compared four different size distributions (they were done using some hurricane Andrew data) and I used the simulations from the actual hurricane Erin data to do only one thus far. My mentor and I will continue this work and we plan to present a paper at the upcoming AMS conference in January. An abstract has already been submitted for consideration.

VI. Discussion and Conclusions

Typical results would have meant that our model fails altogether, but we had some good results, which indicate that it succeeds to a degree. Further improvements to the model are still necessary and correction to the 55.5 GHz planar surface is needed as well in the future. Having had good success though, this model can be used in the future to compute data gathered from more missions like CAMEX and we can really begin to understand what happens in the tops of the hurricanes in terms of frozen particle size distributions. This can help us improve the accuracy of our forecast models because the distributions and quantities of frozen hydrometeors are linked to storm severity and behavior.

VII. Tables and Figures

Figure 1 (Below): This is the visible GOES satellite image taken with the superimposed September 10, 2001 ER-2 aircraft flight track on top of it. The flight line for the data used in this particular study is visible as the solid red arrow, Skofronick-Jackson (2003).

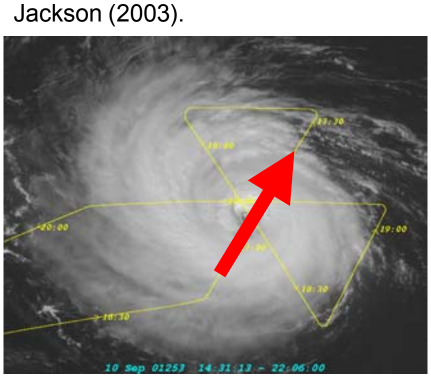
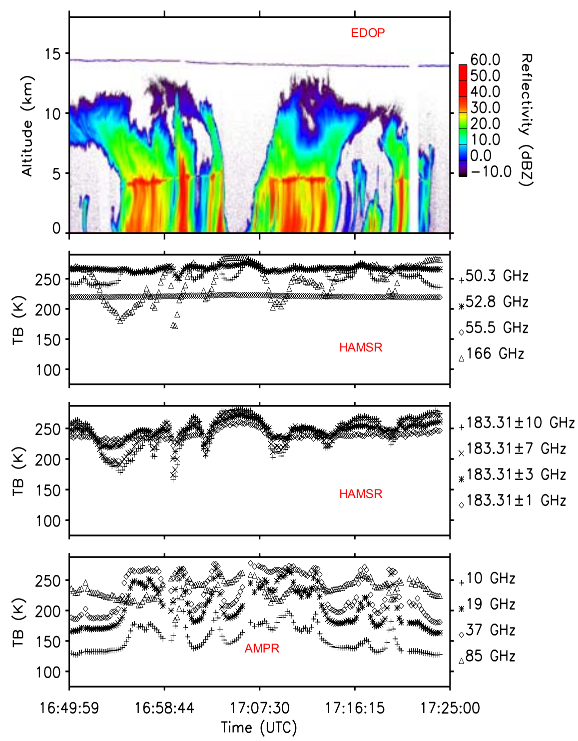


Figure 2 (Right): Observations from the Fourth Convection and Moisture Experiment (CAMEX-4): ER-2 Doppler (EDOP) reflectivities co-located with Brightness Temperatures from the High Altitude MIMC as a Sounding Radiometer (HAMSR) and The Advanced Precipitation Microwave Radiometer (AMPR), Skofronick-Jackson (2003).



The co-located CAMEX-4 observational data set including EDOP, HAMSR, and AMPR measurements from the NASA ER-2 Aircraft

Figure 3: Ideal Slice #123 taken because it best represented the desired parameters listed above.

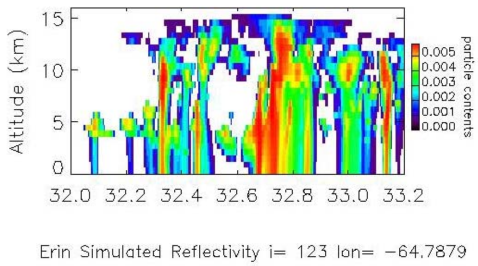


Figure 4: Precipitation bands of Hurricane Erin as seen from above on September 10, 2001.

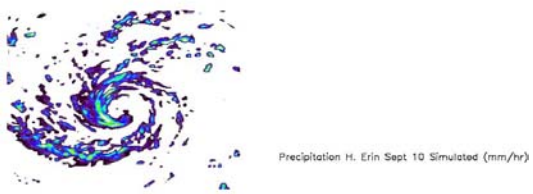


Figure 5: Graph of the Surface Wind speeds through Hurricane Erin.

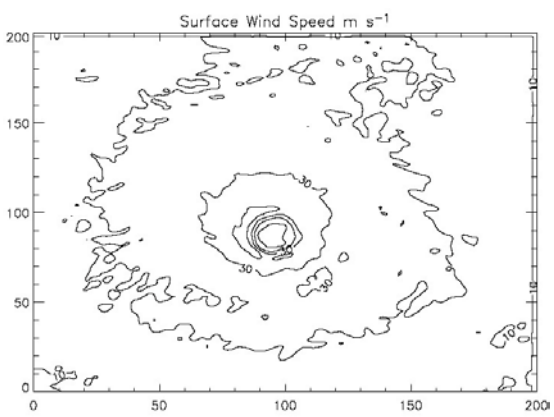


Figure 6: The two accompanying images at top right show that by resizing our data array, we can have a better resolution of the data that can be compared to actual observations without compromising the integrity of the data. The first image is taken at the 2 km resolution, and the second image is taken at the 2.5 km resolution (200 pts.)

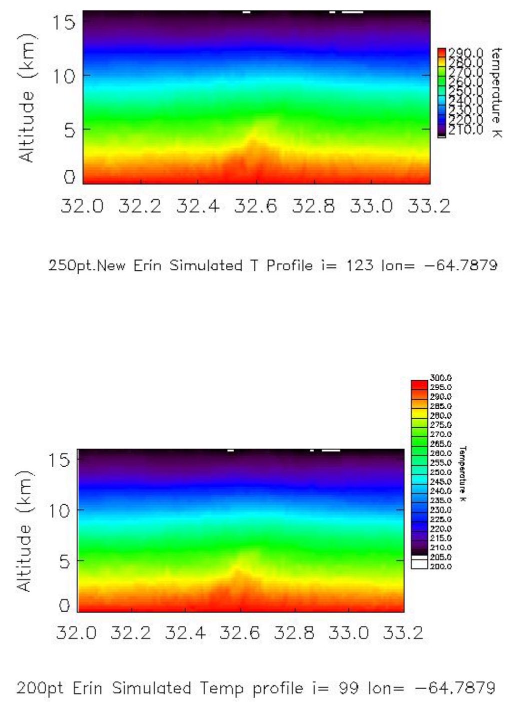


Figure 7: The simulated relative humidity profile at the new resolution.

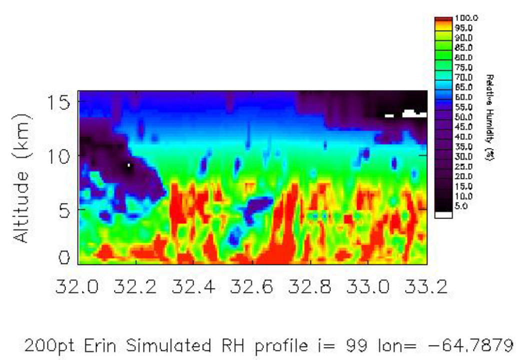


Figure 8: The simulated wind profile at the new resolution.

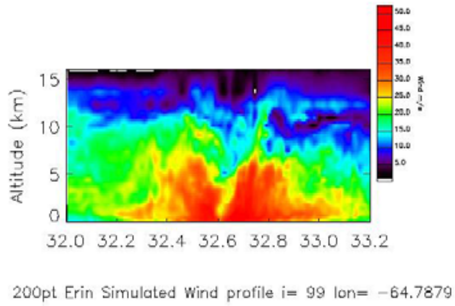


Figure 9: The surface wind profile taken at our slice for the newer resolution data.

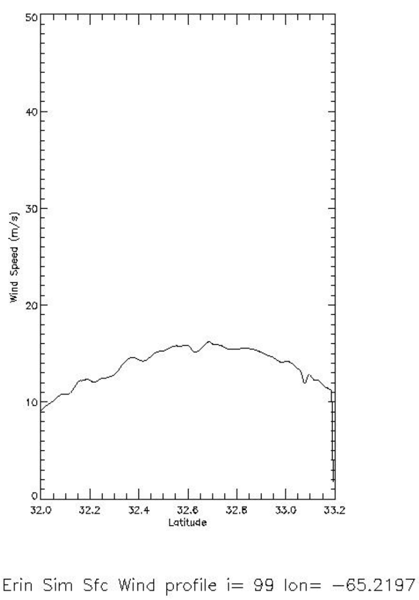


Figure 10: The interpolated snow density profile.

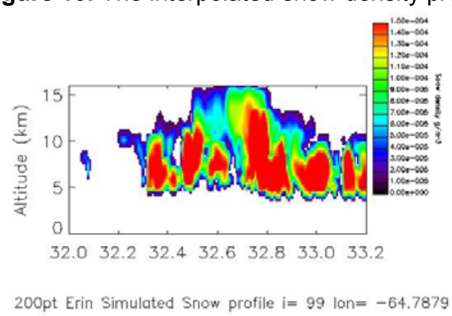


Figure 11: The interpolated graupel density profile.

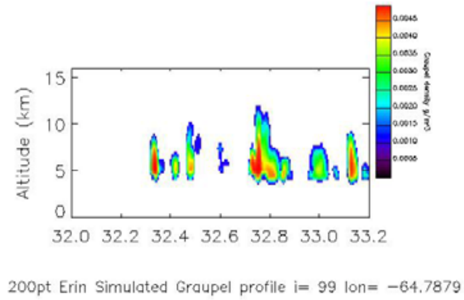


Figure 12: The interpolated cloud water density profile.

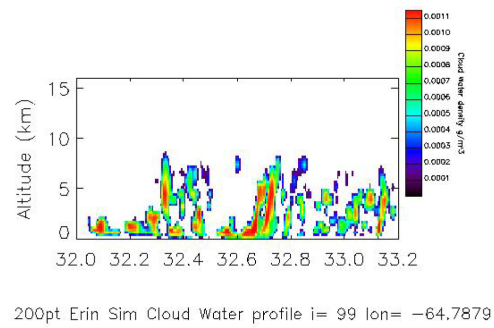


Figure 13: The interpolated cloud ice density profile.

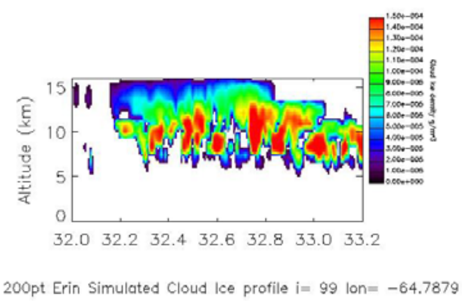


Figure 14: The interpolated rain density profile.

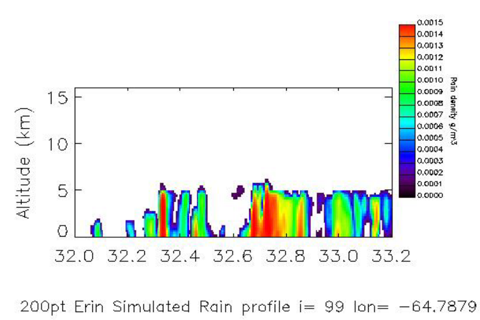
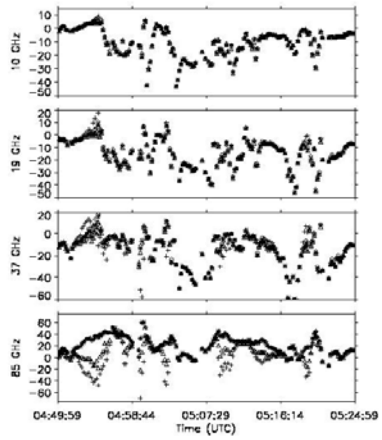
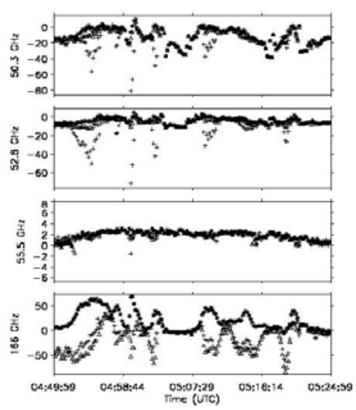


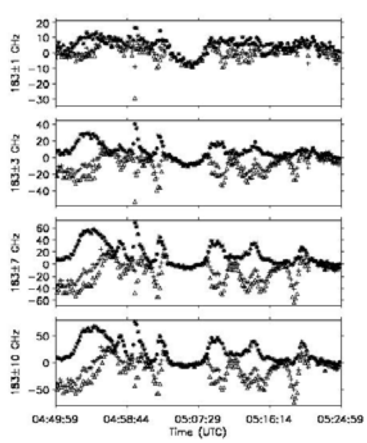
Figure 15: Eric's images (A) Dff10-85pprjpeg and (B) Dff50-166GHzppr and
(C) Dffpm1-10GHzppr1
The time of the observation versus the frequency of the radiometer observation is shown as compared differences from the actual observation, Skofronick-Jackson (2003).



A

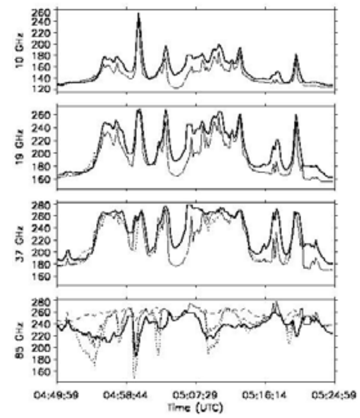


B

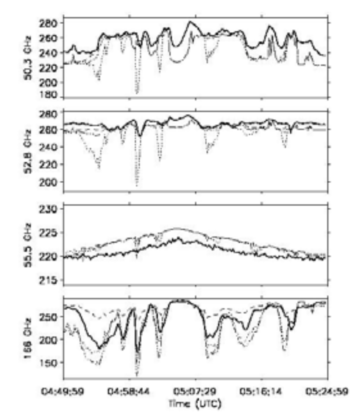


C

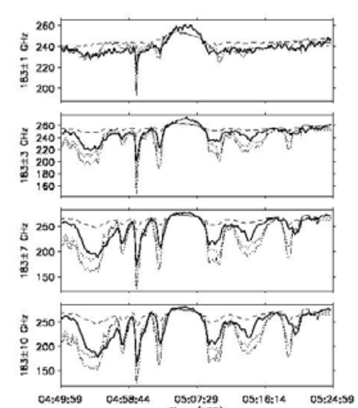
Figure 16: Eric's images (A) Frq10-85pprD (B) Frq50-166GHzpprD (C) Frqpm1-10GHzpprD
The time of the observation versus the frequency of the radiometer observation is shown, Skofronick-Jackson (2003). (Dashed lines indicate Sehkon Srivastava modeling. Dotted lines also indicate Sehkon Srivastava modeling but they make use of hurricane Andrew data and the dashed lines are using the hurricane Erin simulations. The solid line indicates actual observations taken during the physical hurricane Erin event.)



A

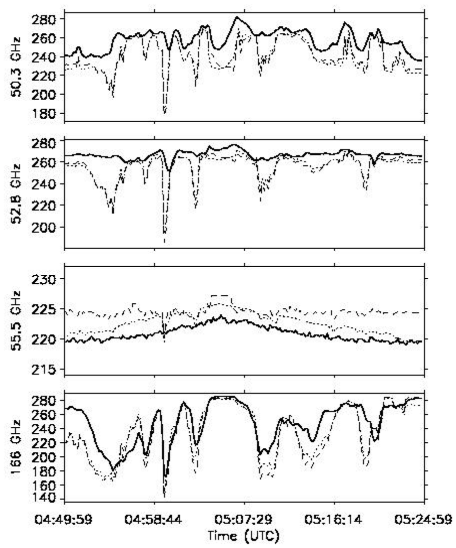


B

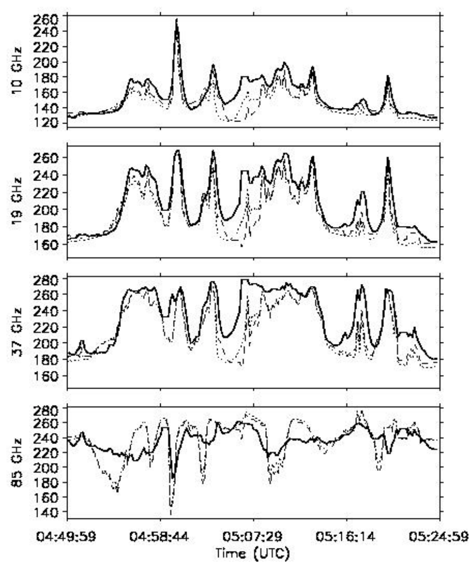


C

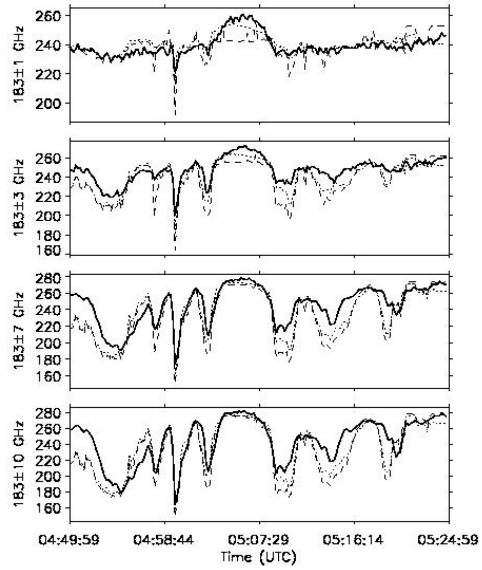
Figure 17: Cerese's images (A) Frq10-85pprDCerese (B)Frq50-166GHzpprDCerese (C) Frqpm1-10GHzpprDCerese
The time of the observation versus the frequency of the radiometer observation is shown.
(Dashed lines indicate Sehkon Srivastava modeling. Dotted lines also indicate Sehkon Srivastava modeling but they make use of hurricane Andrew data and the dashed lines are using the hurricane Erin simulations. The solid line indicates actual observations taken during the physical hurricane Erin event.)



A



B



C

Figure 18: [4]

Eddington's approximation

To solve radiative transfer equation, Eddington's approximation assumes that the radiance can be simply approximated by a linear function, i.e.

$$I(\tau, \mu) = I_0(\tau) + I_1(\tau)\mu$$

Under the boundary condition that the medium is only illuminated from above by a known source of radiation,

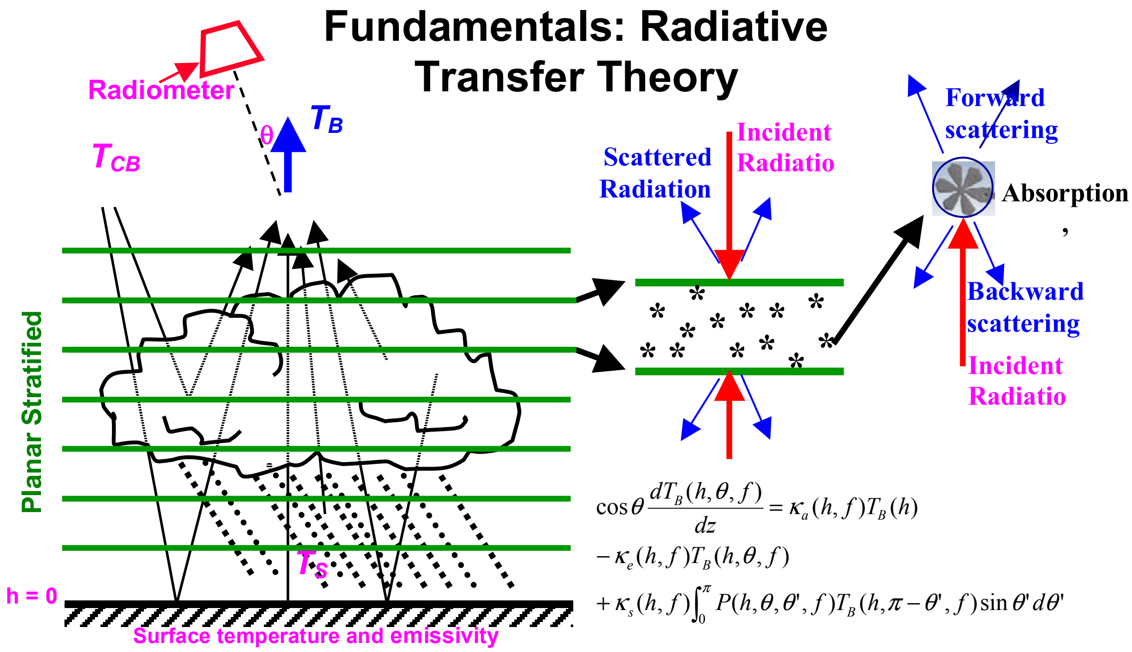
$$F^-(0) = -F_0, \qquad F^+(\tau_c) = 0$$

The reflectivity and transmissivity of the medium are:

$$R = \frac{(1-U^2)(e^{k\tau} - e^{k\tau})}{(1-U)^2 e^{-k\tau} - (1+U)^2 e^{k\tau}}, \qquad T = \frac{4U}{(1-U)^2 e^{-k\tau} - (1+U)^2 e^{k\tau}}$$

$$\text{Where} \quad k = \sqrt{(1-\omega)(1-\omega g)}, \qquad U = \sqrt{\frac{4(1-\omega)}{3(1-\omega g)}}$$

Figure 19:



References:

[1] Liu, Guosheng. 2004: Approximation of Single Scattering Properties of Ice and Snow Particles for High Microwave Frequencies. *Journal of the Atmospheric Sciences*: Vol. 61, No. 20, pp. 2441–2456.

[2] Skofronick-Jackson, Gail, 2000: Deriving Microphysical Cloud Profiles suing Airborne Active and Wideband Passive Microwave Observations October 5, 2000 Proposal submitted to NASA Research Announcement: NRA-00-OES-06 Convection and Moisture Experiment (CAMEX) Investigations

[3] Skofronick-Jackson et-al., 2003: Microphysical Characterization of Ice for Hurricane Erin for Wide Band Passive Microwave Comparisons December 9, 2003
Submitted to the *Journal of Atmospheric Sciences CAMEX-4 Special Issue*

[4] http://www.geo.mtu.edu/volcanoes/vc_web/background/graphics/fig03.gif