Investigating Gravity Wave Effects on Cirrus Clouds using a One Dimensional Cirrus Cloud

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***Abstract*—This proposed study involves the design of numerical experiments and application of a 1-dimensional cirrus cloud model to address a fundamental question about the net role of ambient gravity waves in affecting cirrus cloud properties. The model output will be processed and analyzed using appropriate methods to evaluate the net effect of gravity waves. The 1-dimensional cirrus parcel model explicitly accounts for nucleation cirrus ice crystals by homogeneous and heterogeneous processes. It also accounts for the subsequent ice particle growth in a fully particle-size-resolved manner on a vertical column of grid points (Eulerian) subject to imposed forcing. Account is also made for the effects of radiative heating/cooling. The model is typically used to simulate the formation and evolution of cirrostratus in response to weak, uniform, and constant synoptic forcing. It was part of the Cirrus Parcel Model Comparison Project of the GEWEX Cloud System Studies Working Group on Cirrus Cloud Systems. We will examine the effects of gravity waves on cloud formation and maintenance by performing a series of tests of the model response to various time-dependent vertical motion which realistically mimic the temporal/spatial scales and intensity of gravity waves. Propagating gravity waves are an ubiquitous feature of the upper troposphere and are caused by a variety of physical mechanisms operating on a range of scales. Our hypothesis is that the longer wavelength waves, typically of lesser intensity in terms of peak vertical motions, have a more significant effect on cirrus cloud processes and properties than the more intense but shorter wavelength waves that have a much shorter duration. The net effect is a result of nonlinear cloud processes such that the response is at least partially irreversible.**

I. Introduction

Clouds are very important to the Earth's energy and moisture balance. They help regulate the Earth's energy balance by absorbing the Earth's infrared energy and reflecting and scattering solar radiation. They are an important part of the hydrologic cycle because they are required for precipitation.

The stability of the atmosphere is a great indicator of cloud development. The two factors needed to access the stability of the atmosphere include the vertical temperature profile of the environment and the vertical temperature profile of the parcel of air. At a given altitude, if the air parcel's temperature is greater than the environmental temperature, then it tends to rise. This is because the air parcel is less dense than the environment. If, at a given altitude, the air parcel's temperature is less than the environmental temperature then it tends to sink. As the air parcel rises, it adiabatically cools and expands. Adiabatic is the process where no heat is exchanged as the parcel temperature changes due to expansion or compression. Cloud development is due to the synoptic lifting of air parcels and cooling to saturation. At saturation, relative humidity is 100%. Further lifting results in condensation and cloud formation with an accompanying release of latent heat into the rising parcel of air. Some lifting mechanisms that cause cloud development include orographic uplifting, convergence or frontal lifting, and convergent lifting. Orographic uplifting is the vertical lifting of air parcels due to the presence of elevated topographic barriers. Frontal lifting is vertical lifting of less dense air mass by denser air mass by a frontal transitional zone. Convergent lifting is the vertical lifting of air parcels through the heating of the atmosphere.

There are various types of clouds, but this study is specifically interested in cirrus and cirrostratus clouds. These are high clouds composed of ice crystals. Their cloud bases are typically above 6 kilometers (km). Cirrus clouds have a wispy appearance while cirrostratus clouds have a thin, sheet-like appearance resulting from thickening cirrus clouds. Common features of these types of clouds are fall streaks (falling ice crystals) and halos which form around the sun or moon due to the light refraction by the ice crystals.

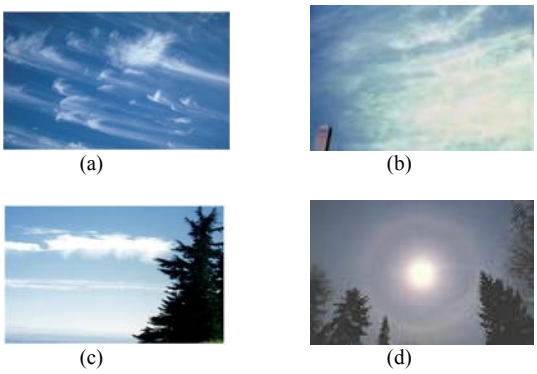

Figure 1: Pictures of cirrus clouds (a), cirrostratus clouds (b), fall streaks (c), and halos (d).

Cirrostratus clouds are important because they are often good indicators of precipitation within 12 to 24 hours and they are important in global climate system. They have a strong influence on the radiation balance in that they absorb upwelling infrared radiation from much warmer surface and lower troposphere. However, they infrared emissivity is limited because of their cold temperatures. Cirrostratus clouds allow solar radiation into the lower atmosphere and the surface because they are optically thin. They act as a greenhouse gas because they contribute to the heating of the

surface by allowing in solar radiation and prohibiting the infrared radiation from escaping into space. Important cirrus cloud characteristics include the ice water path, cloud cover, cloud depth, particle composition and shape, and cloud structure. The ice water path (IWP) is the integral of the ice water content through the depth of an ice cloud layer. It is used for determining optical depth and cloud absorption.

Recent studies have shown that gravity waves in the upper troposphere and lower stratosphere influence the formation of high cirrus clouds considerably (Jensen et al., 2001, 2005; Jensen and Pfister, 2004; Haag and Kärcher, 2004). Gravity waves are oscillations of air parcels caused by the displacement of air parcels which is restored to its initial position by gravity. The generation of gravity waves must occur in a stable atmosphere. In a gravity wave, the air parcel will attempt to remain at a location in the atmosphere where there are no forces causing it to rise or sink. Once a disturbance shifts the air parcel from its original state of equilibrium, the parcel will try to regain its equilibrium. It will, however, overshoot and undershoot that original position each time it is rising or sinking because of its own momentum. Gravity waves can propagate vertically and horizontally. They can result from a passage of wind across terrestrial forms and convection penetrating a stable region. They can also be generated as adjustments to imbalances in the atmospheric flow. They are observed at all levels in the atmosphere and seen in the troposphere as oriented bands of clouds. Gravity waves transport momentum and energy from the troposphere to the middle atmosphere. They are used and parameterized in global circulation models. Important properties of gravity waves include horizontal and vertical wavelengths, momentum, and phase speeds. Typically they are investigated using pressure sensors, in situ aircraft measurements, and imaging data.

The goal of this study is to evaluate the net effect of gravity waves on the evolution and maintenance of cirrostratus cloud properties using a 1-dimensional cirrus cloud model. We seek to

II. METHODS

A. 1-Dimensional Cirrus Cloud Model

The one-dimensional cirrus cloud model is a parcel model with explicit microphysics that played a key role in the Cirrus Parcel Model Comparison Project (CPMCP). It simulates the development of cirrostratus clouds synoptically forced by a weak, uniform, constant vertical motion (Lin et al., 2001). The 1-D model is a time dependent model that accounts for the nucleation of cirrus ice crystals by homogeneous and heterogeneous nucleation. Note, nucleation is the onset of a phase transition or the initiation of a phase change of a substance to a lower thermodynamic energy state. The 1-D model also accounts for the subsequent ice particle growth in a fully particle-size-resolved manner on a vertical column of grid points subject to imposed vertical motion.

In this model, ice crystals and aerosol particles are grouped into bins according to their ice mass and solute mass to account for the development of particle size distributions (Lin et al, 2001). Ice crystals in all simulations are assumed to be columnar. The governing equation for particle concentration in any size bin is given by

$$\frac{\partial N_k}{\partial t} = -\frac{\partial}{\partial z}(W - V_{t,k})N_k + W\frac{d\ln\rho}{dz}N_k + \frac{\partial N_k}{\partial t}\Big|_{growth} + \frac{\partial N_k}{\partial t}\Big|_{agg} + \frac{\partial N_k}{\partial t}\Big|_{HF} + \frac{\partial N_k}{\partial t}\Big|_{HET}$$

where N_k is the number concentration of a bin, W is the vertical motion, t is time, ρ is density, k is the bin number, and V is the ice crystal terminal fall speed. The terms

$$-\frac{\partial}{\partial z}(W - V_{t,k})N_k, W\frac{d\ln\rho}{dz}N_k$$

mimics the particle flux divergence in the vertical direction. The terms

$$\frac{\partial N_k}{\partial t}\Big|_{growth}, \frac{\partial N_k}{\partial t}\Big|_{agg}, \frac{\partial N_k}{\partial t}\Big|_{HF}, \frac{\partial N_k}{\partial t}\Big|_{HET}$$

corresponds to the rate of change of the number concentration due to particle growth, aggregation (the collision of two ice crystals), homogeneous nucleation (HF), and heterogeneous nucleation (HET) (Lin et al., 2001). The finite difference scheme used to treat the particle transport in the vertical direction is a second-order in space monotonic upstream biased transport scheme (Allen et al., 1991). Other schemes included in the model include a time splitting to address the rate of uplift and a hybrid method-of-moment scheme to treat the rate of change of the number concentration due to growth and aggregation. The 1-D cirrus model also assumes that the particle size distribution in a bin is a piecewise linear function (Lin et al, 2001). For detailed information on the 1-D Cirrus Cloud Model please refer to *Nucleation in Synoptically Forced Cirrostratus* by Ruei-Fong Lin et al.

B. Model Setup

The model input are temperature and pressure profiles based on radiosonde data.

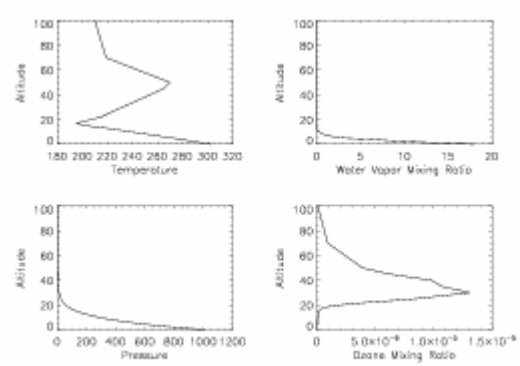

Figure 2: 1-D Cirrus Cloud Model atmospheric sounding model input.

The model domain is from ~3.8 – 10.8 km with an initial guess of a relative humidity profile. Input parameters that maybe modified by the user are the relative humidity profile and the synoptic scale vertical wind (uplift). In 2005, Lin et al. led a study that ran series of tests using the 1-D cirrus

cloud model on homogeneous freezing and heterogeneous nucleation modes. The study showed that in the first 3 hours of simulation, the initial humidity profiles affected cloud development while throughout the 7 hour simulation the synoptic scale vertical wind affected the cloud depth, cloud height, and ice water path. At a certain relative humidity threshold, the nucleation process is initiated.

The time step for the finite difference scheme is 5 seconds for the advection terms with grid spacing of 4 meters (m) or greater. The time step for particle growth is 0.1 seconds.

To account for gravity waves, we modified the model by allowing the synoptic vertical uplift to vary with time, i.e.

$$W = \overline{W} + W_g \ ,$$

where $\overline{w}$ is the mean vertical uplift and Wg is a sine curve simulating a gravity wave given by

$$W_g = W_{amp} \sin\left(\frac{W_{spd}\, t}{W_{wvlen}}\right)$$

$$\Rightarrow Z = \frac{W_{amp} * W_{wvlen}}{2\pi W_{spd}}\left(1 - \cos\left(\frac{2\pi W_{spd}\, t}{W_{amp} * W_{wvlen}}\right)\right)$$

where W_{amp} is the wave amplitude, W_{spd} is the wave speed, and W_{wvlen} is the wavelength. Recall that the amplitude is simply the height of the wave, the wave speed is the distance which a point on a wave travels per unit of time, and the wavelength is the horizontal distance from one wave top to the next.

To appropriately construct and implement gravity waves into the 1-D cirrus cloud model we must choose the wave parameters (amplitude, wavelength, and speed) such that

- the Courant-Levy-Friedrichs (CFL) condition is not violated

$$\frac{\Delta t(W)}{\Delta z} < .25$$

  The CFL condition controls the numerical stability of a finite difference scheme.
- realistically mimics a gravity wave in our model's domain

L. Wang et al. conducted a study that retrieved information on small scale gravity waves in wind and temperature measurements during a flight campaign. Gravity wave events were identified with vertical wavelengths of ~5 km and horizontal wavelengths shorter than 20 km. Average wave amplitudes were ~0.69 m/s, 0.75 m/s, 0.35 m/s, and 0.39 K for the wind components and temperature (L. Wang et al., 2006). To understand the relationship between wavelengths, wave amplitudes, we constructed contours of maximum displacement with wave amplitudes ranging from 0.02 – 1.5 m/s , wavelengths ranging from 1 – 100 km, and wave speeds of 10 m/s, 15 m/s, and 20 m/s.

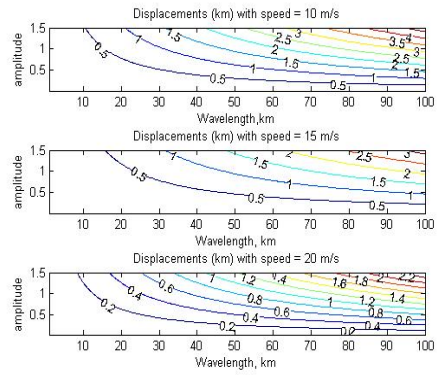

Figure 3: Contour plots of maximum displacements with varying wave amplitudes and wavelengths.

From figure 3 we see that the trend is for a fixed W_{amp} and W_{wvlen}, slower waves generate larger displacements, Z_{max}. Note that the units of Z_{max} are km in the above figure. For a fixed W_{spd}, shorter and more intense waves experience greater displacements than longer and less intense waves. Gravity waves that induce displacements on the order of one kilometer are not cases of interest for this study because not many cases occur where gravity waves are ~1km large. Further assessment of the plots shows that for amplitudes of ~0.5 m/s our wavelength region of interest is 1 - ~100 km. Whereas for amplitudes of ~ 1 m/s, our wavelength region of interest is up to ~ 30 km (wave speeds of 10m/s) and u to ~ 40 km (wave speed of 15 m/s). Contour plots of maximum displacements were constructed because maximum displacement implies maximum adiabatic cooling which results in a greater amount of ice crystals produced.

Thus the blueprint for our construction of gravity waves to study its impact on the development of cirrostratus clouds consist of

- comparing short more-intense waves to longer less-intense waves
- constructing a wave train of 4 or 5 waves on a quasi-steady state cirrostratus cloud subject to a constant vertical uplift of .02 m/s.

For the comparison of short more-intense waves to longer less-intense waves, we use the following table

Wavelength, km	Amplitude, m/s	Wave Speed, m/s	$Z_{max,\ m}$
5	.60 1	15	63.22 106.10
10	.20 .60 1	15	42.44 127.32 212.20
20	.20 .60	15	84.88 254.64
50	.10 .20	15	106.10 212.20
100	.10	15	212.20

We will use a small mean vertical uplift of 0.02 m/s. The basic model parameter input includes

- no calculation of radiative transfer
- no initial cloud

- activate heterogeneous nucleation
- time step for advection terms of 5 seconds
- time step for microphysical module of 50 seconds
- with aggregation
- columnar ice crystal shape
- grid spacing of 4 m
- domain base height of 3.8 km

III. Results and Discussion

We are designing numerical and applying it to a 1D Cirrus Cloud Model to address the question about the role of gravity waves in affecting cirrus cloud properties.

Some problems we've encountered so far include

- Extremely slow model – with the current model setup it takes about 8 hours to run simulations
- Instability – simulations are encountering blow ups

The following steps were taken to resolve the above issues.

- Decreased the ice bin size from 50 to 25 (Note: Ice crystals and aerosol particles were grouped into bins according to their ice mass and solute mass to resolve the evolution of particle size distributions.
- Increased the grid spacing from 4 km to 20 km
- Modified the CFL condition to $dt*w/dz < .25$. Note that dt = time step, dz = grid resolution, w = vertical uplift.

Preliminary Results. We ran the following simulations from our parameter space

1.
- wave with wavelength 10km, wave amplitude 1m/s, wave speed 15 m/s
- dt = 5.0 s idmr = 50 s – time step for the microphysical module
- dz = 20 m
- mean vertical uplift, i.e. $\overline{w}=0.02$

2.
- wave with wavelength 10km, wave amplitude 1m/s, wave speed 15 m/s
- dt = 5.0 s idmr = 50 s – time step for the microphysical module
- dz = 20 m
- mean vertical uplift, i.e. $\overline{w}=0$

3.
- no wave
- dt = 5.0 s idmr = 50 s – time step for the microphysical module
- dz = 20 m
- mean vertical uplift, i.e. $\overline{w}=0.02$
- 4. wave with wavelength 10km, wave amplitude .20 m/s, wave speed 15 m/s
- dt = 5.0 s idmr = 50 s – time step for the microphysical module
- dz = 20 m
- mean vertical uplift, i.e. $\overline{w}=0.02$

5.
- wave with wavelength 10km, wave amplitude .20 m/s, wave speed 15 m/s
- dt = 5.0 s idmr = 50 s – time step for the microphysical module
- dz = 20 m
- mean vertical uplift, i.e. $\overline{w}=0$

The results from these simulations can be viewed in the attachment according to the description and its corresponding number. The results in the appendix will include

- plots of the relative humidity profile(RH_i), rate of ice crystal production (dN_i), and ice crystal number concentration(N_i)
- plots of ice water path(IWP) and ice crystal number concentration (N_i)
- color figures of ice water content (IWC) and ice crystal number concentration (N_i)

We are currently completing the simulations of the parameter space. Initially we see differences in the development of cirrostratus when inserting gravity waves, but no final conclusions can be suggested until all simulations are completed. Future work for this study includes implementing wave trains into the 1D Cirrus Cloud Model to investigate its effects on cloud developments

References

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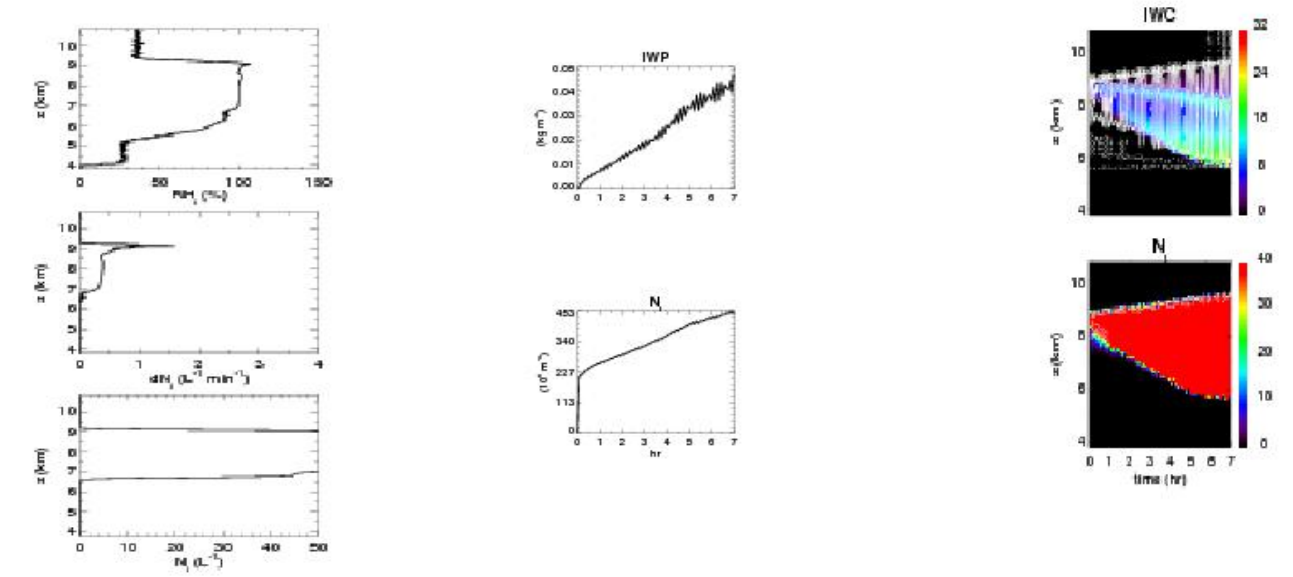
Acknowledgements. This study would like to acknowledge and thank Dr. David O'Starr of the Mesoscale Atmospheric Processes Branch of NASA GSFC, Dr. Ruei-Fong Lin of UMBC GEST, and NASA Graduate Student Summer Program (GSSP).

APPENDIX

1.



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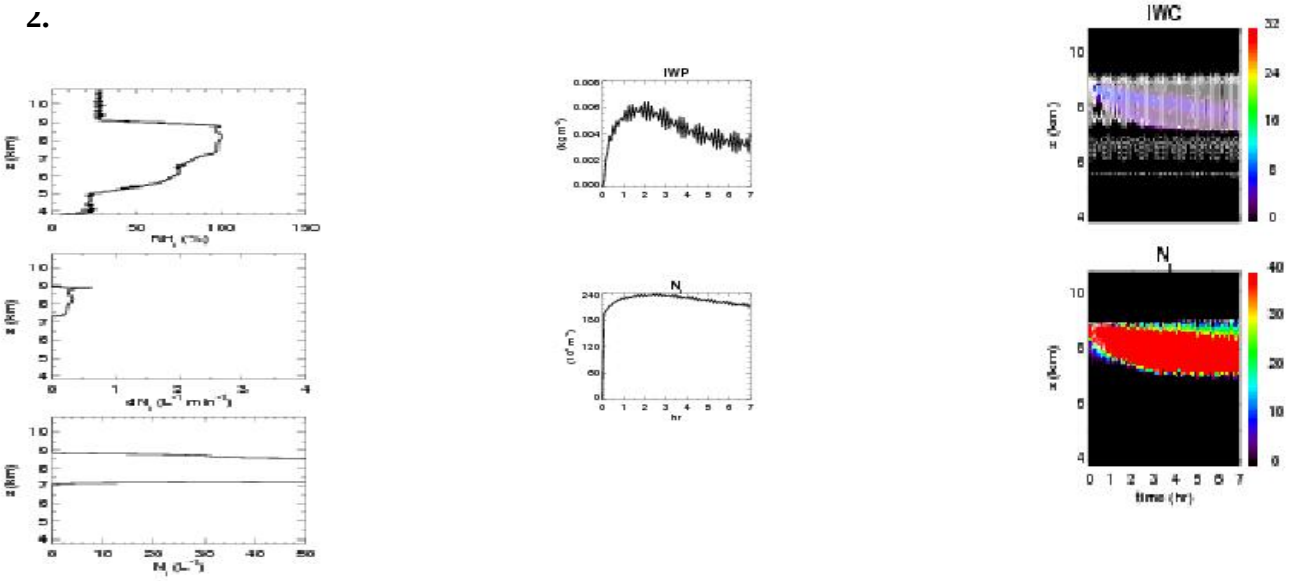

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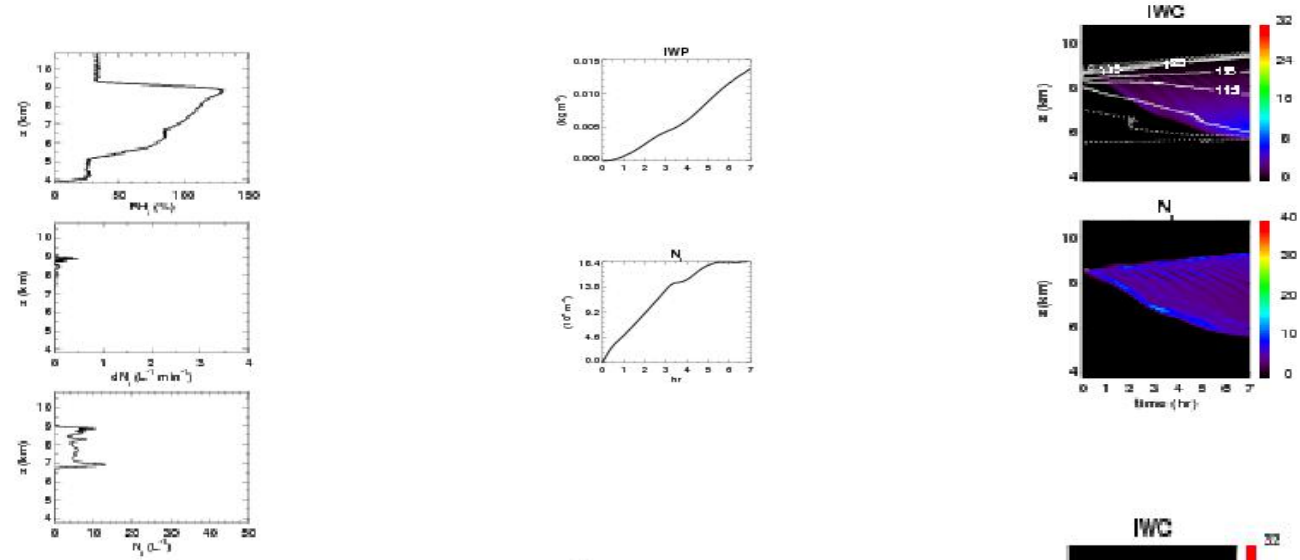
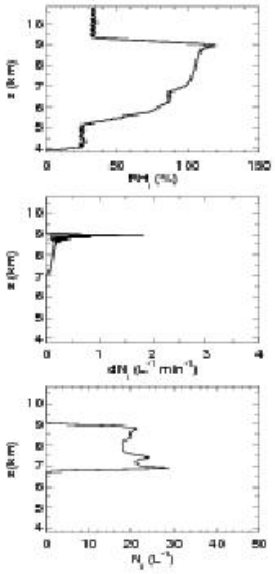
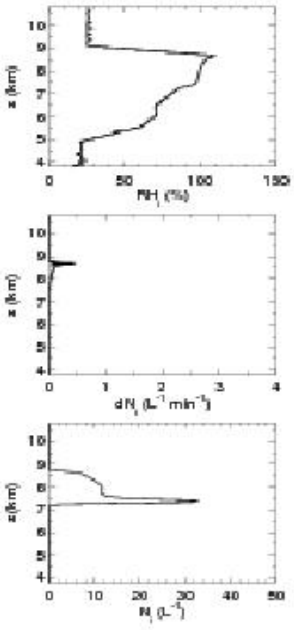
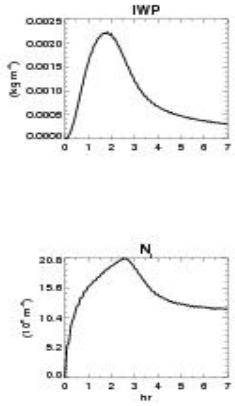
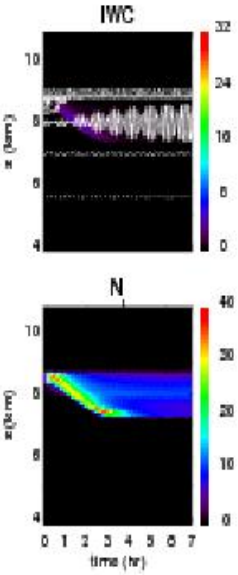



z (km)
RH_i (%)
dN_i (L^-1 min^-1)
N_i (L^-1)

5.


z (km)
RH_i (%)
dN_i (L^-1 min^-1)
N_i (L^-1)


IWP
(kg m^-2)
N_i
(10^6 m^-3)
hr


IWC
z (km)
N_i
z (km)
time (hr)