UNIVERSITY OF LEEDS

MRES CLIMATE AND ATMOSPHERIC SCIENCE

PRACTICAL WEATHER FORECASTING

Hurricane Katrina

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Introduction

Hurricane Katrina is a very well known tropical cyclone (TC) because of the human and economical losses that made it the most harmful event in US recent history since it left behind over 1800 deaths and $ 44 billion US dollars in losses. Katrina is a very well studied hurricane, whose genesis can be synthesized as an interaction of a tropical wave, a trough, that provided cyclonic vorticity, and Tropical Depression Ten TD10 that, once destroyed by shear, moved its vortex to a zone of potential instability that would become Katrina (McTaggart-Cowan et al., 2007; Knabb et al., 2006).

Katrina started its long life cycle on August 23 on Bahamas, made landfall over Florida as a category-1 Hurricane and then intensified to category 5 on August 28, as observed in figure 1. This work is concerned with the period between August 28-30, when Katrina moved northward towards Louisiana, where it eventually made landfall with category-3 deathly winds (near 55 m s^{-1}) (McTaggart-Cowan et al., 2007).

Methodology

The Weather Research and Forecasting Model (hereafter "WRF") was implemented on the *arc2* server to run a 49 time step simulation in a grid of approximately 30x30 °in longitude and latitude covering a large portion of the Gulf of Mexico and southeast US under a default configuration for all parametrizations, this included the use of the Yonsei University Scheme for PBL and Kessler Scheme for microphysics. The implementation of WRF in a UNIX-system requires the build up of several modules, roughly, this include the setup of *geogrid* and *ungrib* to produce the necessary files to then

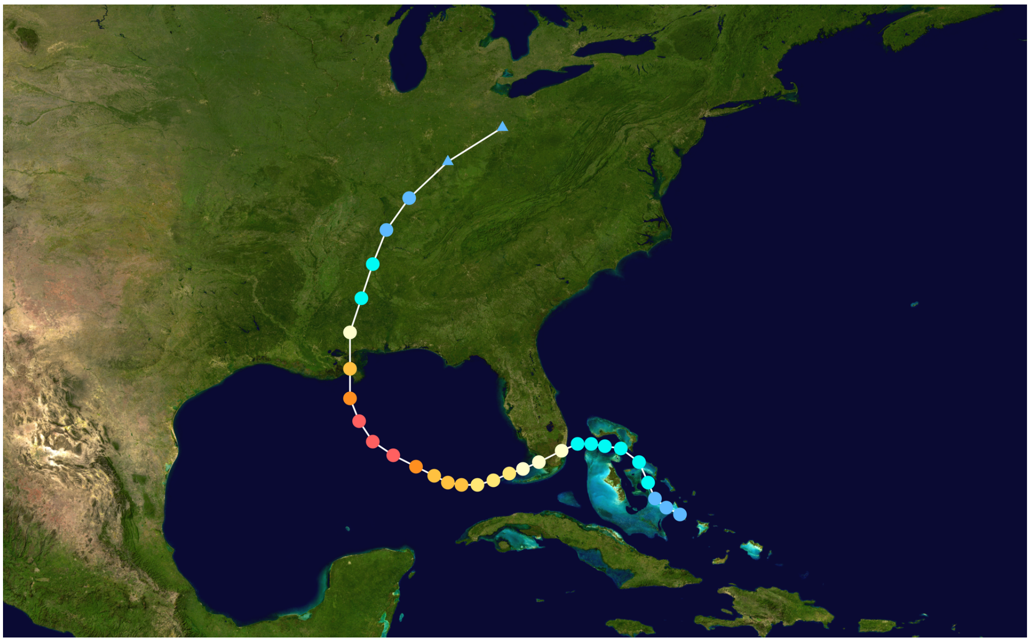


Figure 1: Track of Hurricane Katrina color-coded for intensity. Source: Wikipedia (2017)

build *metgrid*, initialize and finally run the model.

The model was re-run by changing the cumulus parametrization scheme in the namelist.input; the *cu_physics* was originally set to 2, indicating the use of the Betts-Miller-Janjic Scheme, and was changed to option 1 which is the Kain-Fritsch Scheme. Outputs were analyzed using NCL and Python and are discussed in the following sections.

RESULTS / DISCUSSION

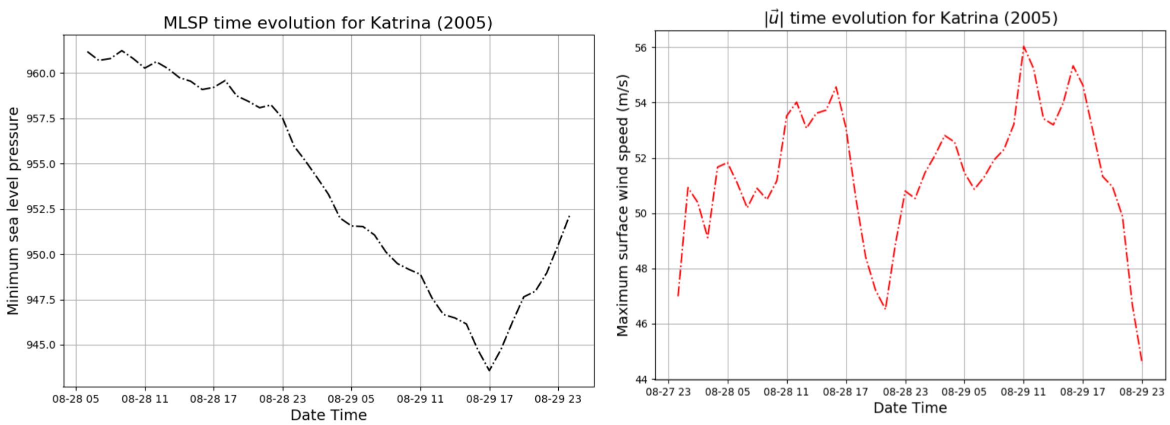
Intensity evolution

Minimum pressure and maximum wind speed are metrics to assess the intensity of a TC, in this case, minimum sea level pressure (MSLP) and maximum horizontal wind speed (MWS) were obtained for each time step, assuming that the MSLP occurs at the eye of the storm and MWS happens at the vicinity of the hurricane. Figure 2 shows that the MSLP decreases for the larger part of this simulation whereas the maximum wind speed roughly tends to increase, both indications of intensification.

Cross sections

Vertical cross sections orientated east to west were obtained for August 29 at 13:00, a time-frame where Katrina presents high intensity, and are shown in figures 3 to 6. In figure 5a and 5b the eyewall appears as a relatively narrow region with strong ascent, since vertical velocity w is greater than 1, and a high mixing ratio, however, using figure 5c, ice occurs in a higher section about 250 hPa and not in the region of strongest ascent.

Radial velocity, figure 5d, was estimated through the x-component (u) of the $\vec{u}$ field. Considering that an east-to-west cross section allows a local equivalence between radial and u velocities it is shown the strong convergence towards the center of the storm at low levels, meanwhile, the eye is



(a) MSLP.

(b) MWS.

Figure 2: Time evolution of minimum sea-level pressure (a) and maximum horizontal wind speed (b).

characterized as the region of weaker winds.

The hydrometeor distribution, figure 6, shows the total (fig. 6a), rain (6b), snow (6c) and graupel (6d). The majority of hydrometeors are accounted as snow particles in the higher portion of the eye wall, meanwhile, rain is mostly represented in the region of maximum ascent and graupel is the least concentrated hydrometeor since it only covers a small portion of the upper-levels. In general, the vast majority of precipitation is located in the eyewall and its outer upper region.

The eyewall has been shown to be a region of strong ascent, which is produced by the feedback of surface winds importing moisture and heat from the ocean's surface to the atmosphere; the moisture, reflectivity and potential temperature (θ) distributions, figures 3 and 4, support this argument since relative humidity and reflectivity are maximum in the eyewall. In contrast, upper parts of the eye are very dry, with low reflectivity and a subsidence in θ accounting for a cloud-free sky.

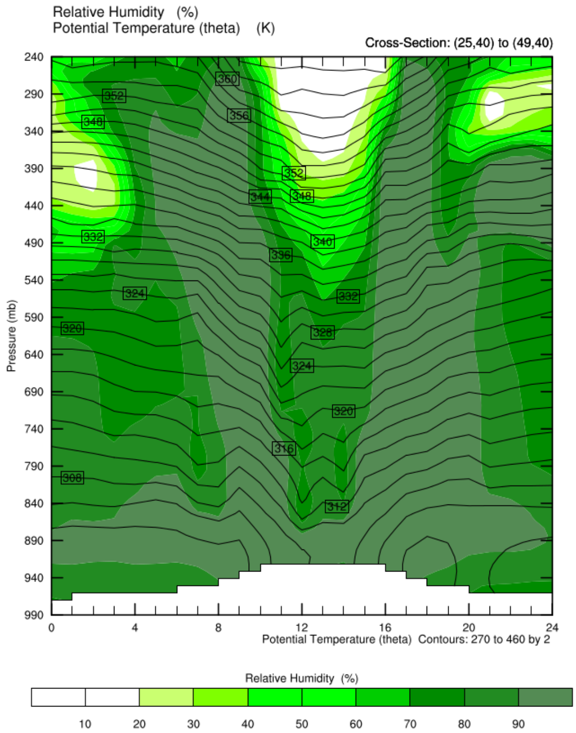


Figure 3: Relative humidity (%) in color contours and potential temperature (K) in solid lines, as in fig. 5.

Cloud localization

Stratus are low-level clouds formed under low vertical velocities, $w < 1$ m/s. Figure 7a shows the plain view at 800 hPa of rain number concentration which, using 6b, indicate that the eyewall and its vicinity present the larger amount of rain at low levels. Figures 6d and 6c show that there are no relevant ice particles at this level. Therefore, we can locate stratiform clouds to be in the vicinity of the eyewall, outside the zone of high vertical velocities.

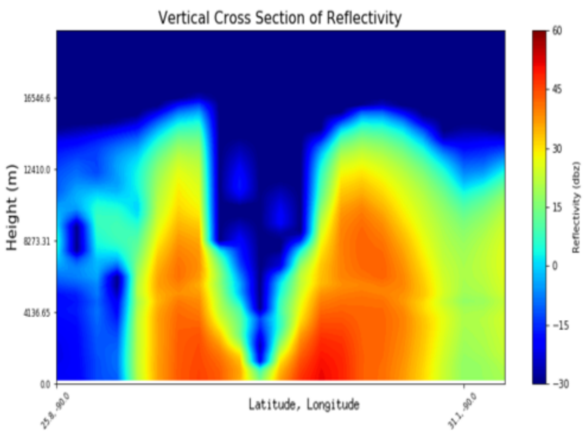


Figure 4: Reflectivity (N-S) cross section as in fig 12.

Figure 7b shows a higher level (300 hPa), plan view to observe cirrus location as a spiral-

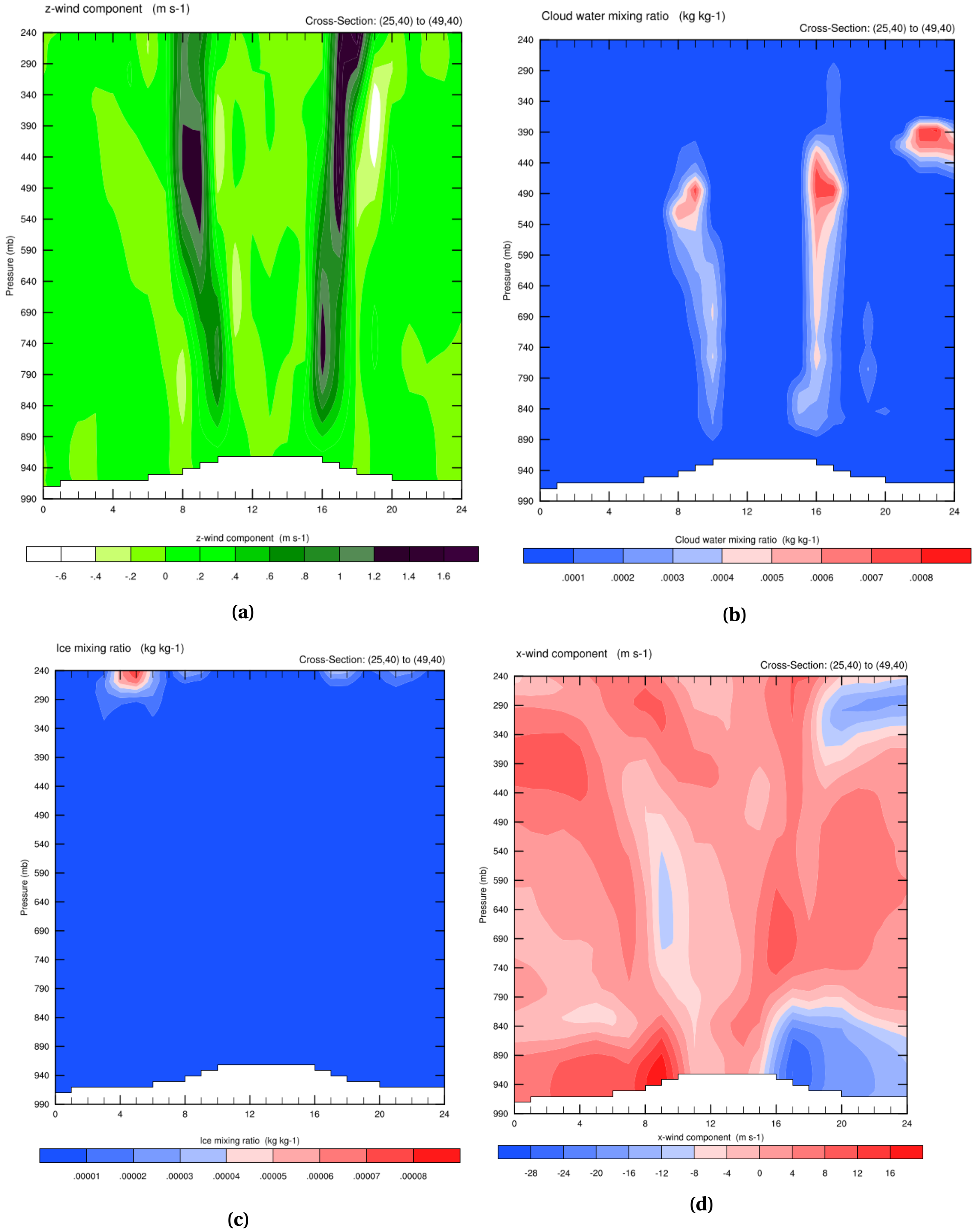


Figure 5: Vertical cross sections for vertical wind speed (a), cloud-liquid (b) and ice cloud (c) mixing ratios and radial velocity (d).

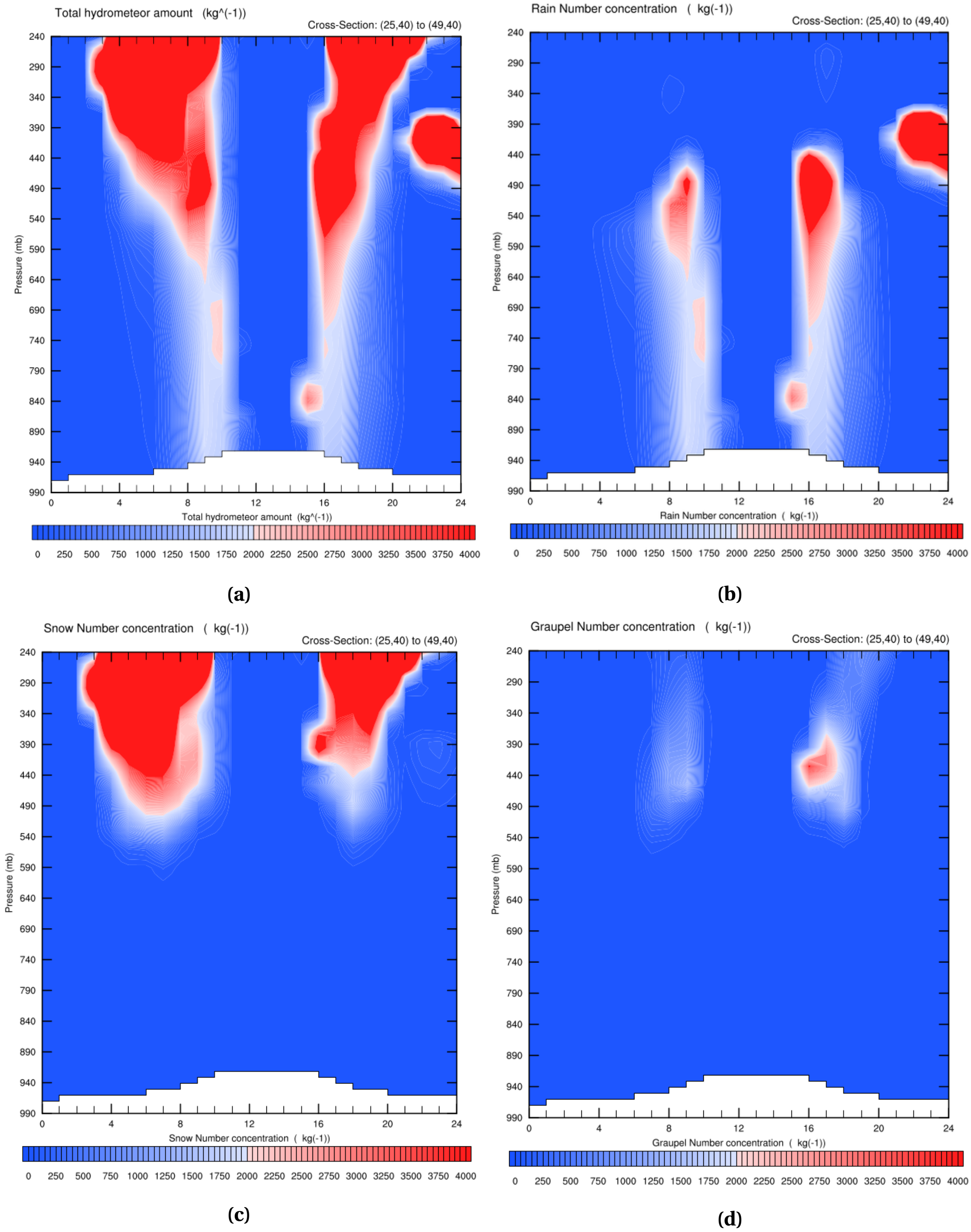
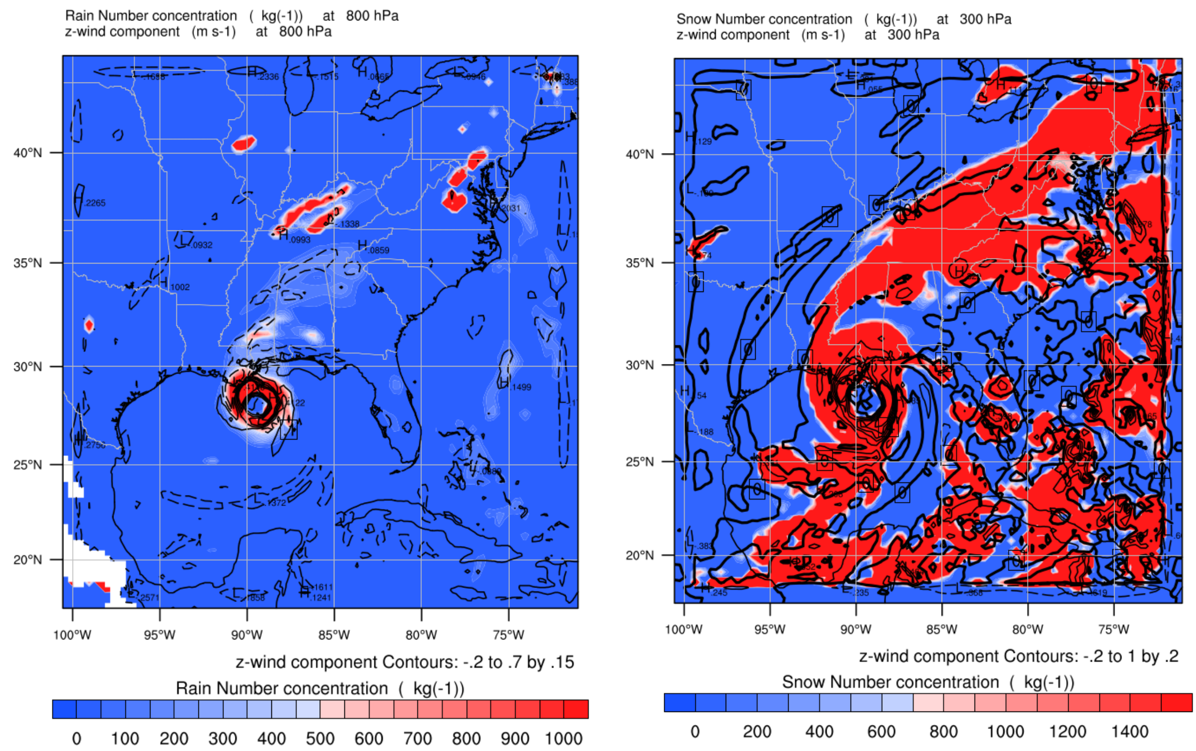


Figure 6: Hydrometeor amount for (a) total, (b) rain-only hydrometeors, (c) snow and (d) graupel, analogous to fig. 5.



(a) 800 hPa: rain and w.

(b) 300 hPa: ice and w.

Figure 7: Plan views locating stratus a) and cirrus b) clouds with rain or snow number concentration on color contours as well as vertical wind speed in lines (black contours).

like flow of snow concentration number going out of the storm's center.

Cumulunimbus clouds are observed, figure 8, using velocity contours and rain number concentration. It is argued, with the help of figure 5a, that this view at 600 hPa showing large vertical velocities ($w > 1$) and a high number of hydrometeors indicates the distribution of cumulunimbus clouds.

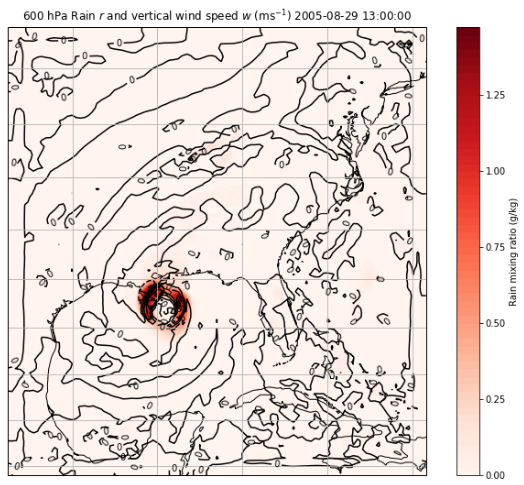
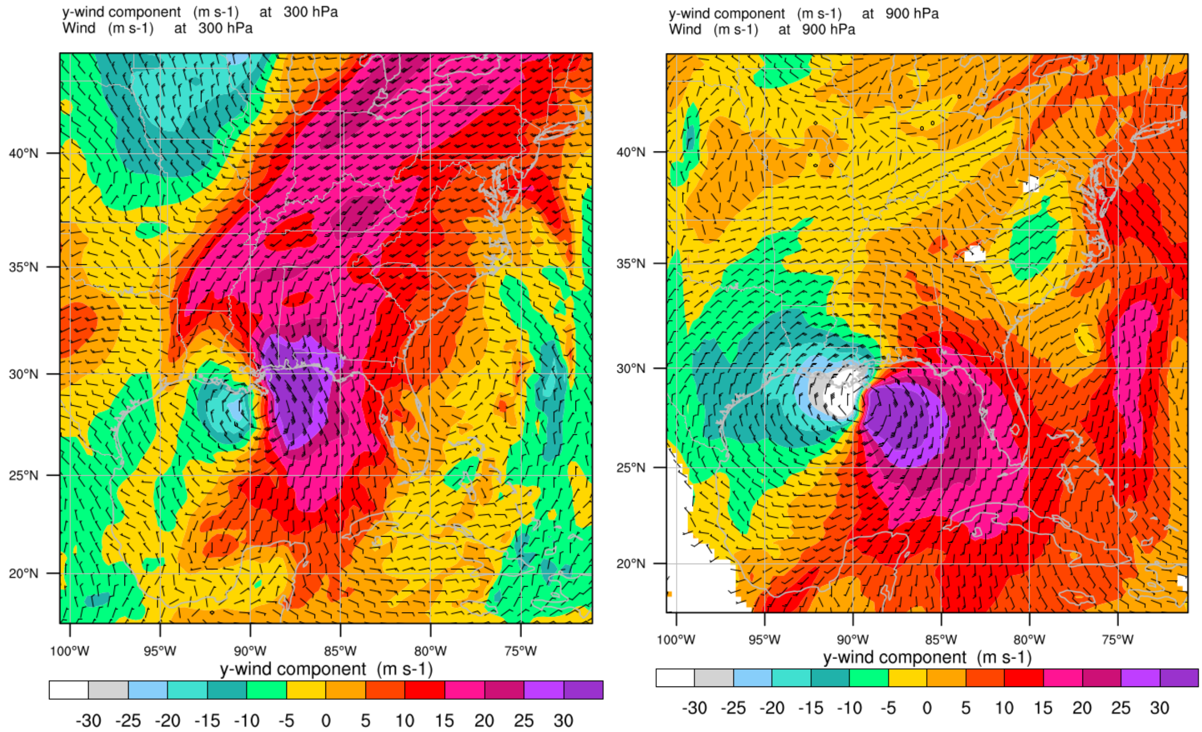


Figure 8: Plan view at 600 hPa of w (m/s) line-contours and rain mixing ratio (g/kg) in red-color-contours.

Outflow analysis

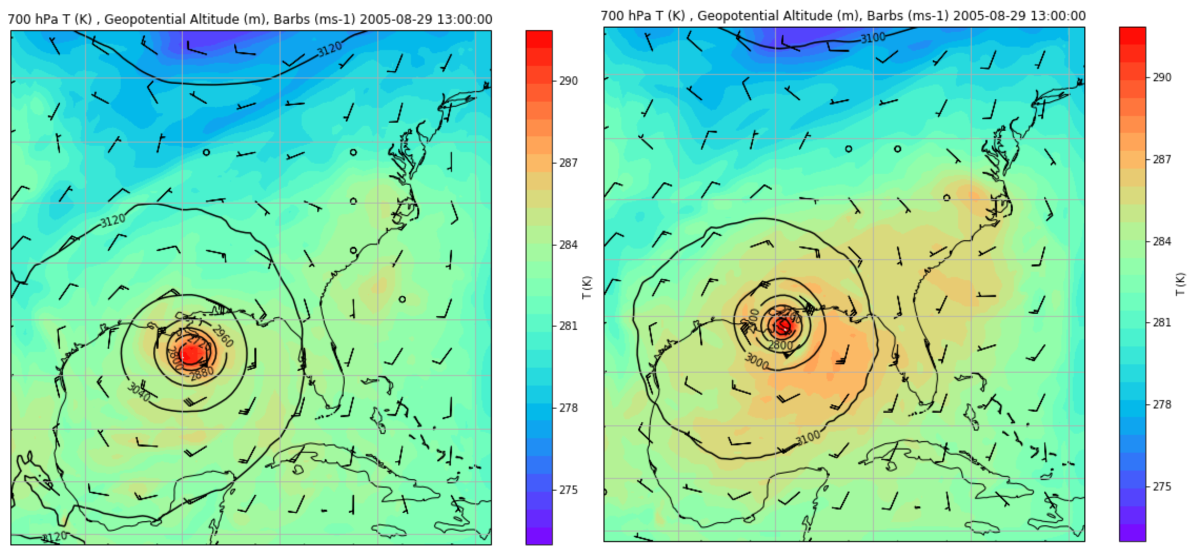
Circulation in a hurricane is characterized by low level inflow with cyclonic (counterclockwise) flow in the Northern Hemisphere (Montgomery and Smith, 2011). Figure 9a shows the low-level juxtaposition of two flow metrics as are wind barbs and v, this low-level flow is observed to be cyclonic and stronger in the vicinity of the eye.



(a) 300 hPa

(b) 900 hPa.

Figure 9: Flow motion, v (y-component) wind color contours overlapped on wind barbs for two pressure levels, analogous to previous figures.



(a) Betts-Miller-Janjic Scheme.

(b) Kain-Fritsch Scheme.

Figure 10: Flow motion as wind barbs, temperature colored-fields and geopotential contours (black-solid lines) for two cumulus parametrization schemes.

High-level flow in figure 9b does not present this dominant circulation, cyclonic or anticyclonic, and this might be due to the model's set up making it unable to reproduce high-level anticyclonic flow as theory suggests.

Potential Vorticity

Potential vorticity (PVO), used to locate vortex lines in potential temperature surfaces, (Markowski and Richardson, 2011), is observed through plan views on *isentropic* or theta-constant (in adiabatic motions) surfaces in figure 11 for 315, 330 and 350-K.

Katrina's maximum PVO is observed at low and high levels with a noticeable decrease at the middle θ level. This feature is explained by considering that PVO is a metric for the flow's tendency to turn, which in a hurricane is dominant at the upper and lower levels.

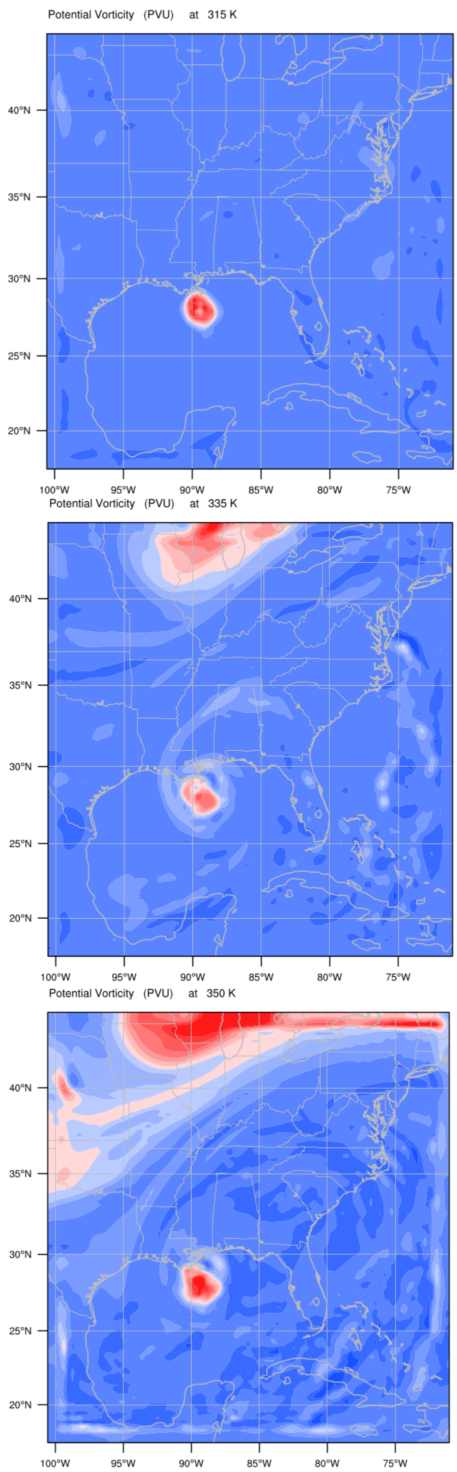


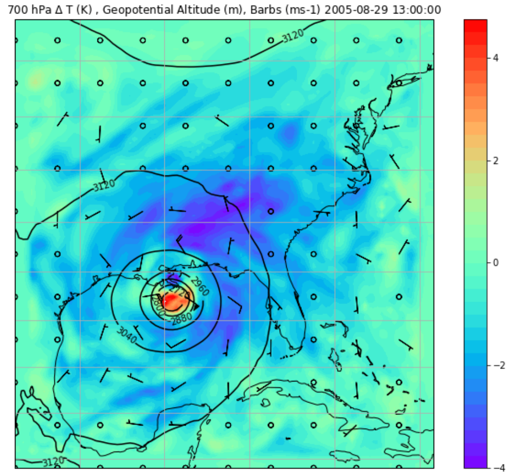
Figure 11: Potential vorticity at 3 isentropic levels.

CP scheme

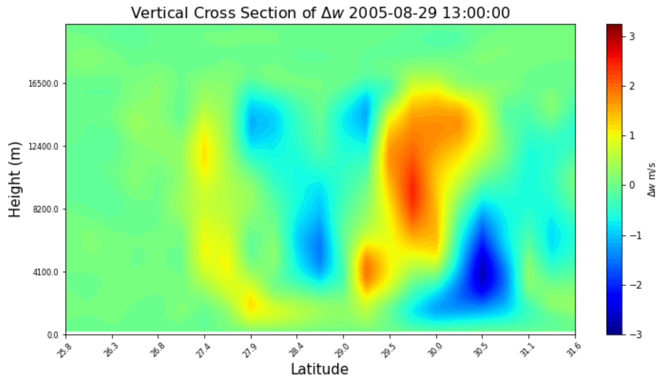
The cumulus parametrization change from a Betts-Miller-Janjic to a Kain-Fritsch Scheme compares adjustment (BMJ) and mass flux (KF) schemes. Figure 10 overlays the wind speed and direction, temperature and geopotential altitude for both cumulus schemes in16 our prefixed time step. The differences are actually presented in figure 12, where 12a represents the arithmetic anomaly between figure 10a and 10b. Analogously, this is shown for N-S cross sections of a small set of variables across the longitude 90 °W from latitude 26 to 31 N in figure 12.

Katrina's track is affected by the CP scheme since fig. 12 suggests that the eye has been displaced considering the high anomaly in horizontal and vertical wind speeds (figures 12b and 12e) and precipitation has also drifted since the mixing ratios for ice and water show localized increments (figure 12d, 12c), also supporting t+he idea that the storm has moved northwards in the Kain-Fritsch Scheme.

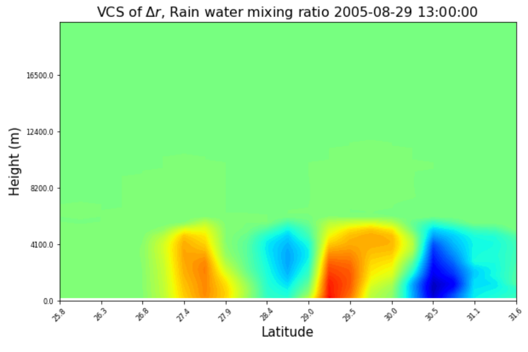
The use of NWP models, as WRF, inherently generate uncertainties, in this particular case, errors arise from two



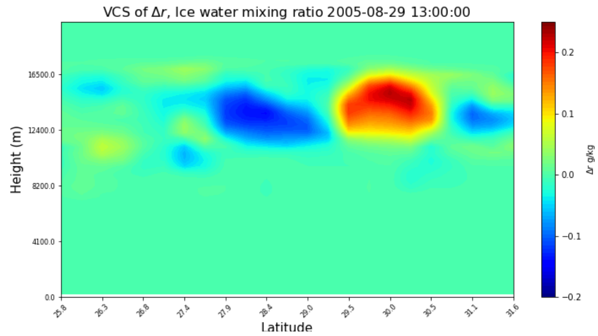
(a) $\Delta\Phi$, T and $\vec{u}$.



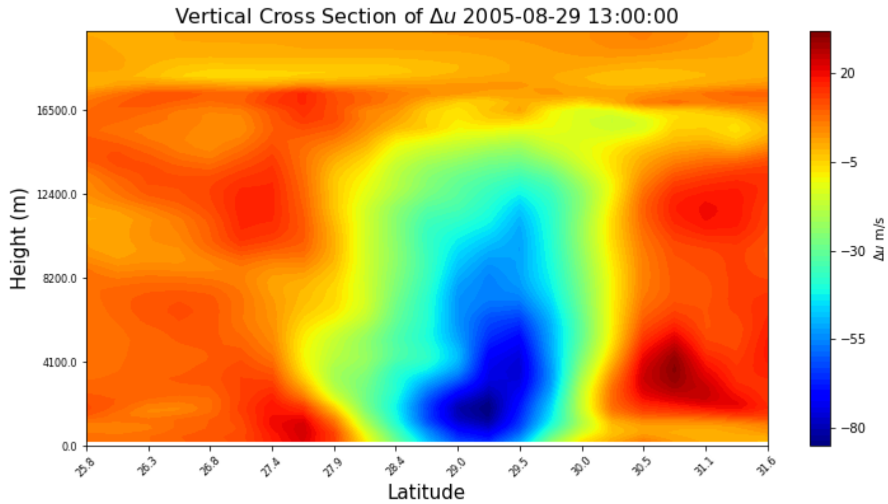
(b) Δw



(c) Δr_w



(d) Δr_i



(e) Δu

Figure 12: Anomalies of a) geopotential altitude, T and wind speed, and (N-S) cross sections for x (e) and z (b) wind components, rain (c) and ice (d) mixing ratios between two CP schemes.

main sources:

- Numerical discretization errors: integration of differential equations tend to depart from real solutions due to the change from the continuous to the discrete domain.

- Physical: parametrizations schemes for instance, are an approximation to represent a physical processes, keyword being *approximation*.

Moreover, the atmosphere is a chaotic environment which mathematically means it is very sensitive to initial conditions, *i.e.* WRF, literally, cannot represent all necessary processes.

SUMMARY

Hurricane Katrina was modeled using WRF for a two-day period simulation. Results show a distinguishable eye and eyewall region, the former characterized as a dry relatively calm region and the latter presented strong ascent and large precipitation. A discussion and examples of how the parametrization scheme and numerical errors can affect the simulation is also included.

TexCount (2017) word count = 1481 words.

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