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Mass Flux in Hurricane Irma

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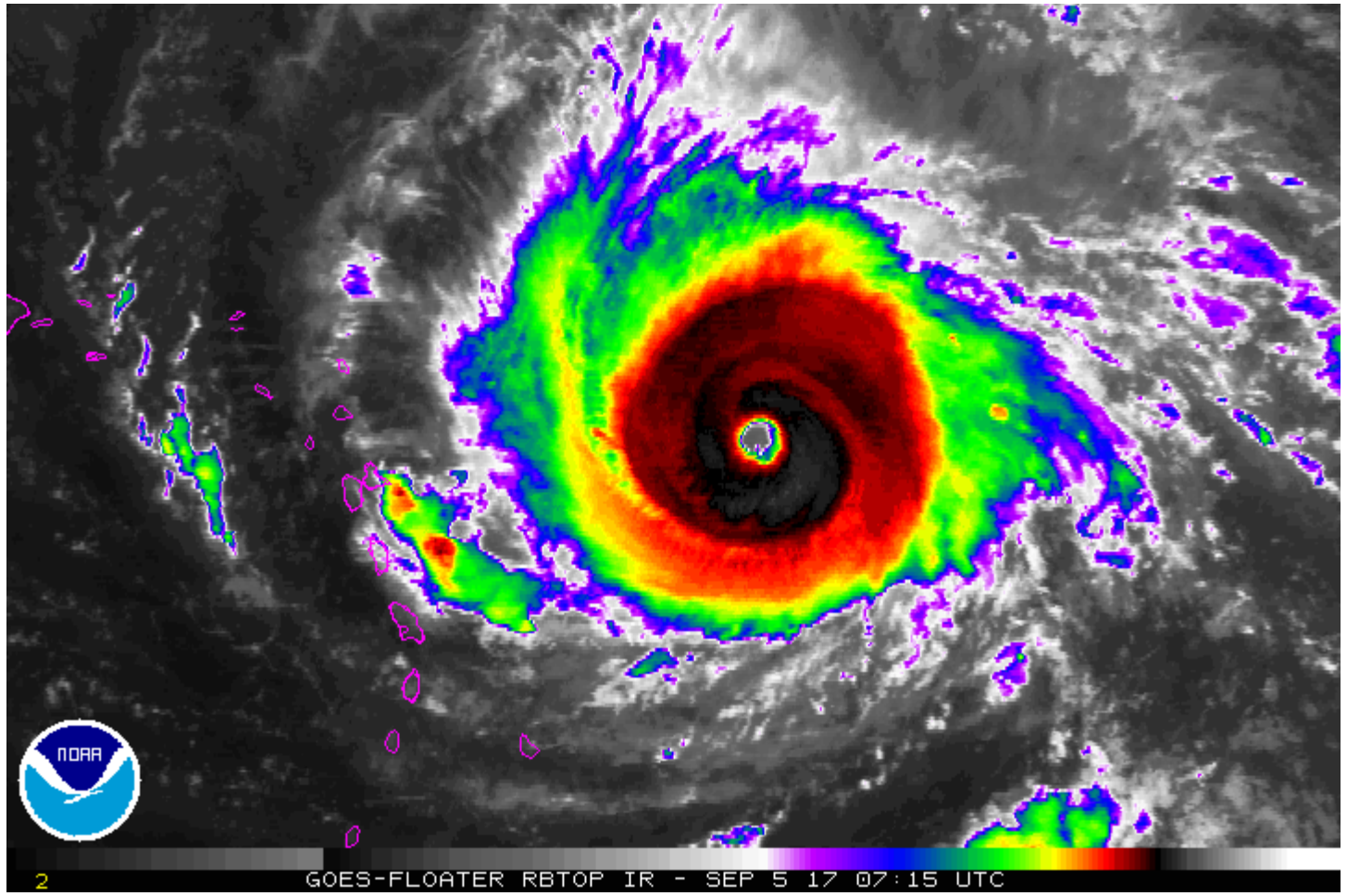
Hurricane Irma



Hurricane Irma

– Hurricane Irma was an extremely powerful and catastrophic Cape Verde hurricane, the strongest observed in the Atlantic in terms of maximum sustained winds since Wilma, and the strongest storm on record to exist in the open Atlantic region. Wikipedia

– **Total fatalities**: 134

– **Highest wind speed**: 177 mph

– **Date**: August 30, 2017 – September 13, 2017

– **Affected areas**: Florida, Cuba, Saint Martin (Island), Puerto Rico, MORE

– **Category**: Category 5 Hurricane (SSHWS), Category 4 Hurricane (SSHWS), Category 1 Hurricane (SSHWS)

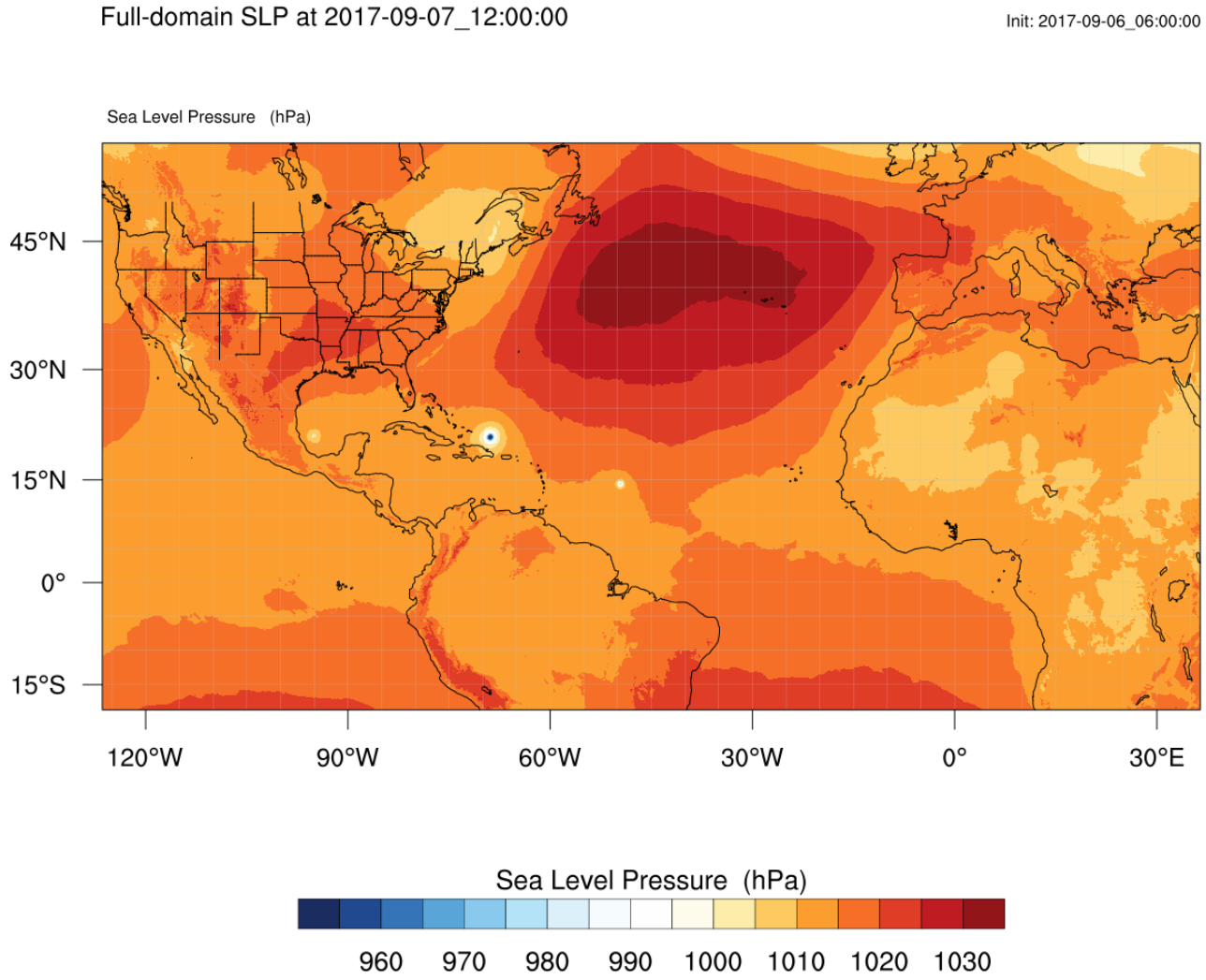
– **Did you know**: Irma is the fifth-costliest Atlantic hurricane ($64.8 billion in damage). wikipedia.org

https://en.wikipedia.org/wiki/Hurricane_Irma

Case Setup

- *2017.9.06 Hurricane Irma*
- *Grid: x-3100, y-1600, z-45*
- *Resolution: 5.4 km*
- *Forecast: 6 days*
- *Output Frequency: 1 hour*
- *Time step: 20 seconds*

Sea Level Pressure at Full Domain



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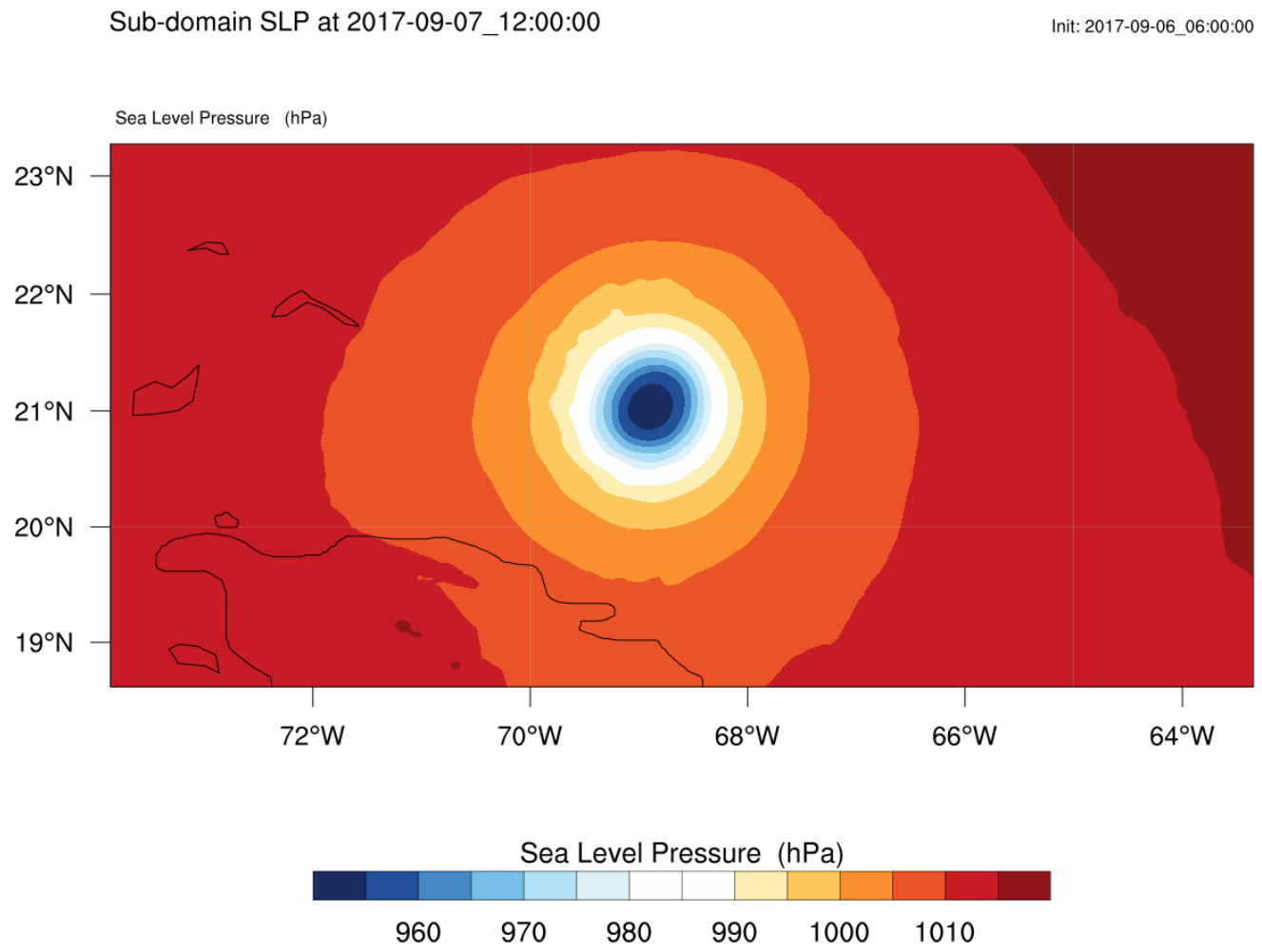
Sea Level Pressure at Sub-domain



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Calculate Mass Flux

- Continuuity equation:

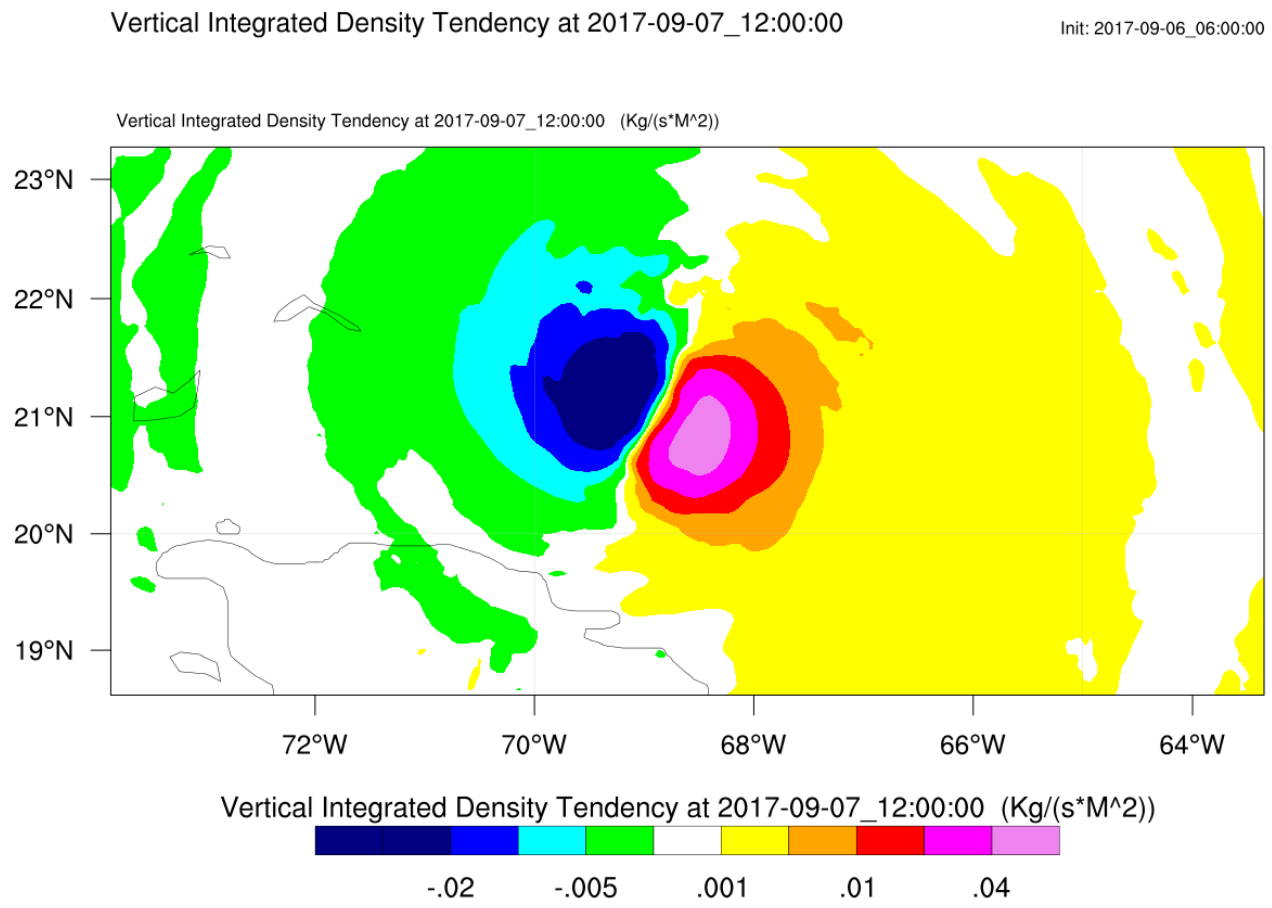
$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V}\right) = 0 \qquad (1)$$

- Can be rewrite as:

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \left(\rho \vec{V}\right) \qquad (2)$$

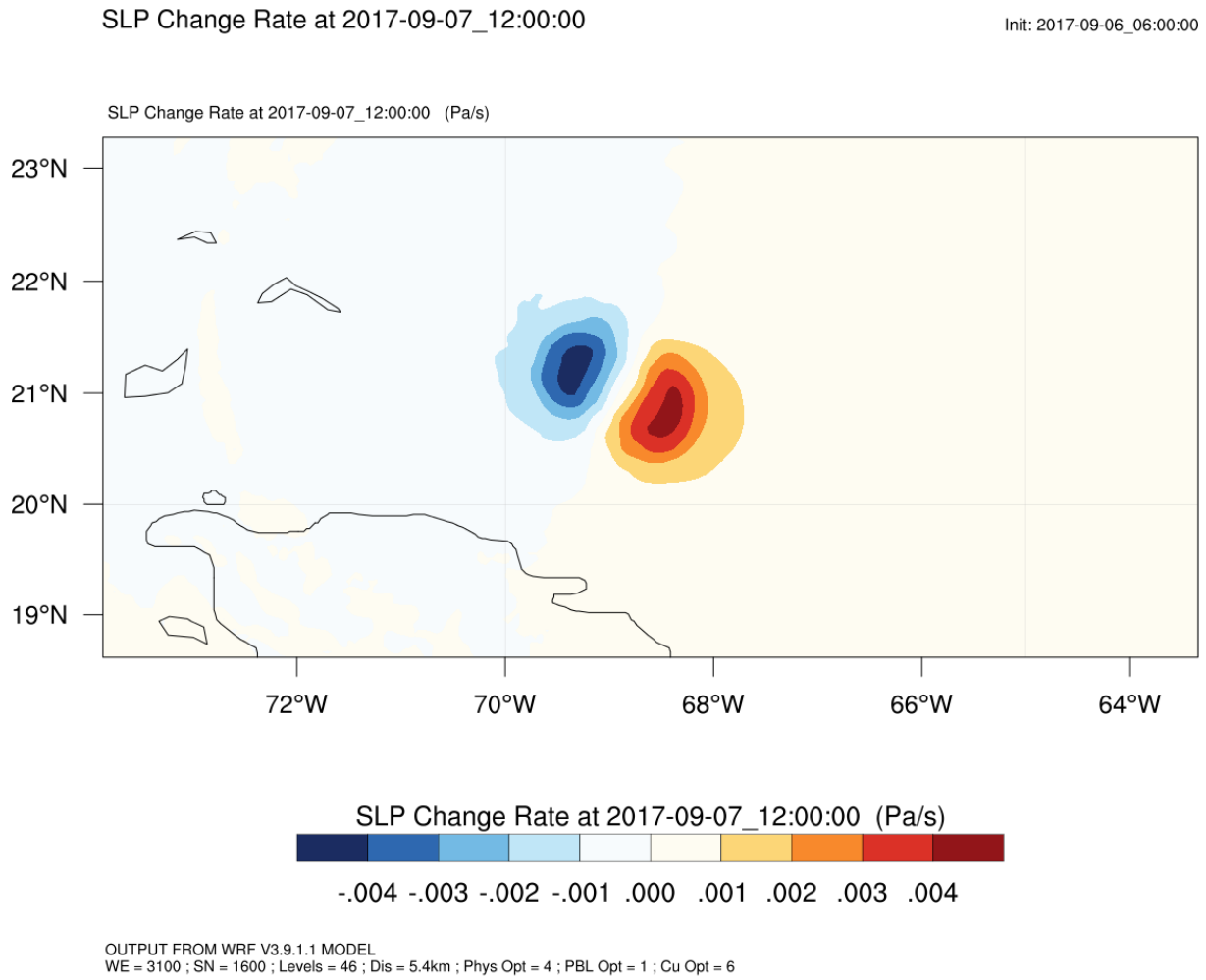
- Integrate the above equation along vertical direction to get air column mass change at left hand side, and mass flux at right hand side.

Mass Change Rate



OUTPUT FROM WRF V3.9.1.1 MODEL
WE = 3100 ; SN = 1600 ; Levels = 46 ; Dis = 5.4km ; Phys Opt = 4 ; PBL Opt = 1 ; Cu Opt = 6

Sea Level Pressure Change Rate

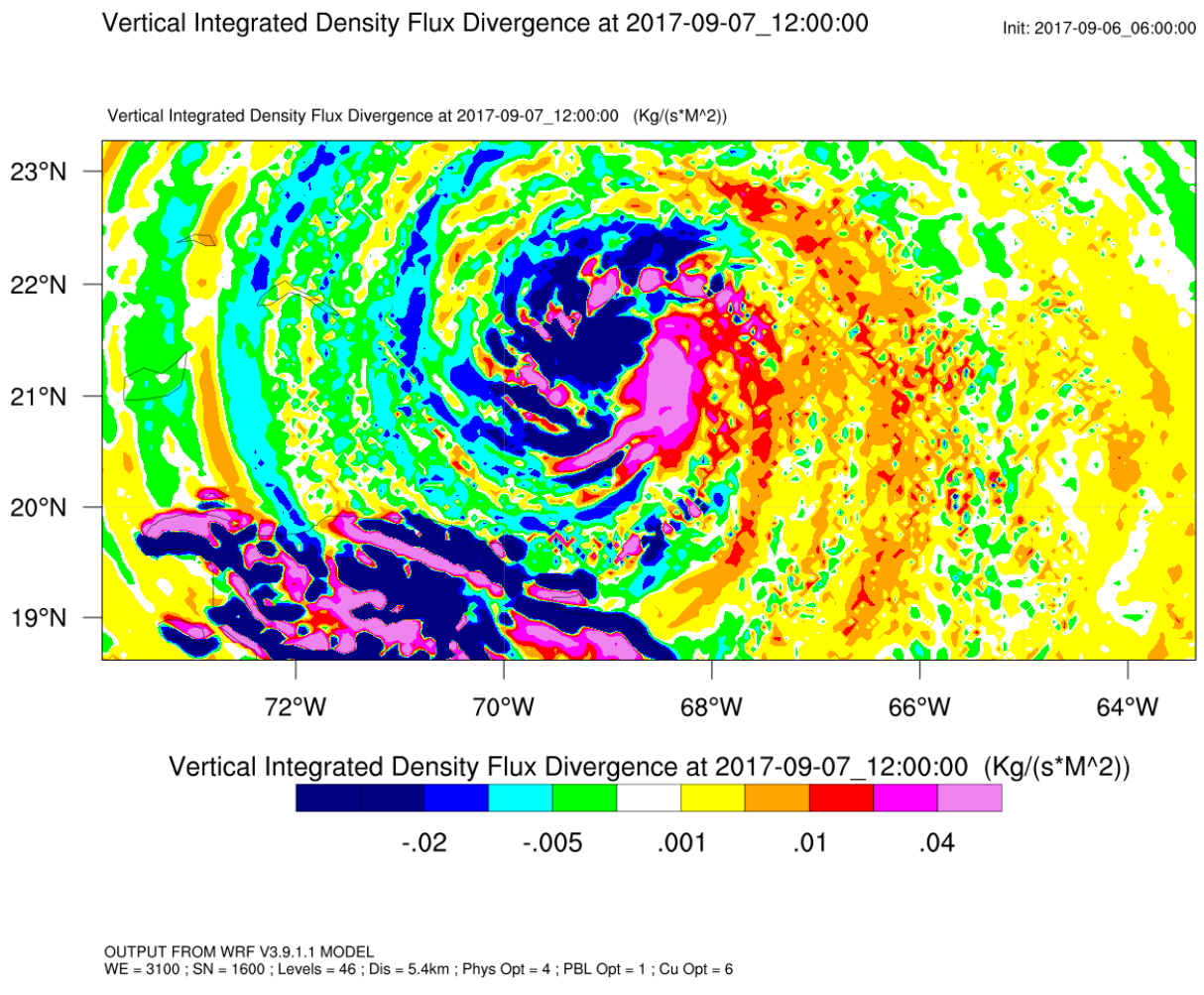


Compare Hourly SLP Change and Integrated Mass Change

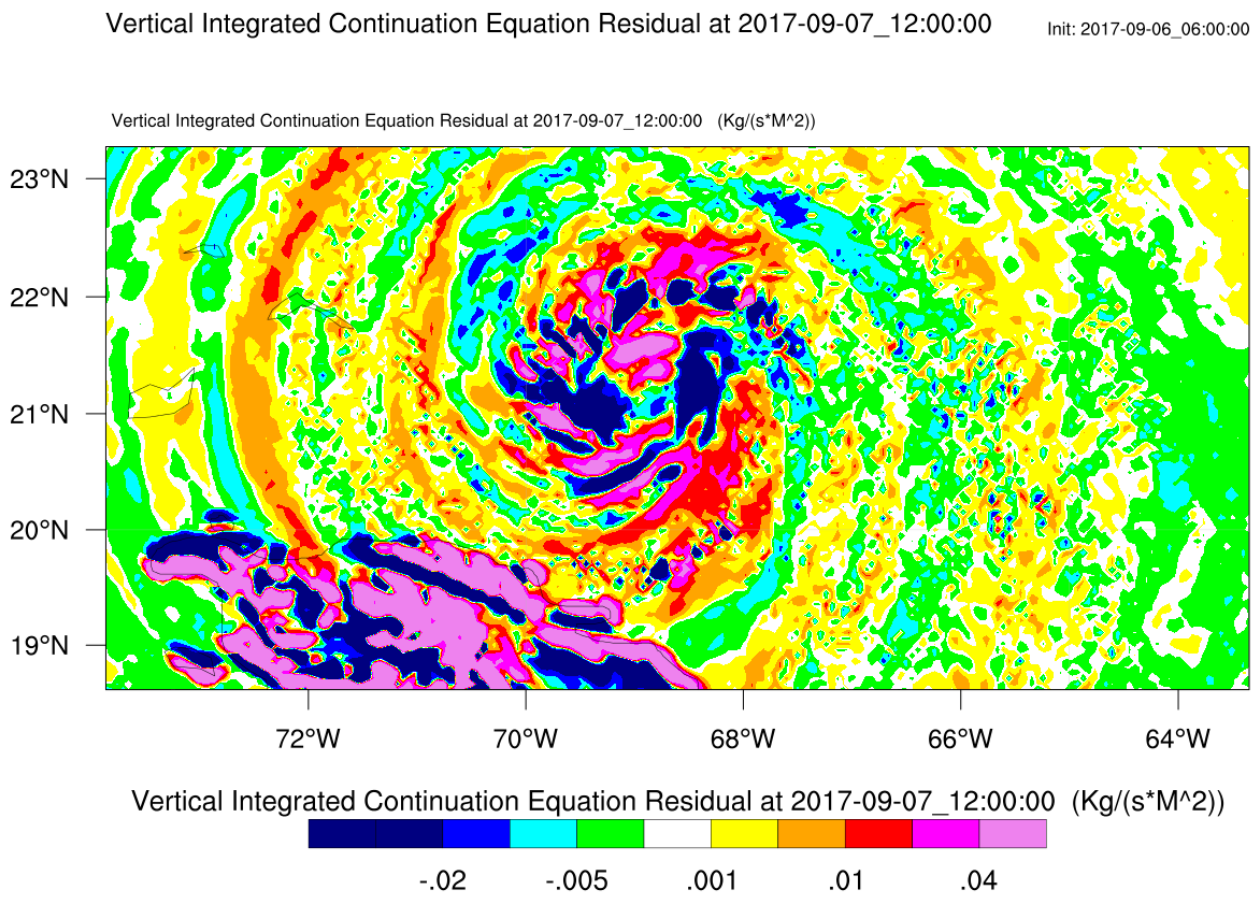
–As surface pressure is caused by the air in the vertical column, so the vertical integrated air mass should have exactly the same pattern as surface pressure (or Sea Level Pressure, if over sea).

–From continuity Equation, we expect that the vertical integrated mass flux, as the right hand side of Eq. 2 should have the similar pattern as hourly vertical mass change, right?

Vertical Integrated Mass Flux Divergence



Vertical integrated (Density tendency – density flux divergence)

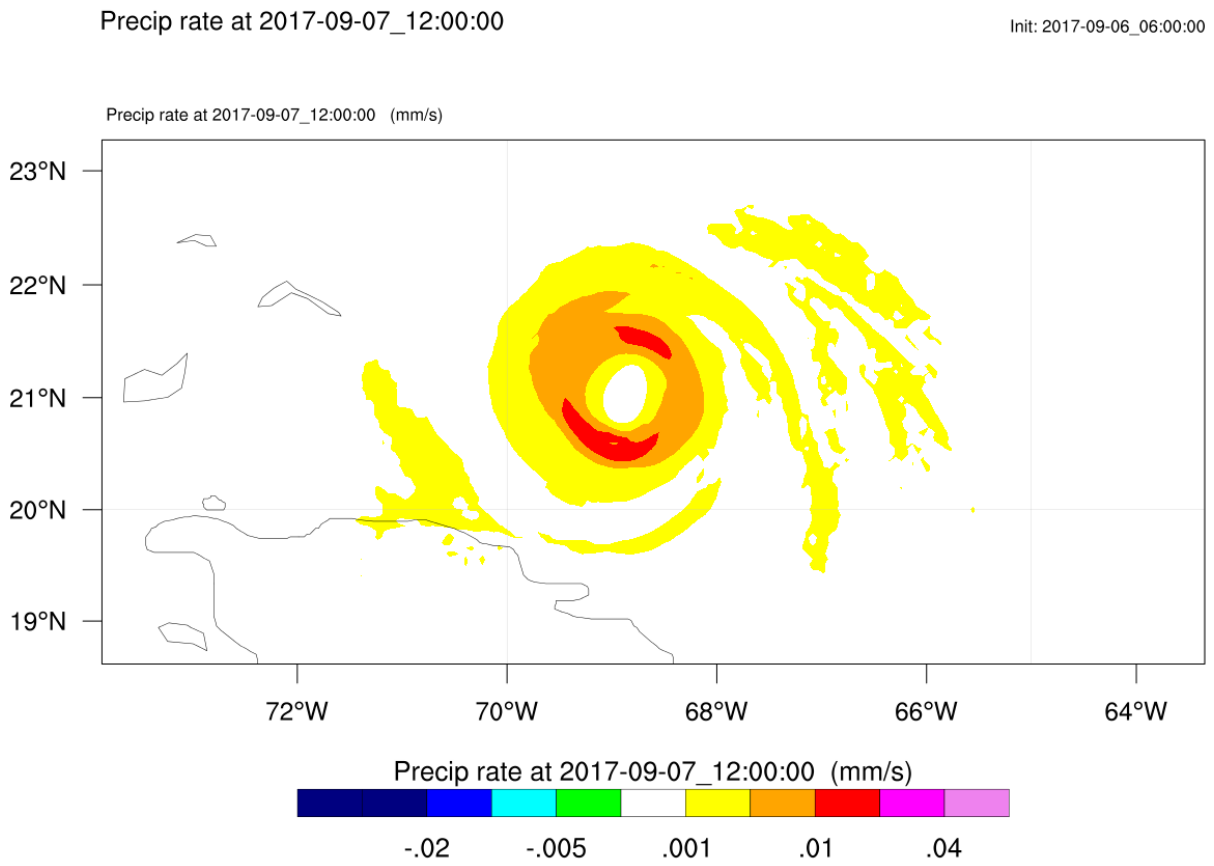


Compare Mass Change and Mass Flux

–In the hurricane region, the vertical integrated mass (hourly) change has totally different pattern to the vertical integrated Mass Flux.

–What the vertical integrated mass flux similar to?

Total Precipitation Rate



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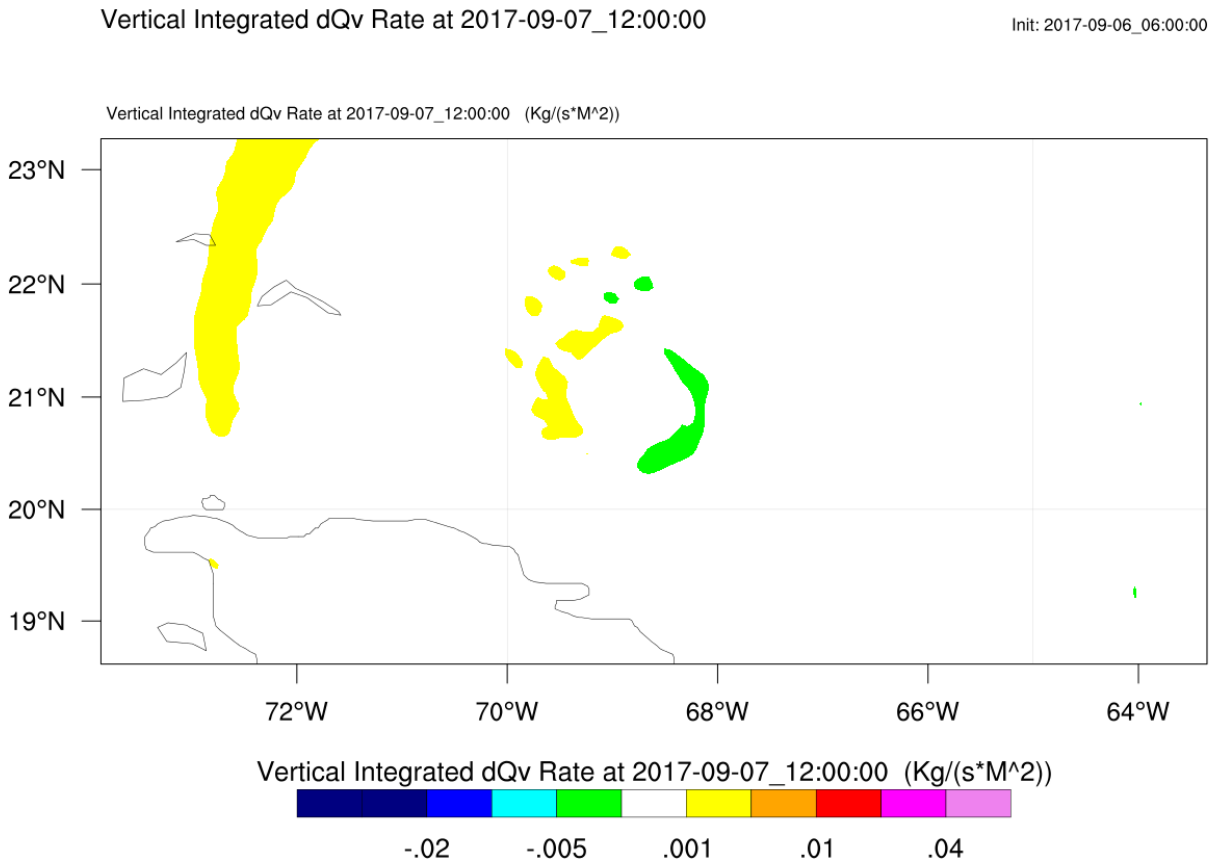
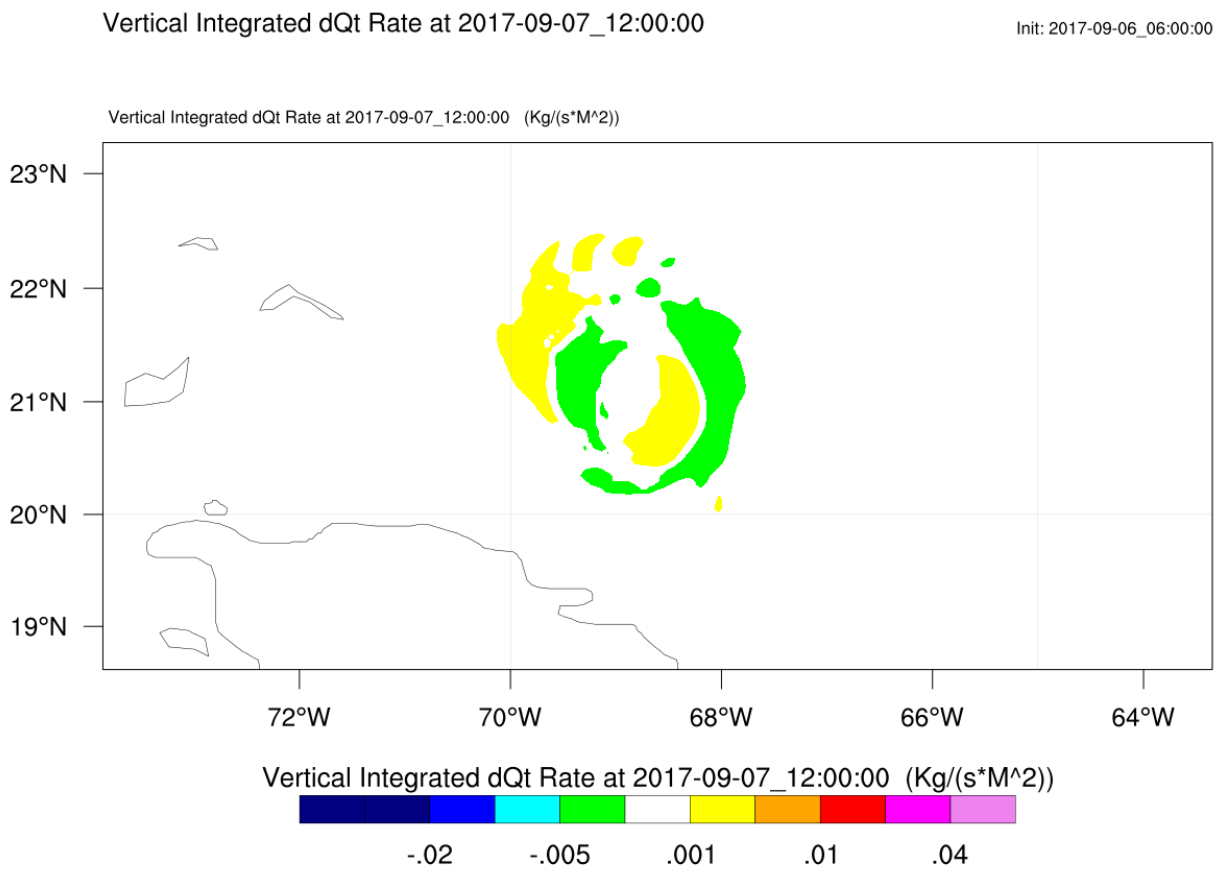
Water Vapor



OUTPUT FROM WRF V3.9.1.1 MODEL
WE = 3100 ; SN = 1600 ; Levels = 46 ; Dis = 5.4km ; Phys Opt = 4 ; PBL Opt = 1 ; Cu Opt = 6

Vertical Integrated Water Components Change Rate

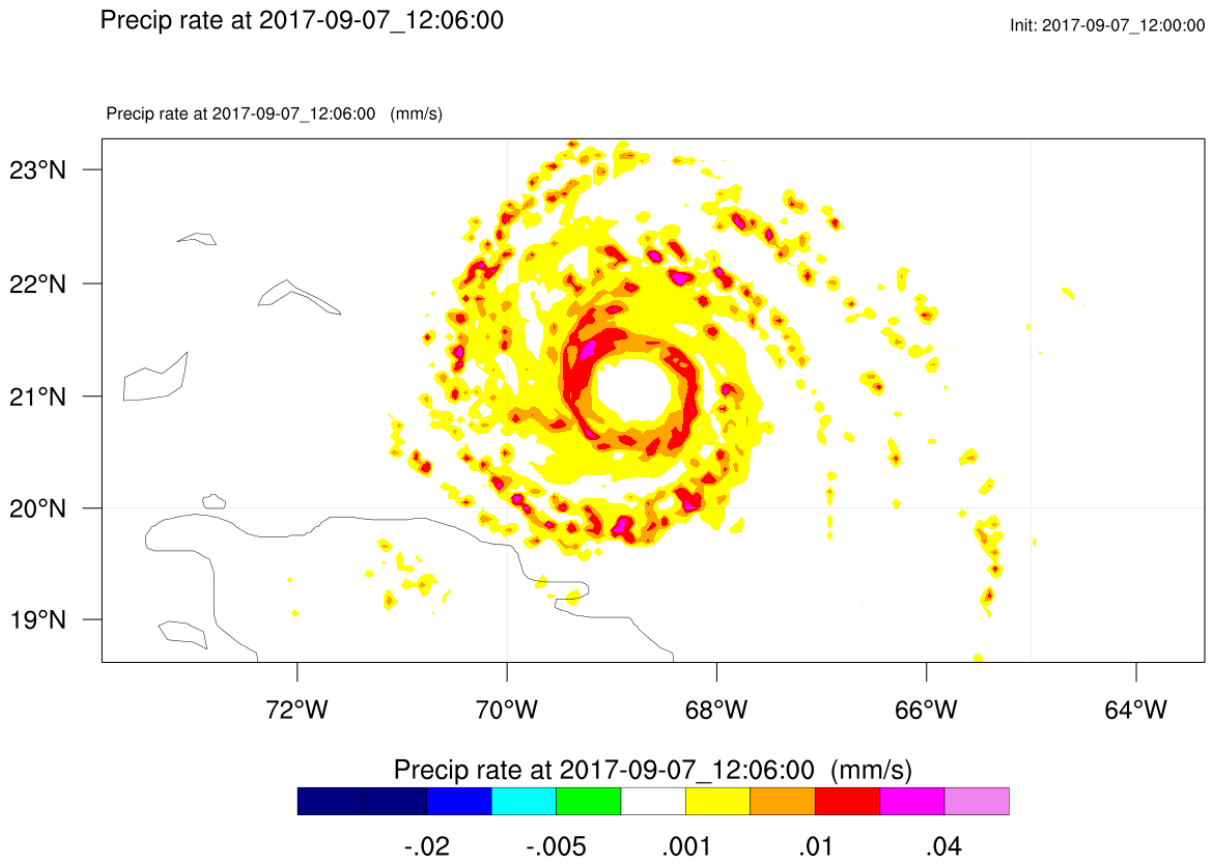


Compare Density Flux Divergence with Precipitation, and Water Vapor, etc

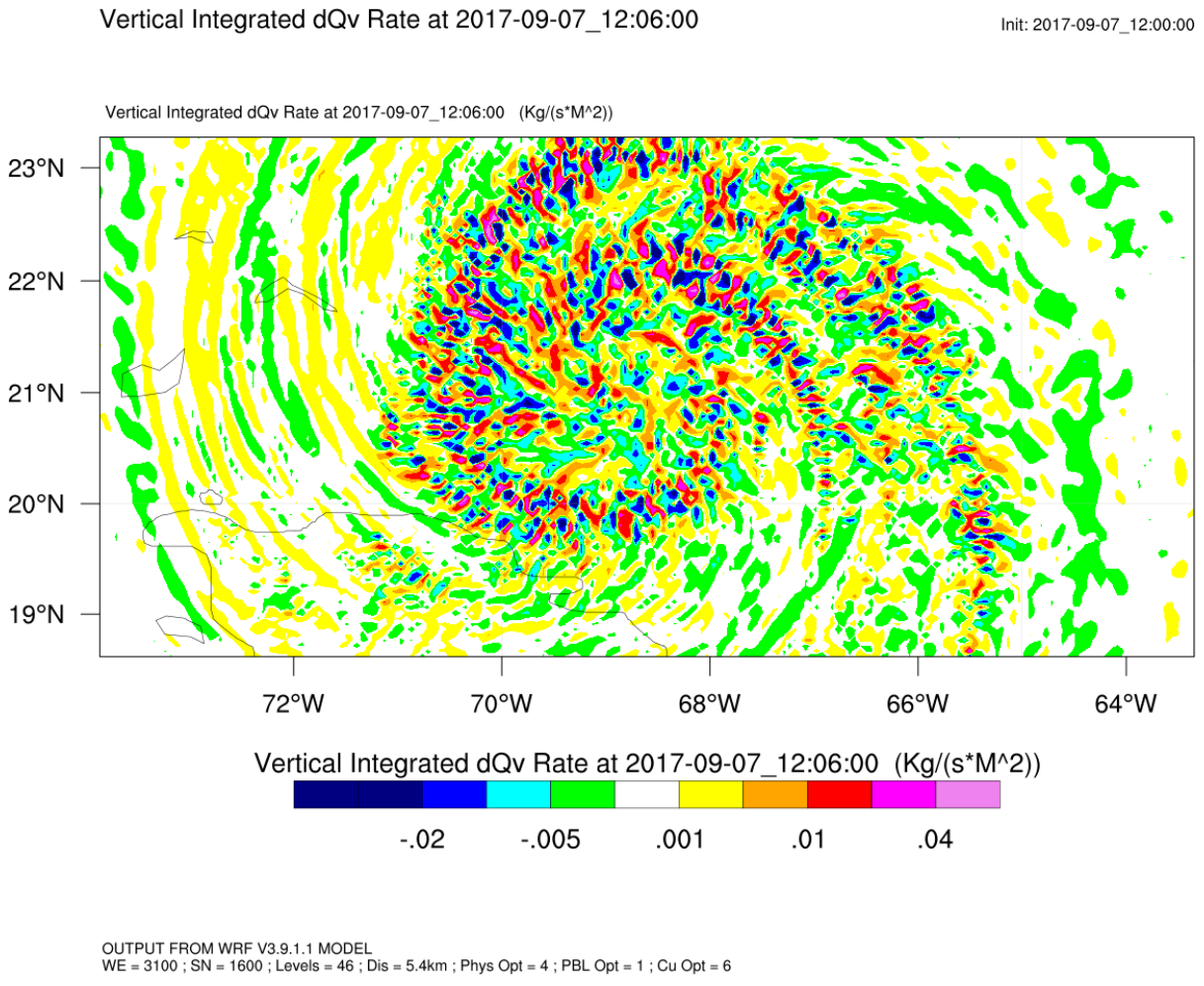
– Density Flux Divergence has lots of small scale features

– Precipitation is two hours, which has not much small scale features.

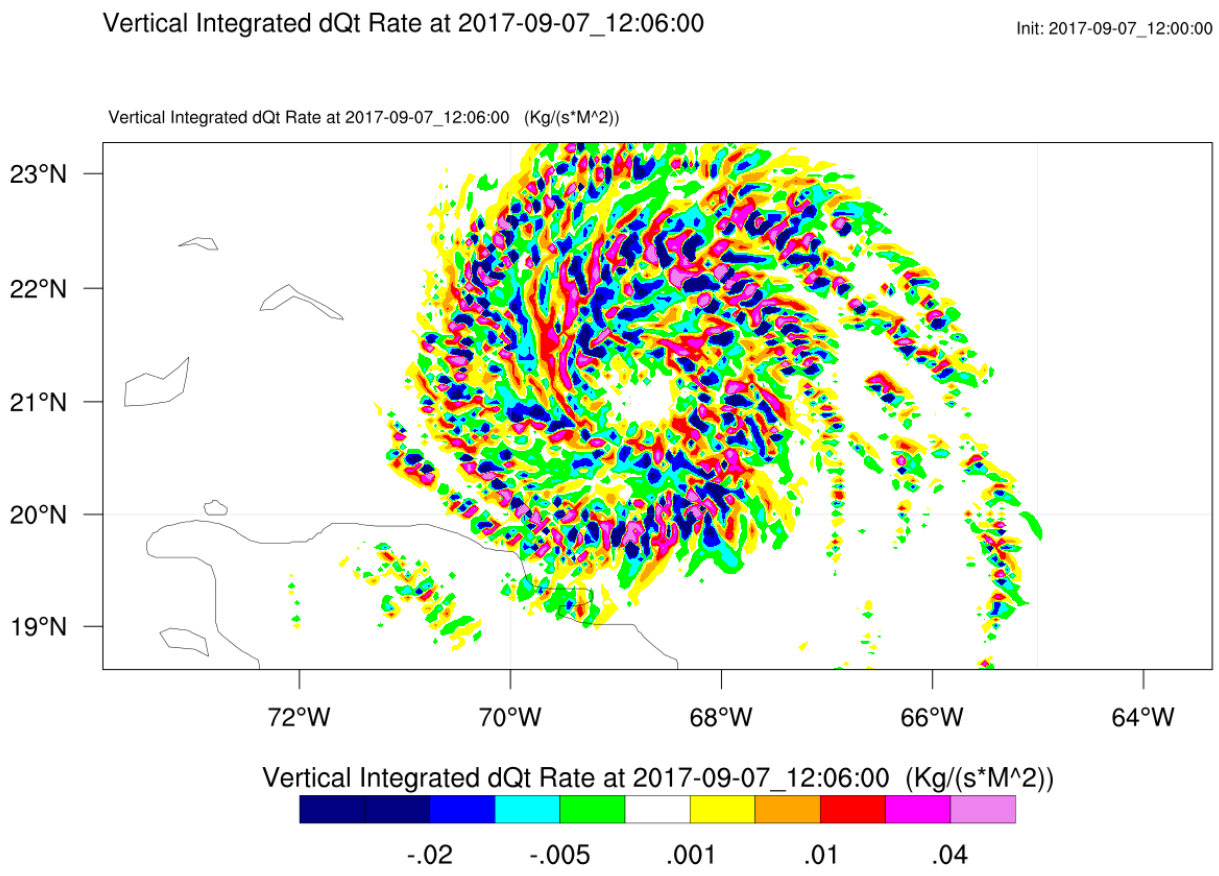
Total Precipitation Rate



Water Vapor


Vertical Integrated dQv Rate at 2017-09-07_12:06:00
Init: 2017-09-07_12:00:00
Vertical Integrated dQv Rate at 2017-09-07_12:06:00 (Kg/(s*M^2))
23°N
22°N
21°N
20°N
19°N
72°W
70°W
68°W
66°W
64°W
Vertical Integrated dQv Rate at 2017-09-07_12:06:00 (Kg/(s*M^2))
-.02
-.005
.001
.01
.04
OUTPUT FROM WRF V3.9.1.1 MODEL
WE = 3100 ; SN = 1600 ; Levels = 46 ; Dis = 5.4km ; Phys Opt = 4 ; PBL Opt = 1 ; Cu Opt = 6

Vertical Integrated Water Components Change Rate



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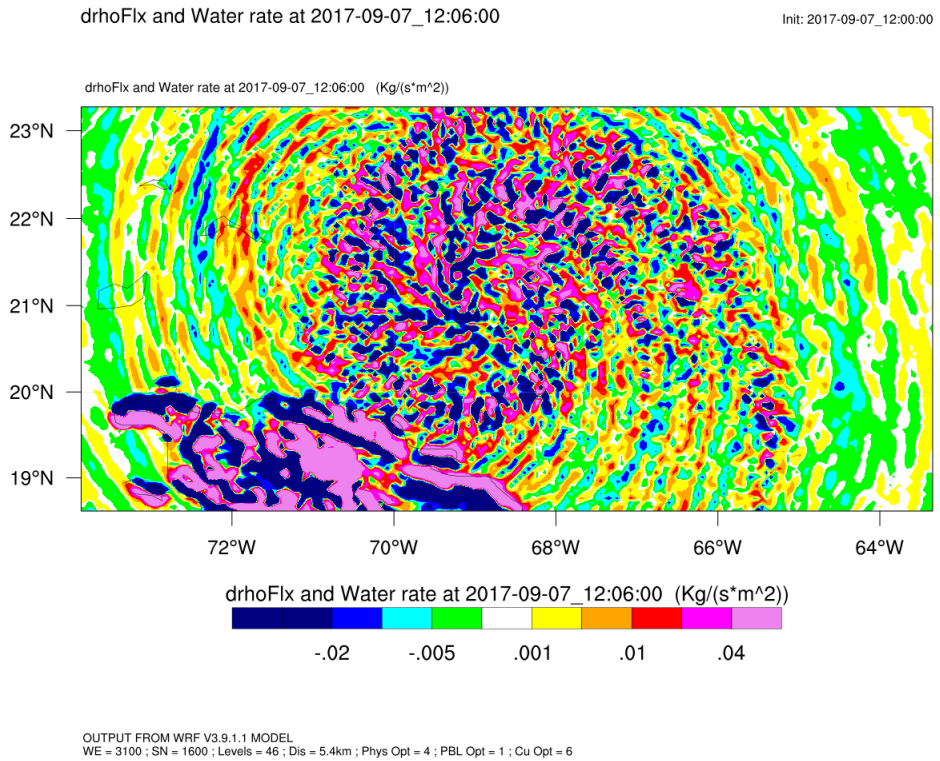
drhoFlx and Water rate at 2017-09-07_12:06:00
Init: 2017-09-07_12:00:00
drhoFlx and Water rate at 2017-09-07_12:06:00 (Kg/(s*m^2))
23°N
22°N
21°N
20°N
19°N
72°W
70°W
68°W
66°W
64°W
drhoFlx and Water rate at 2017-09-07_12:06:00 (Kg/(s*m^2))
-.02
-.005
.001
.01
.04
OUTPUT FROM WRF V3.9.1.1 MODEL
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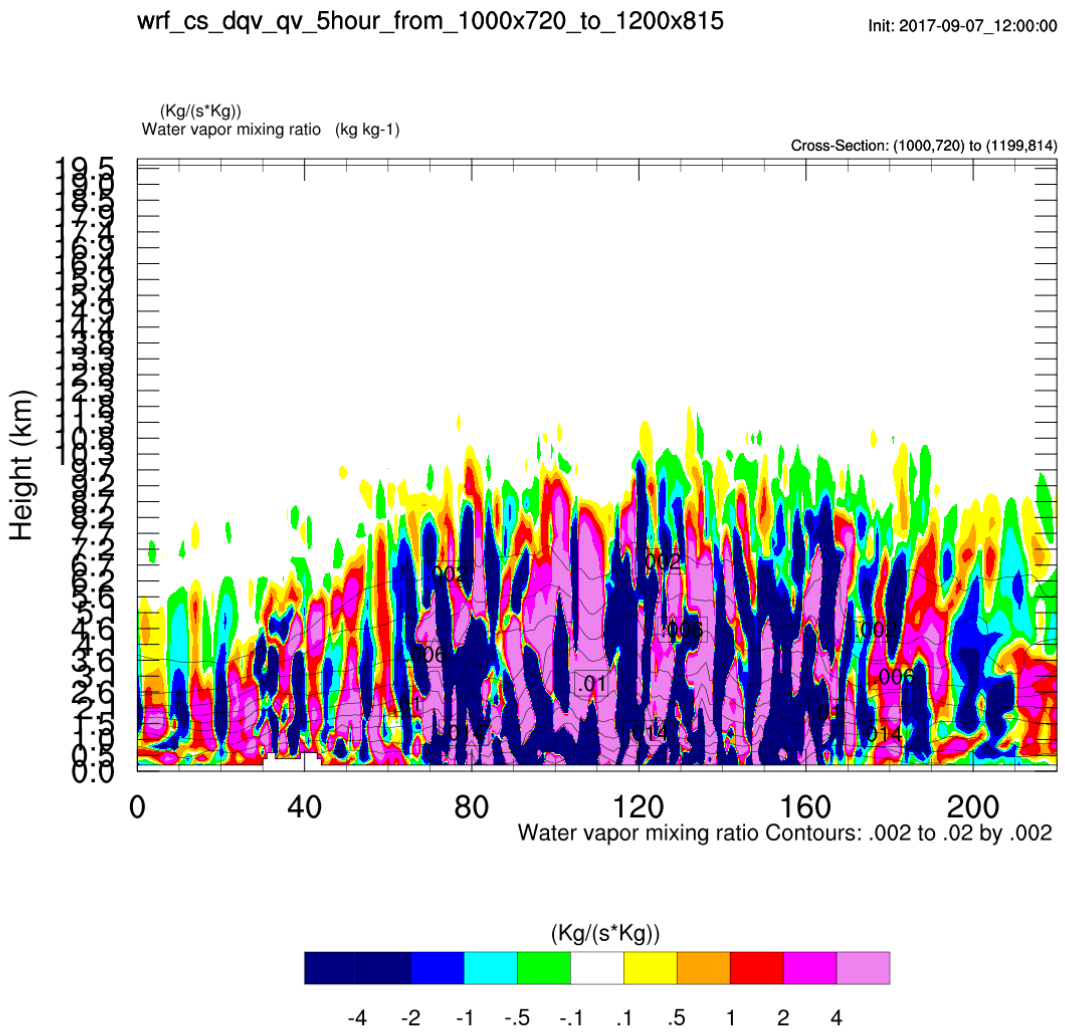
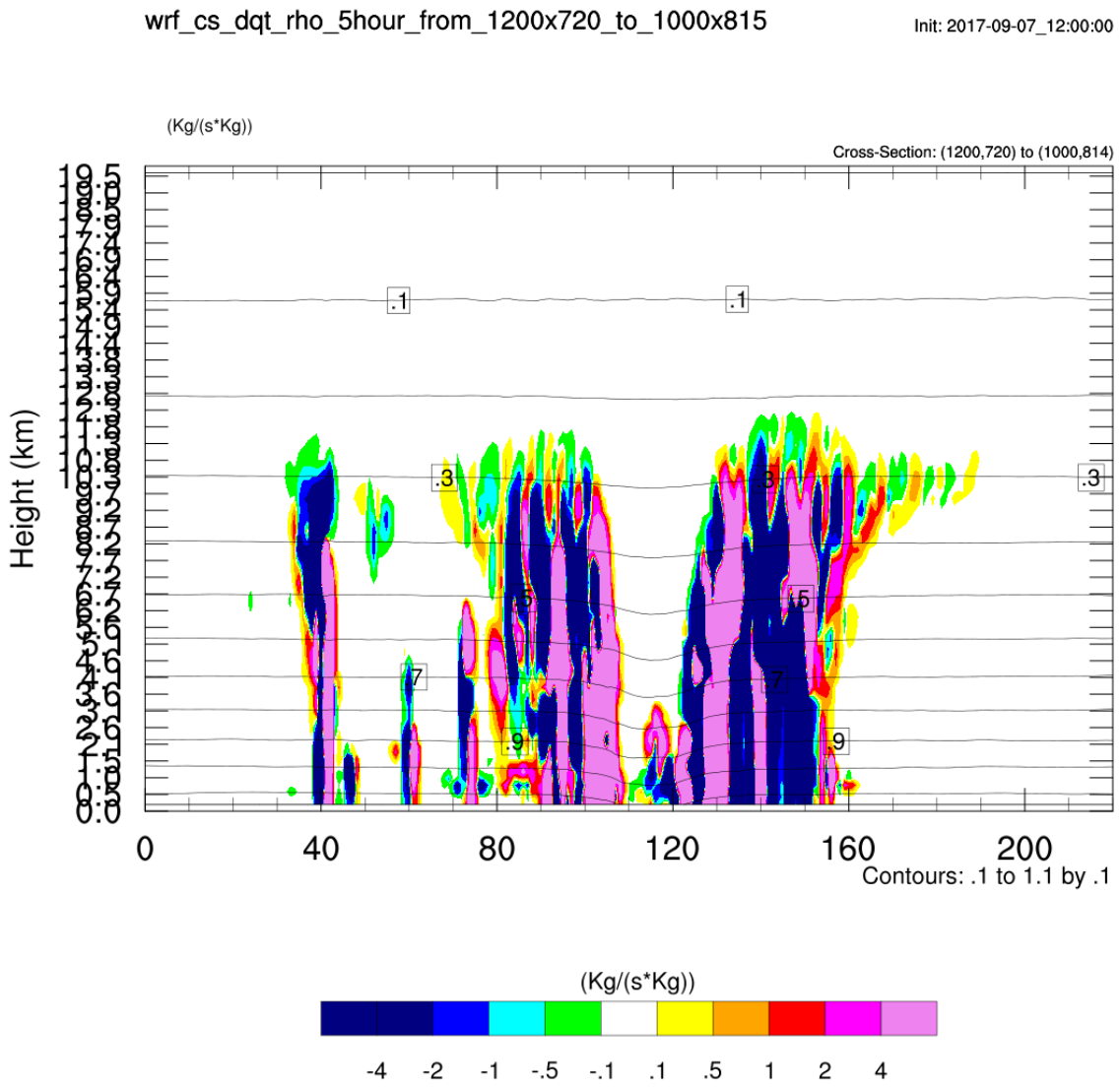
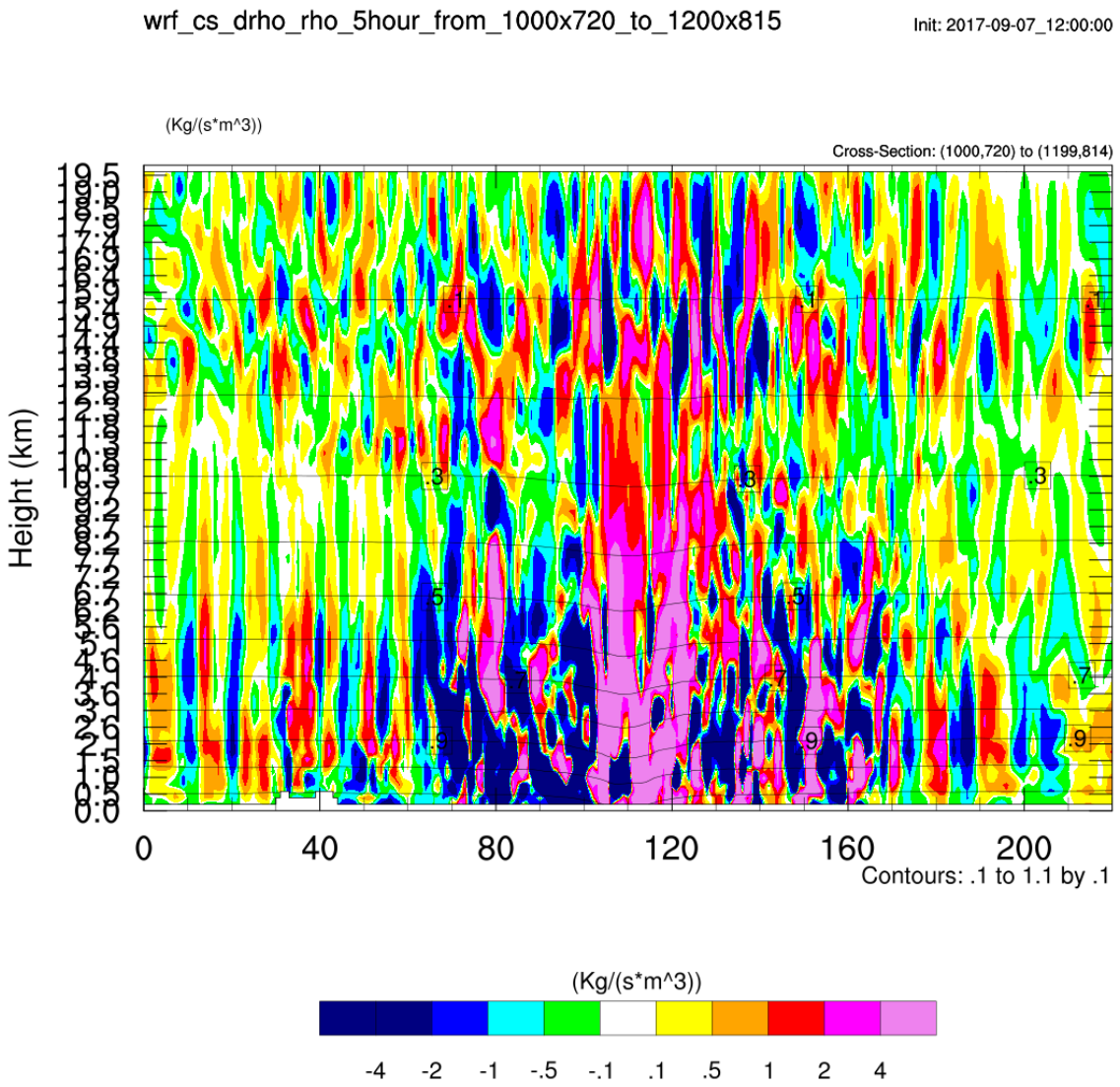
Water Vapor Change Rate



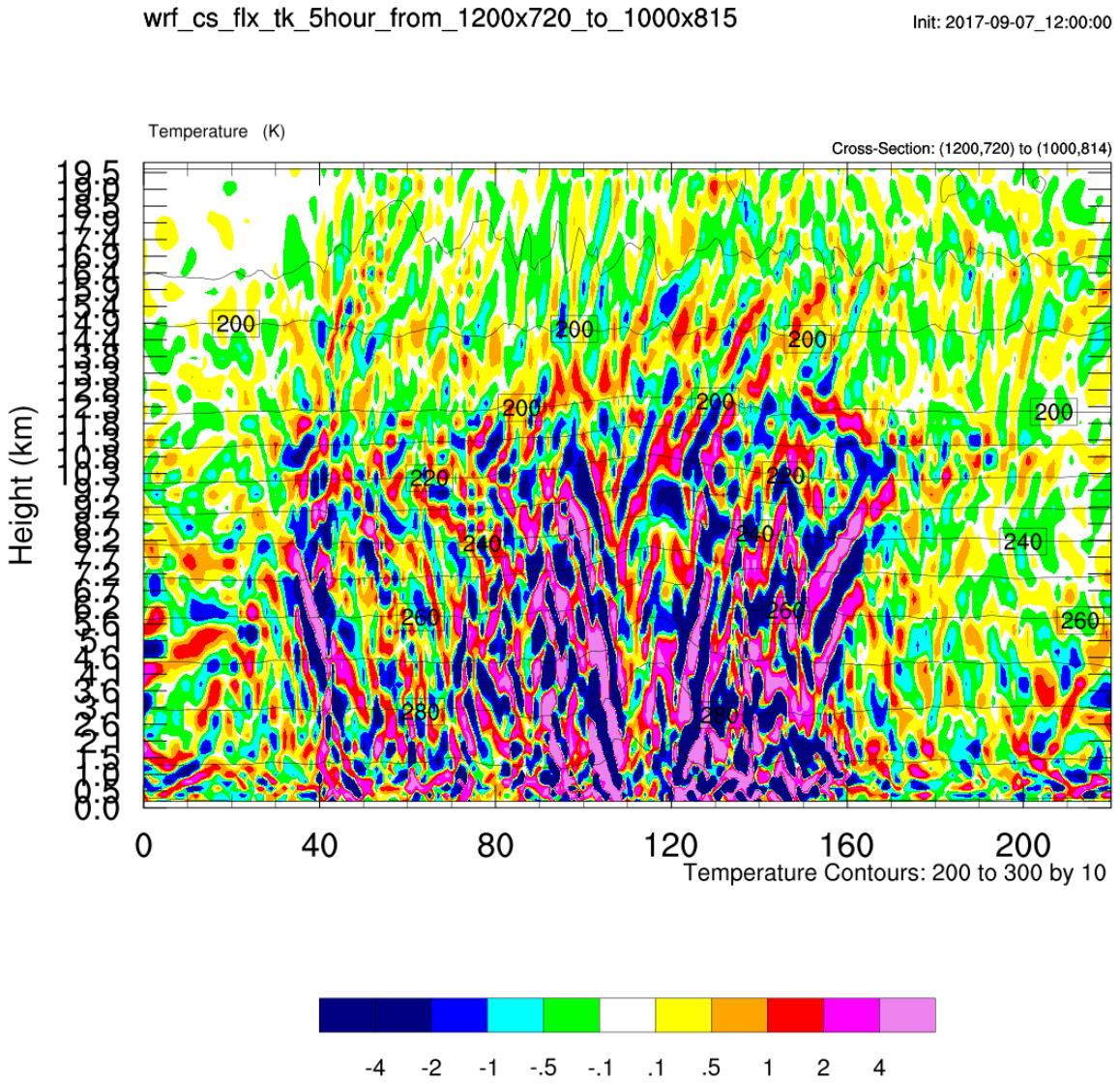
Total of Qc, Qr, Qi, and Qs Change Rate



Density Change Rate



Density Flux Divergence



The Vertical integrated Mass Flux

–More similar to water vapor, or cloud water, or rain water pattern.

–Why?

Mass Change in the Atmosphere

–When the air flow into the hurricane, it contains moisture/water vapor.

–Precipitation (more strictly, condensation) make atmosphere lose moisture, therefor the air lose mass.

–The positive vertical integrated mass flux did not change into air mass, but became precipitation, drop out of the atmosphere.

The Magnitude of Integrated Mass Flux and Precipitation

- From integrated mass flux figure, the positive flux is 0.01 Kg/(m^2*s).
- The precipitation ~ 40 mm.
- If the mass flux all convert to precipitation, the depth of the water is:
  - 0.01 * 3600 (Kg/m^2), which is ~36 mm.

New Continuity Equation

–So we should change continuity equation 1 to:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V}\right) = s \qquad (3)$$

–Where “s” represents the combined air mass source and/or sink:

- –For s < 0, which means air mass loss, or more precipitation than evaporation
- –For s > 0, which means are mass gain, or more evaporation than precipitation

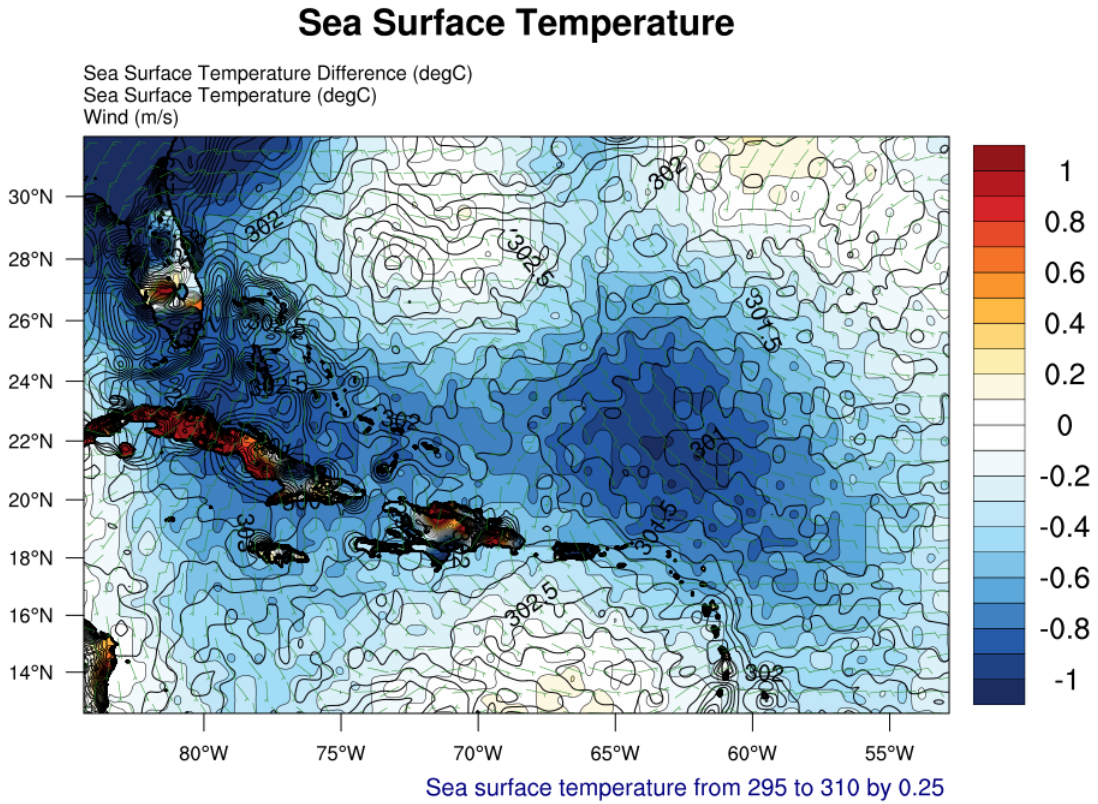
Cold Sea Surface Temperature after Hurricane

–The passage of a tropical cyclone over the ocean causes the upper layers of the ocean to cool substantially, which can influence subsequent cyclone development.

–This cooling is primarily caused by wind-driven mixing of cold water from deeper in the ocean with the warm surface waters.

–https://en.wikipedia.org/wiki/Tropical_cyclone

Cold SST after Hurricane Irma (2017.09.08.18 – 2017.09.06.06)



Questions

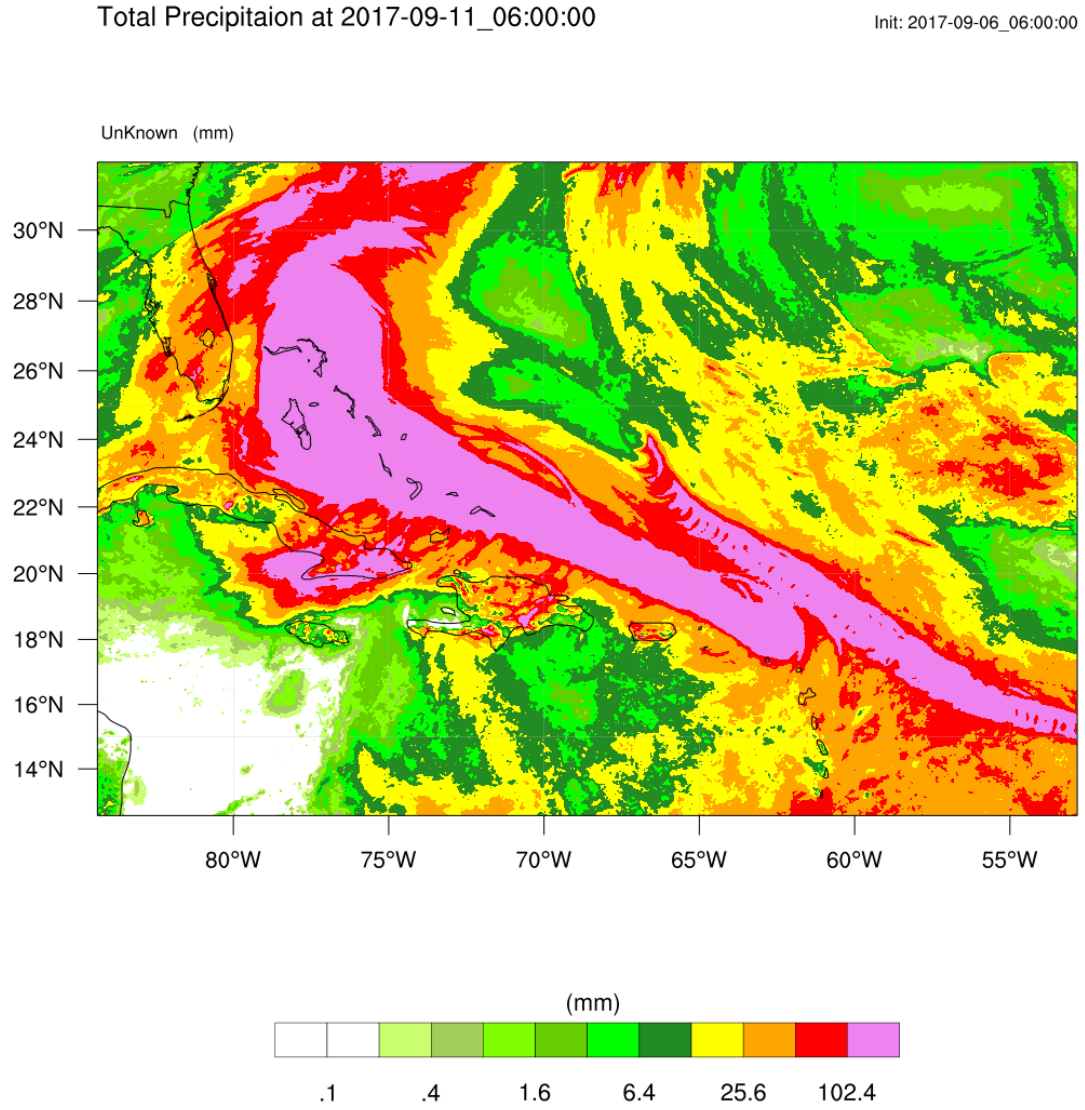
–If the cold SST after hurricane is caused by ocean mixing, then there should a warm pool in the ocean right under the cold pool, right?

–Have we observed any of those warm pools?

–Where did it go?

–We’d like to propose a different thought.

5 Days Accumulated Precipitation



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Discussion

– 5 Days precipitation has a wide band of great than 100 mm, with maximum great than 1000 mm.

– We’d rather believe that the cool pool after hurricane is mostly contributed from precipitation, as:

– Ignore the density difference between precipitation and sea water.

– Assume ocean temperature 26 degree, and rain water temperature 22 degree

– Then 100 mm precipitation, when mixing well, can:

  – Cool down sea surface temperature by 2 degrees up to 20 cm

  – Cool down SST by 1 degrees to 40 cm

Conclusions

- The continuity Equation should modified with an addition term s:
  - Where s > 0, for evaporation, as it increases the atmospheric air mass.
  - And s < 0, for precipitation, as it reduces the air mass.

- The cold SST after hurricane is from the cold rain water.

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Thank You

Reference

- https://ams.confex.com/ams/32Hurr/webprogram/Paper292465.html
- https://ams.confex.com/ams/32Hurr/webprogram/Paper292791.html