# Sensitivity to Humidity Data Assimilation for Hurricane Intensification and Heavy Rains

T.N. Krishnamurti

HFIP Telecon presentation May, 28th 2014 .

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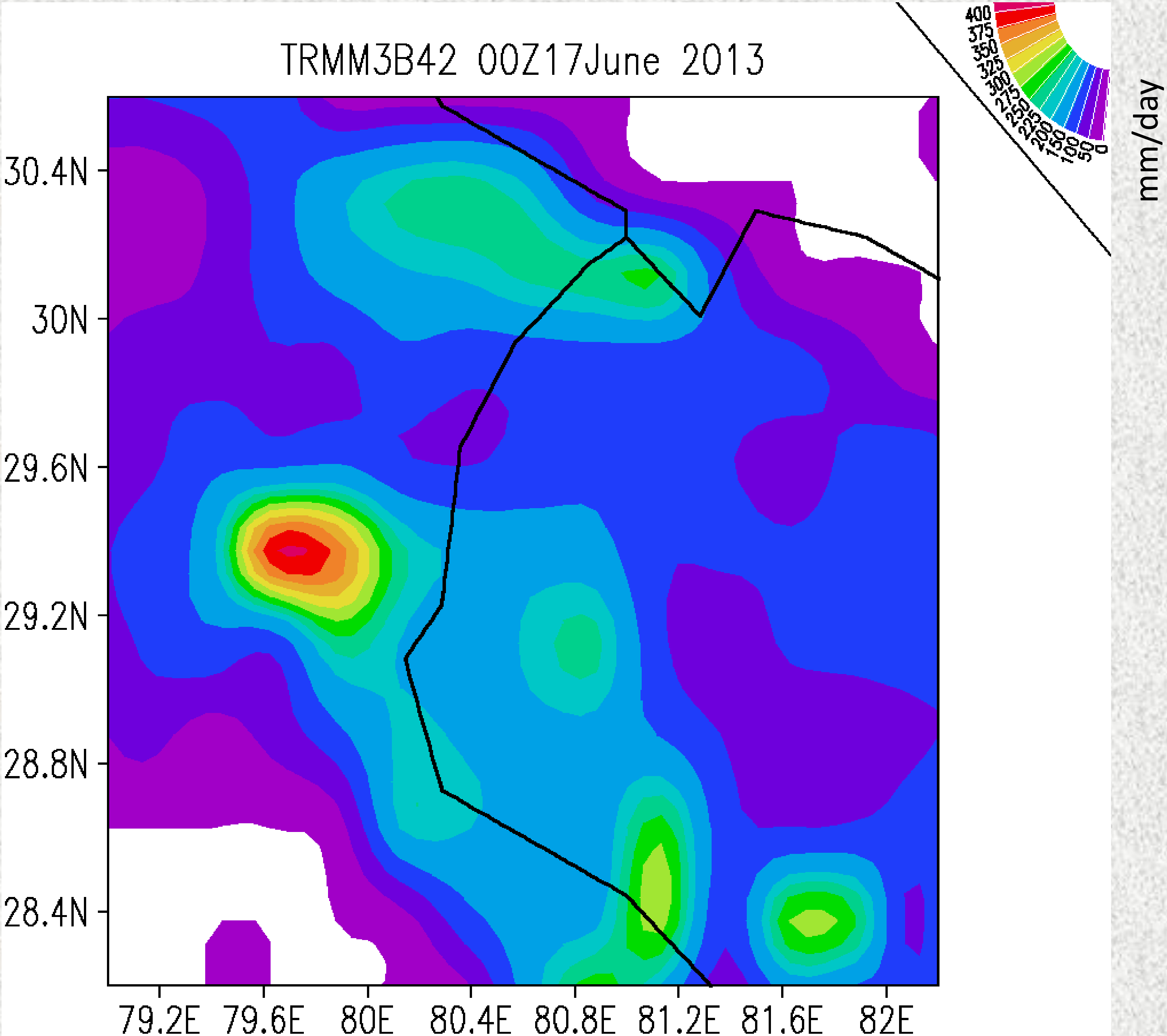
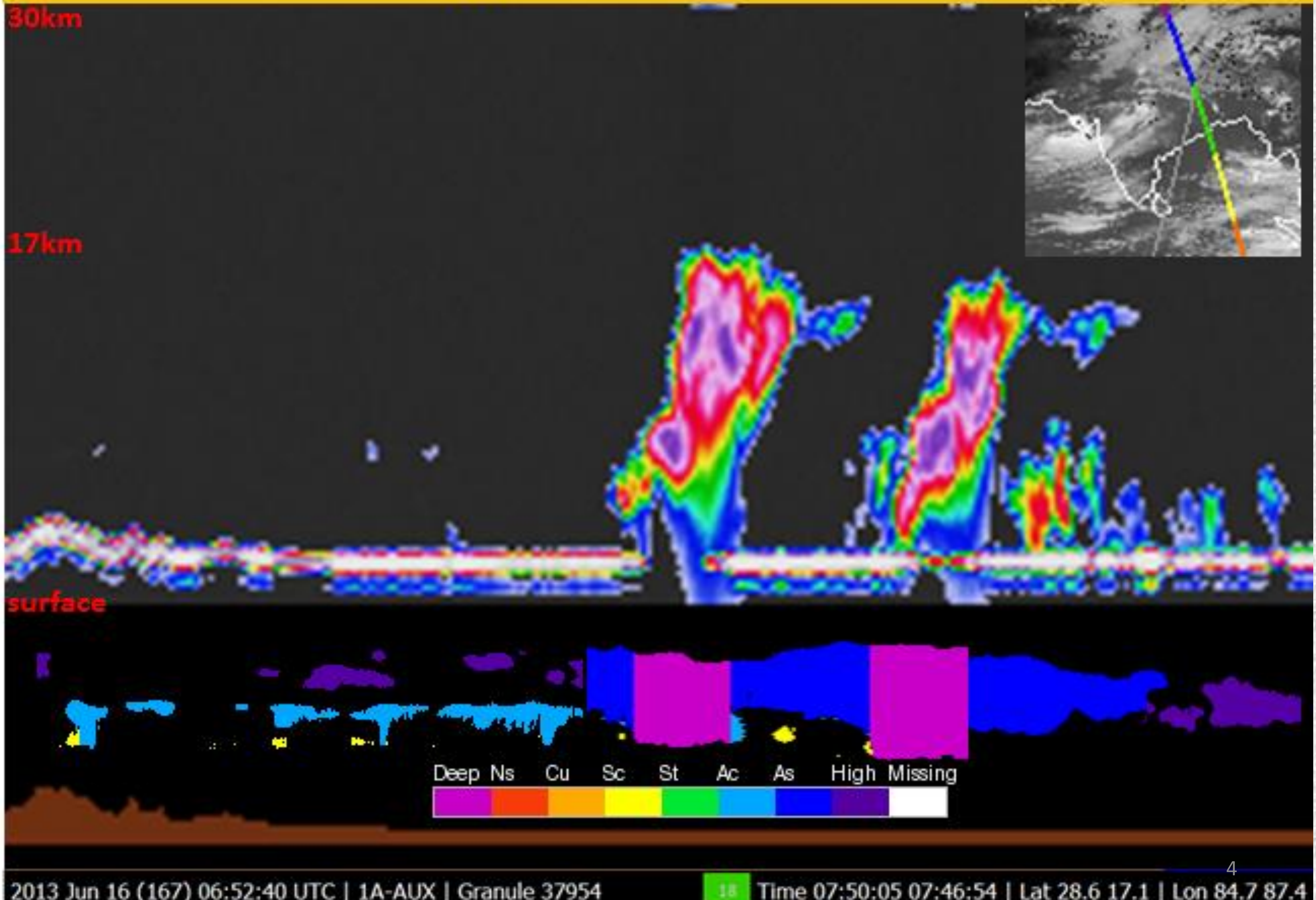
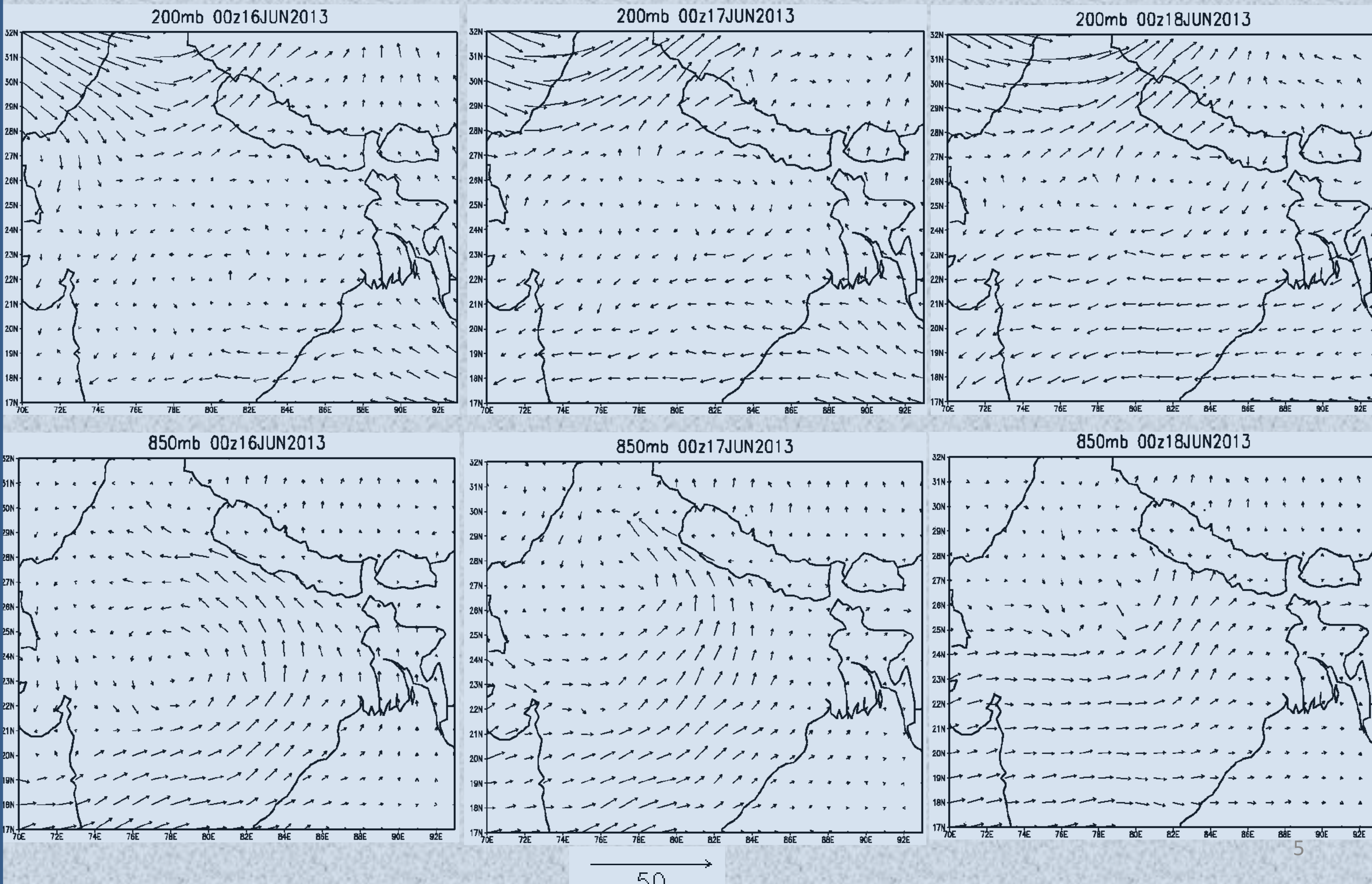
***I will start with the Buoyancy History of an Extreme Rain Event During Passage of Tropical Depression***



TRMM3B42 00Z17June 2013
30.4N
30N
29.6N
29.2N
28.8N
28.4N
79.2E
79.6E
80E
80.4E
80.8E
81.2E
81.6E
82E
400
375
350
325
300
275
250
225
200
150
100
50
0
mm/day

# CLOUDSAT view of deep convection near UTTARAKHAND floods




200mb 00z16JUN2013
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850mb 00z17JUN2013
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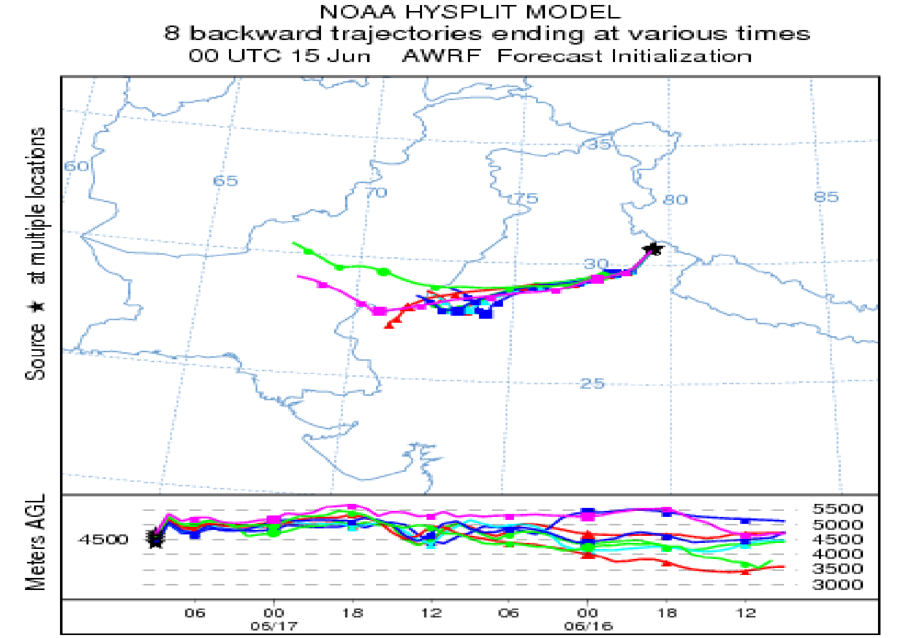
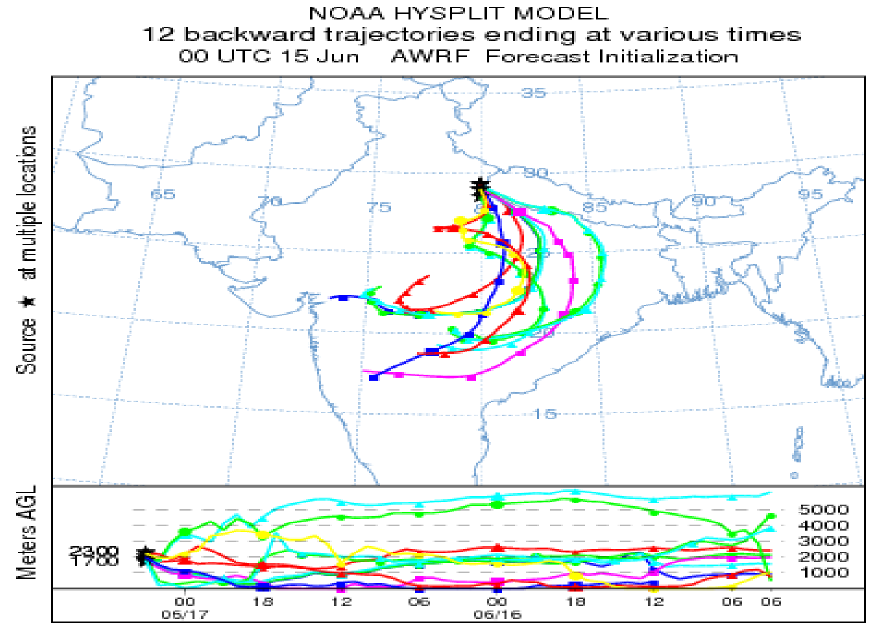
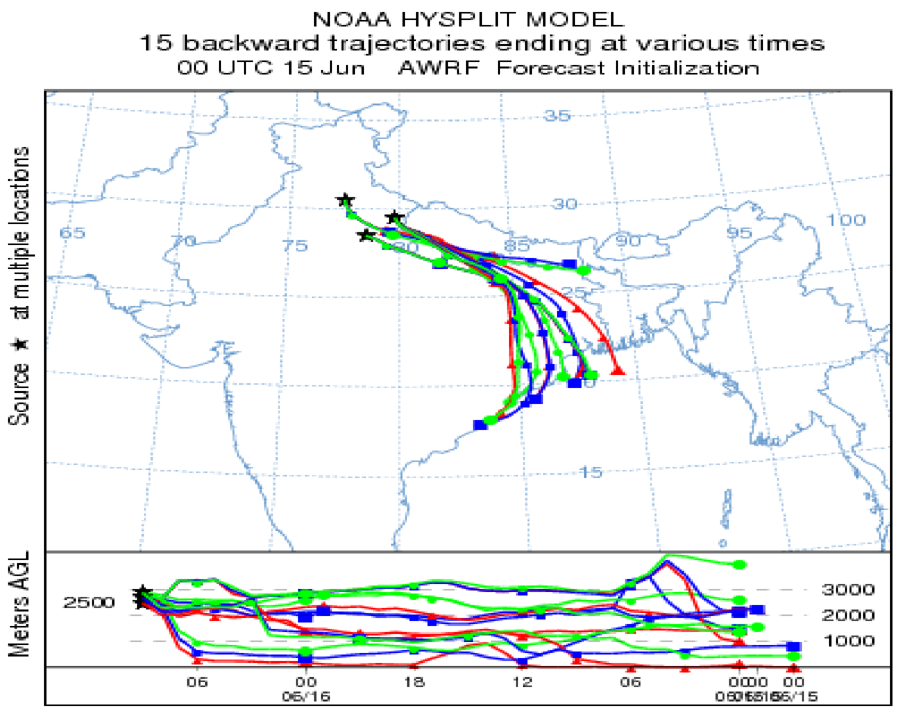
50


NOAA HYSPLIT MODEL
8 backward trajectories ending at various times
00 UTC 15 Jun AWRF Forecast Initialization
Source ★ at multiple locations
Meters AGL
4500
5500
5000
4500
4000
3500
3000
06
00
06/17
18
12
06
00
06/16
18
12


NOAA HYSPLIT MODEL
12 backward trajectories ending at various times
00 UTC 15 Jun AWRF Forecast Initialization
Source ★ at multiple locations
Meters AGL
5000
4000
3000
2000
1000
00
06/17
18
12
06
00
06/16
18
12
06
06


NOAA HYSPLIT MODEL
15 backward trajectories ending at various times
00 UTC 15 Jun AWRF Forecast Initialization
Source ★ at multiple locations
Meters AGL
2500
3000
2000
1000
06
00
06/16
18
12
06


DRY HOT STREAM
LOW
MOIST STREAMS
HOT LAND SURFACE

# An Introduction to Physical Initialization

# What is Physical Initialization?

- Physical initialization for the regional mesoscale model WRF/ARW follows the same principles as in our global model Krishnamurti et al (1991, 1994). This carries four components:
  1. A reverse cumulus parameterization algorithm
  2. A reverse similarity algorithm
  3. A matching of model and satellite based OLR.
  4. All contained within a Newtonian Relaxation.

The reverse cumulus parameterization algorithm follows the method proposed by Treadon (1996).


References:

1. KRISHNAMURTI, T. N., XUE, J., BEDI, H. S., INGLES, K. and OOSTERHOF, D. (1991), Physical initialization for numerical weather prediction over the tropics. Tellus A, 43: 53–81.
2. Krishnamurti, T. N., H. S. Bedi, G. D. Rohaly, D. K. Oosterhof, R. C. Torres, E. Williford, and N. Surgi, 1994: Physical Initialization. ECMWF Workshop, Modelling, validation and assimilation of clouds, 31 October- 4 November 1994, ECMWF, Shinfield Park, Reading, U.K.
3. Treadon, R. E., 1996: Physical initialization in the NMC global data assimilation system. Meteor. Atmos. Phys., 60, 57–86.

# Physical Initialization for Cloud Resolving Models

- **Matching model rain rates** at any horizontal grid point to satellite-based estimates of rain rates (interpolated to that time step) calls for a change of the model's vertical profile of moisture by a factor of (1+ε), where ε is defined by the relation: $\varepsilon = \frac{Rain\ Rate_{Observed}}{Rain\ Rate_{Model}} - 1$

Model total column rain rate: $Rain\ Rate_{Model} = -\frac{P_s}{g}\int_0^1 \dot{\sigma}\frac{\partial q}{\partial \sigma}\, d\sigma$

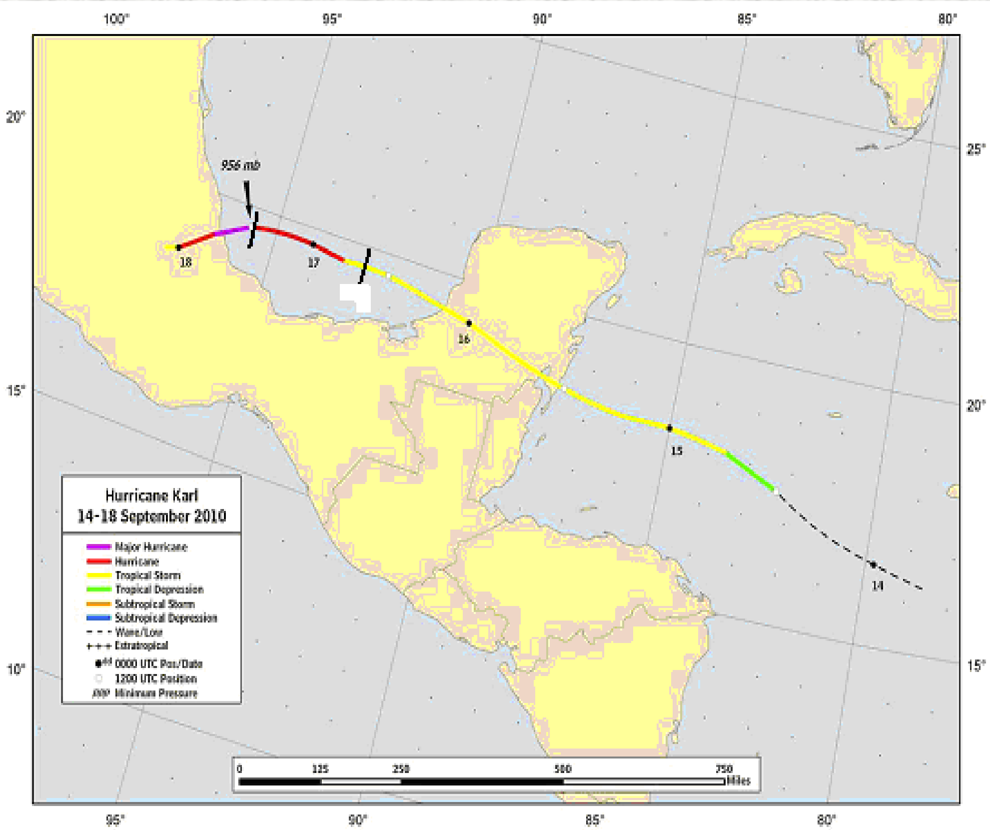
where $\dot{\sigma}$ is the vertical velocity, q is the specific humidity and $p_s$ is the surface pressure.

- $\dot{\sigma}$ is not changed in order to avoid excitation of gravity waves and mass motion imbalances. Moisture is more of a passive variable and its vertical profile is changed during physical initialization.
- Note that the relation $R_{Model} = -\frac{\partial q_s}{\partial t}$ is a measure of the rate of condensation, if super saturation is not permitted.
- This is approximated above by $\frac{\partial q}{\partial t} \approx -\sigma\frac{\partial q}{\partial \sigma}$ (and also note that $q = q_s$ the saturation value).
- The model rain rate is being forced towards the satellite-based value with the modification of the moisture by the parameter 1+ε. However, that does not guarantee that the model will accept that value since all other model variables must come into equilibrium with that change of moisture and the rain rate. This necessitates the other steps of physical initialization.

**EXPLICIT CLOUDS AND NO CUMULUS PARAMETRIZATION**

# First we illustrate Physical Initialization for a Hurricane “ KARL 2010”

# Track and Intensity of Hurricane KARL 14th-18th Sep 2010



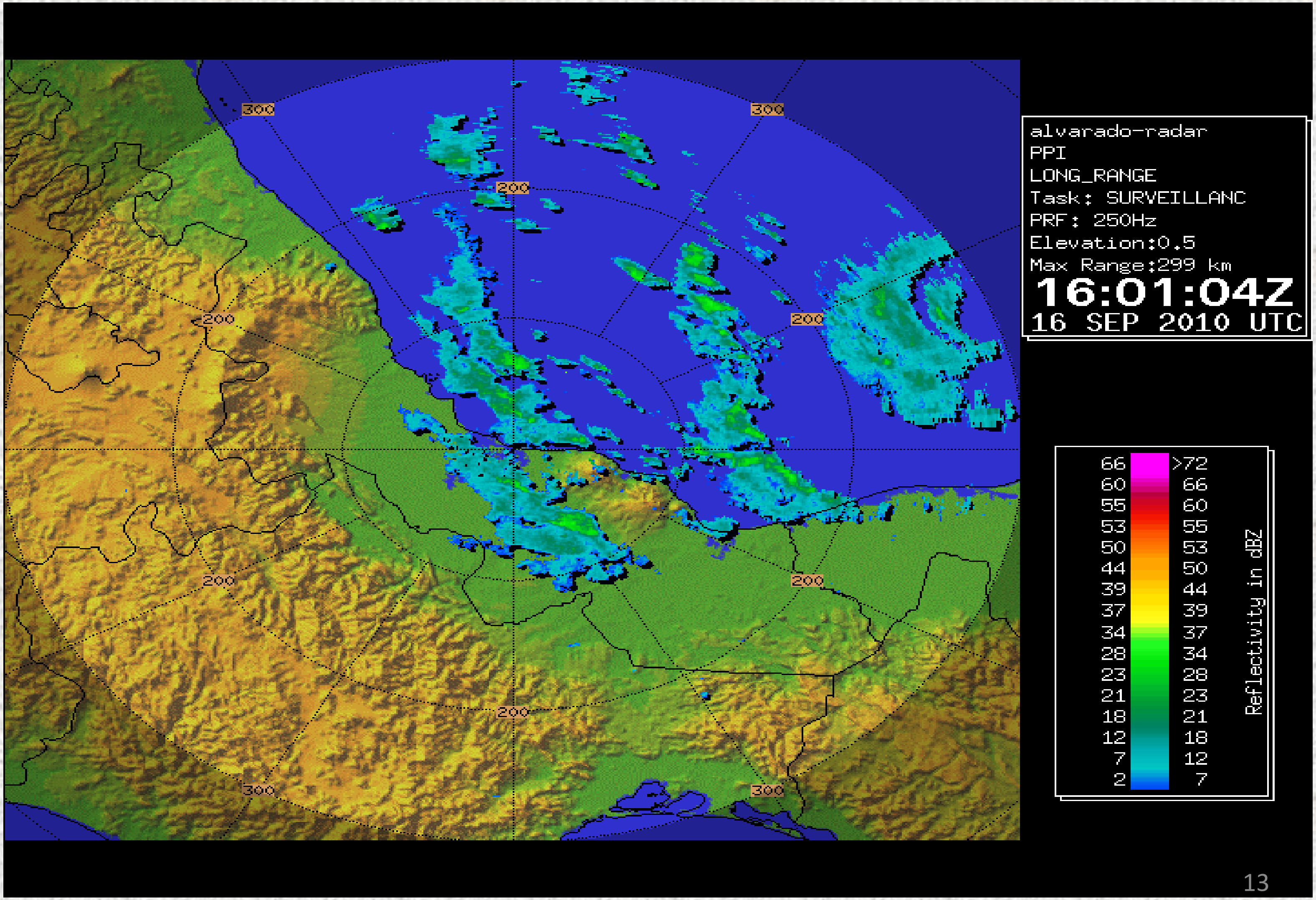

Best track for Hurricane Karl, 14-18 September 2010.

| Date/Time (UTC) | Latitude (°N) | Longitude (°W) | Pressure (mb) | Wind Speed (kt) | Stage |
|---|---|---|---|---|---|
| 13 / 1800 | 16.3 | 78.5 | 1005 | 25 | low |
| 14 / 0000 | 16.6 | 79.8 | 1004 | 25 | " |
| 14 / 0600 | 17.0 | 81.1 | 1003 | 25 | " |
| 14 / 1200 | 17.6 | 82.3 | 1003 | 30 | tropical depression |
| 14 / 1800 | 18.1 | 83.6 | 1001 | 35 | tropical storm |
| 15 / 0000 | 18.3 | 85.0 | 999 | 40 | " |
| 15 / 0600 | 18.3 | 86.2 | 997 | 55 | " |
| 15 / 1200 | 18.5 | 87.6 | 991 | 55 | " |
| 15 / 1800 | 18.8 | 88.8 | 994 | 45 | " |
| 16 / 0000 | 19.2 | 90.1 | 997 | 40 | " |
| 16 / 0600 | 19.4 | 91.1 | 994 | 45 | " |
| 16 / 1200 | 19.6 | 92.2 | 986 | 55 | " |
| 16 / 1800 | 19.6 | 93.3 | 982 | 70 | hurricane |
| 17 / 0000 | 19.7 | 94.1 | 971 | 85 | " |
| 17 / 0600 | 19.7 | 94.9 | 966 | 95 | " |
| 17 / 1200 | 19.6 | 95.6 | 956 | 110 | " |
| 17 / 1500 | 19.4 | 96.0 | 970 | 110 | " |
| 17 / 1800 | 19.2 | 96.4 | 979 | 90 | " |
| 18 / 0000 | 18.7 | 97.1 | 995 | 60 | tropical storm |
| 18 / 0600 | 18.6 | 97.4 | 1005 | 25 | tropical depression |
| 18 / 1200 | | | | | dissipated |
| 17 / 1200 | 19.6 | 95.6 | 956 | 110 | minimum pressure |
| 15 / 1245 | 18.5 | 87.8 | 991 | 55 | landfall along Yucatan coast near Rio Huach, Mexico |
| 17 / 1645 | 19.3 | 96.2 | 976 | 100 | landfall about 10 n mi northwest of Vera Cruz, Mexico |

**The observed track of HURRICANE KARL during September 14 to 18 2010 is shown here.**

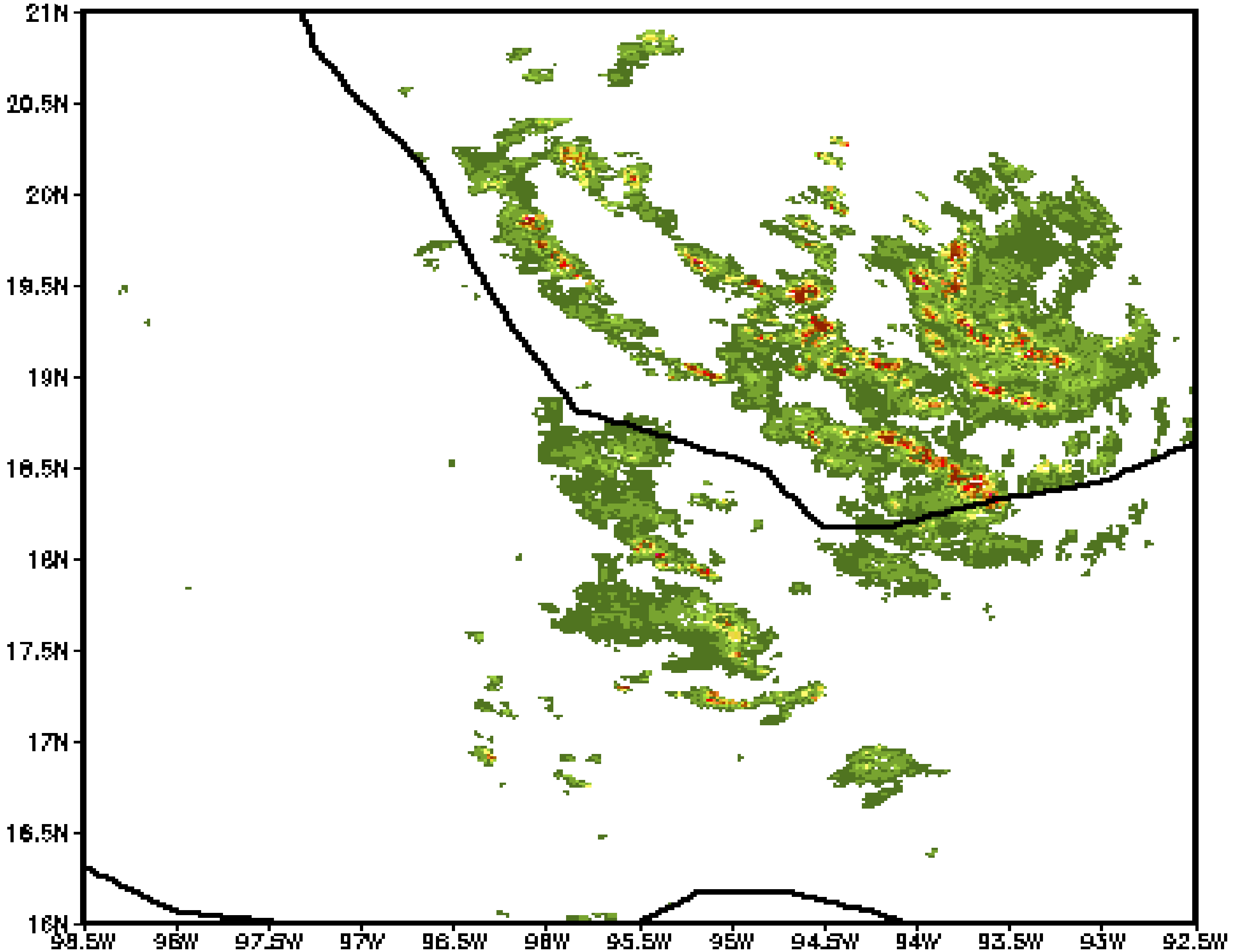
**The red portion of the track, as the hurricane makes a landfall over Mexico is of interest here. Physical initialization at radar resolution was carried out starting on august 16th at 12 UTC and continued for a 24 hour period, thereafter a free forecast was continued.**

**Alvarado radar loop as received from Mexico. This is the radar reflectivity animation covering the period September 16 , 2010 16Z to September 17, 2010 17Z. This is Hurricane KARL that made landfall in Mexico.**

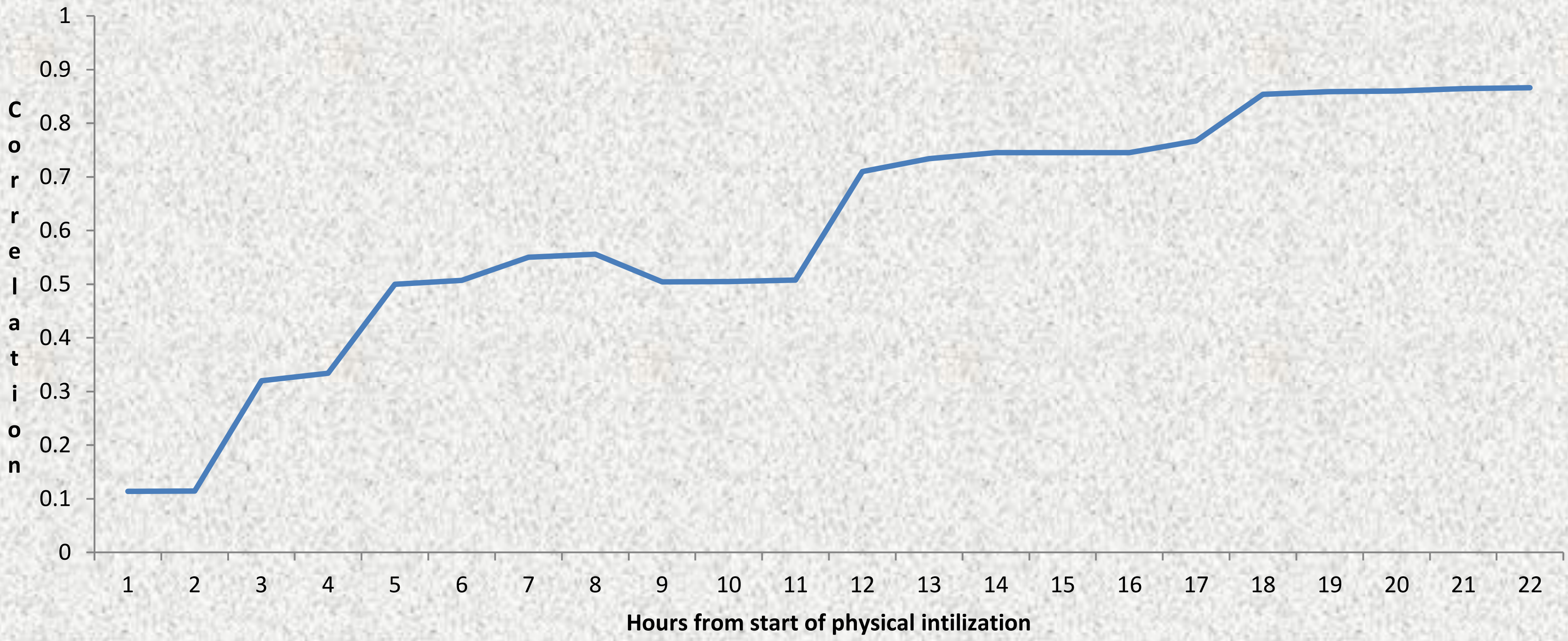


## Alvarado radar data converted to rainfall (mm/hour) at model resolution of 1.33 km. Animation of rainfall during the landfall of Hurricane KARL.

**RAINFALL USED IN MODEL AFTER INTERPOLAION AT 1.33$^{O}$ LAT/LON GRID**

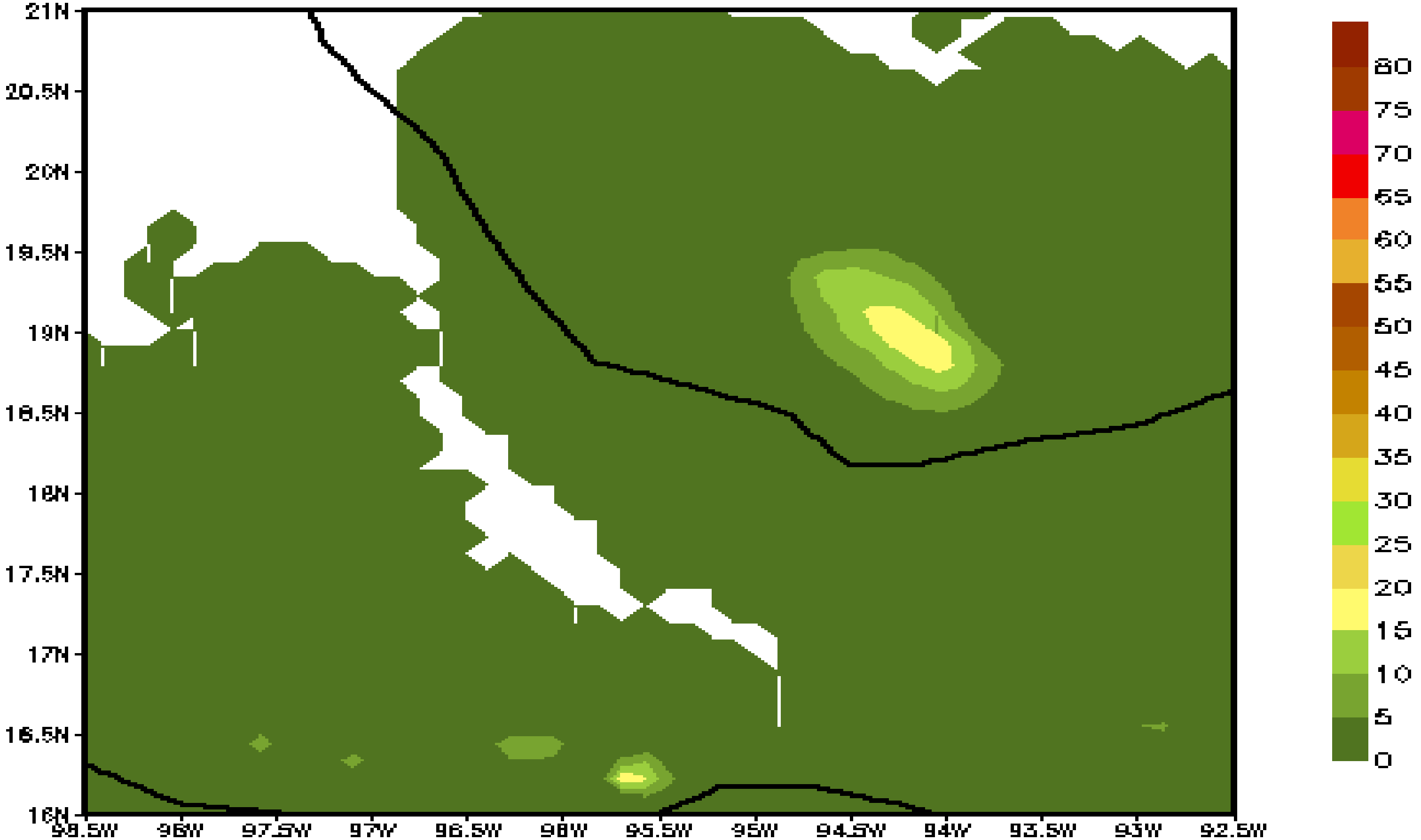


**Spin-up of correlations** between physically initialized rain and rain based on the Alvarado radar, during 22 hours

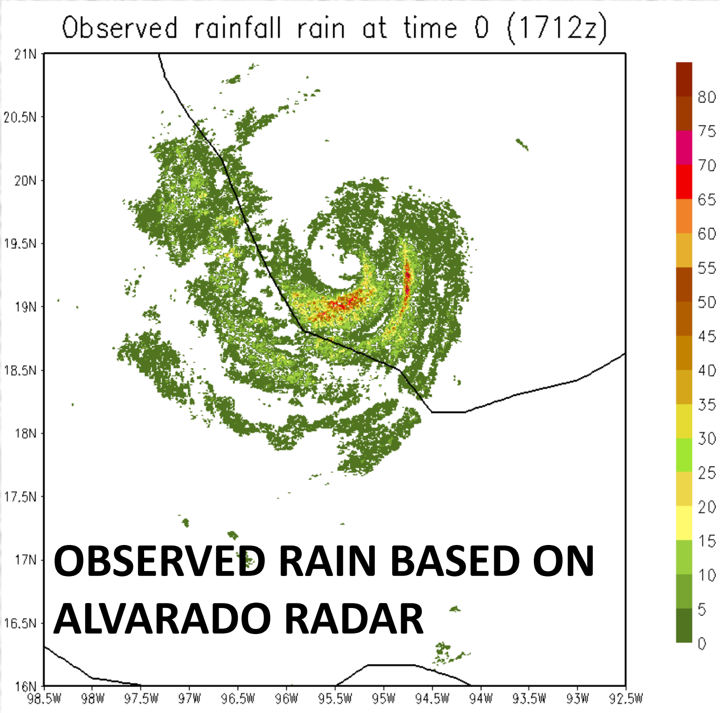



This illustration shows the spin up of model rain towards the radar based rainfall estimates. The **ordinate shows** the **correlation** among these two rainfall (this is within a 100km square centered at the storms center). The correlation starts out with a value of **0.1** and spins up to a value close to **0.8** by around 16 hours (**abscissa**) of physical initialization.

# ANIMATION OF PHYSICALLY INITIALIZED RAIN

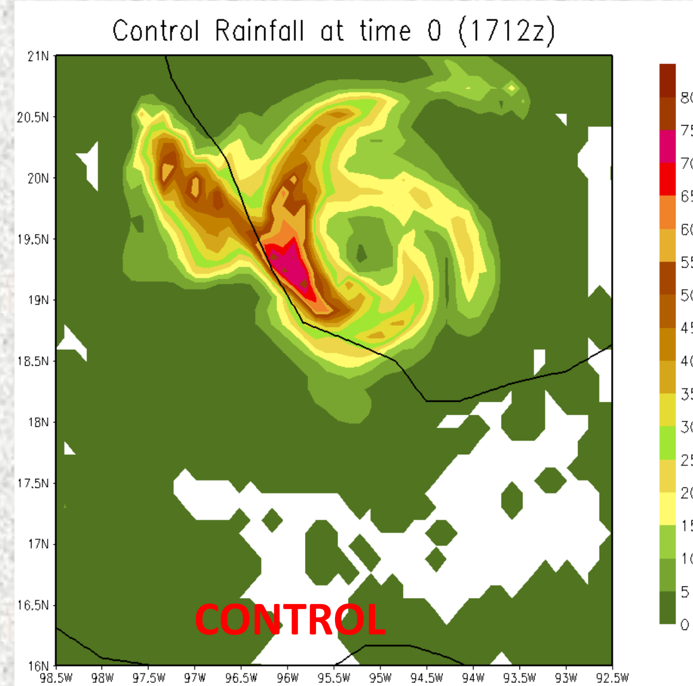


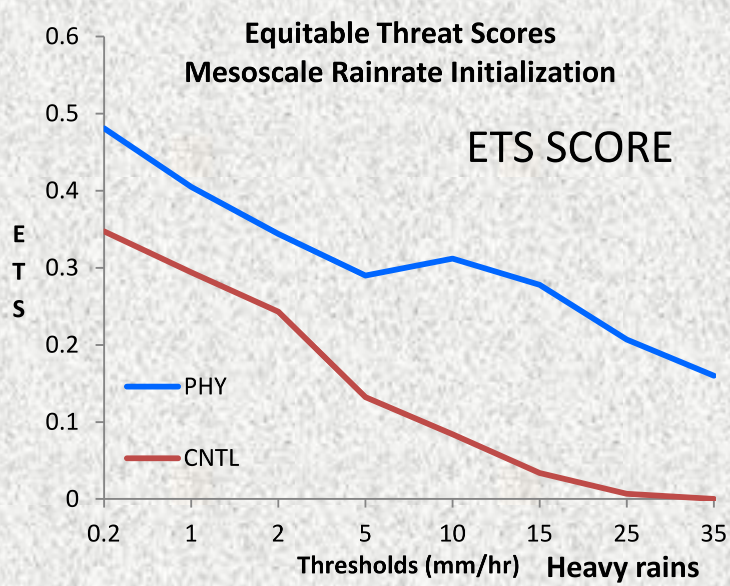

The animation shows the spin up of rains for **Hurricane KARL** during **physical initialization. Frames** were interpolated from the radar reflectivity movie provided by the **Mexican** weather service. Those radar reflectivities were carefully interpolated to a 1.33 km grid and frames were taken for every 5 minutes in time to convert the radar reflectivity to rain rates using a z = r relationship that was carefully calibrated and validated against rain gauges over Mexico. This animation shows that the **WRF/ARW model** catches up to the radar rains very closely by around 16 hours after the start of the physical initialization.

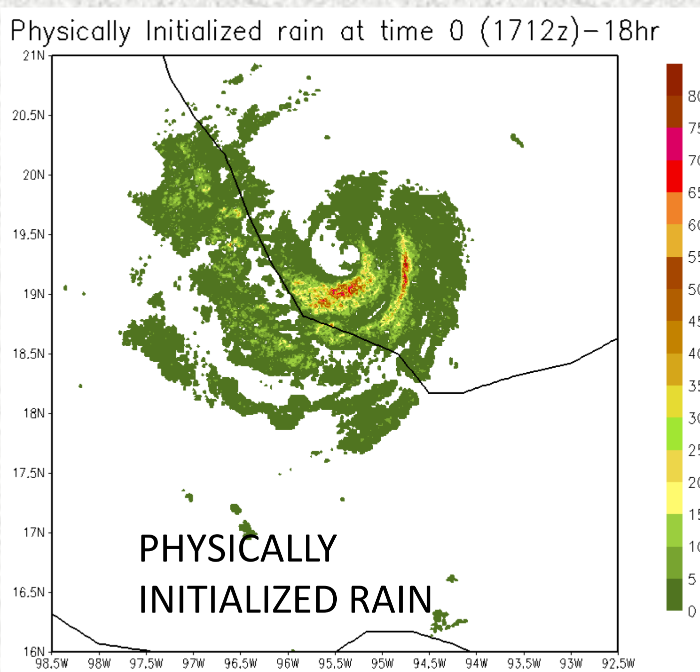



RMSE =10.4mm/hour
Corr. = 0.32

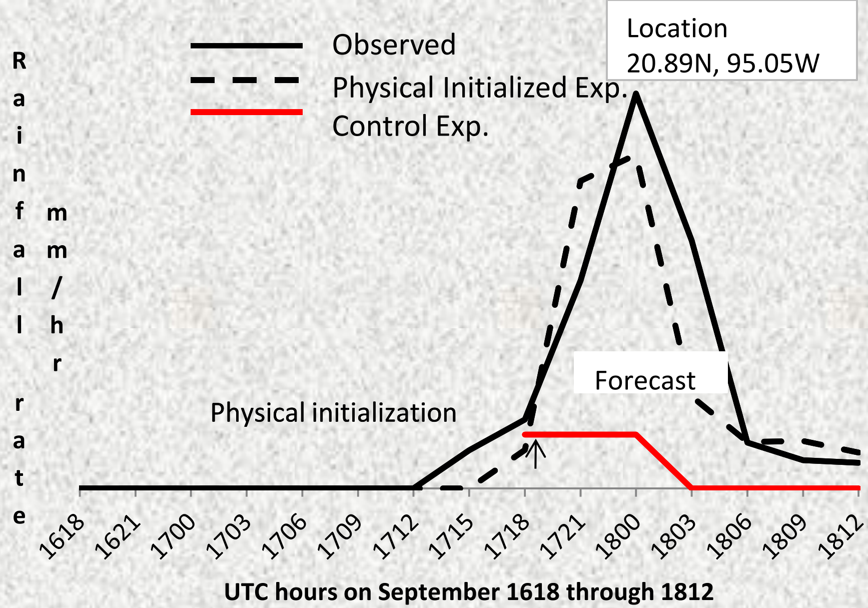
FIELDS AT THE END OF PHYISCAL INTIALIZATION t=0

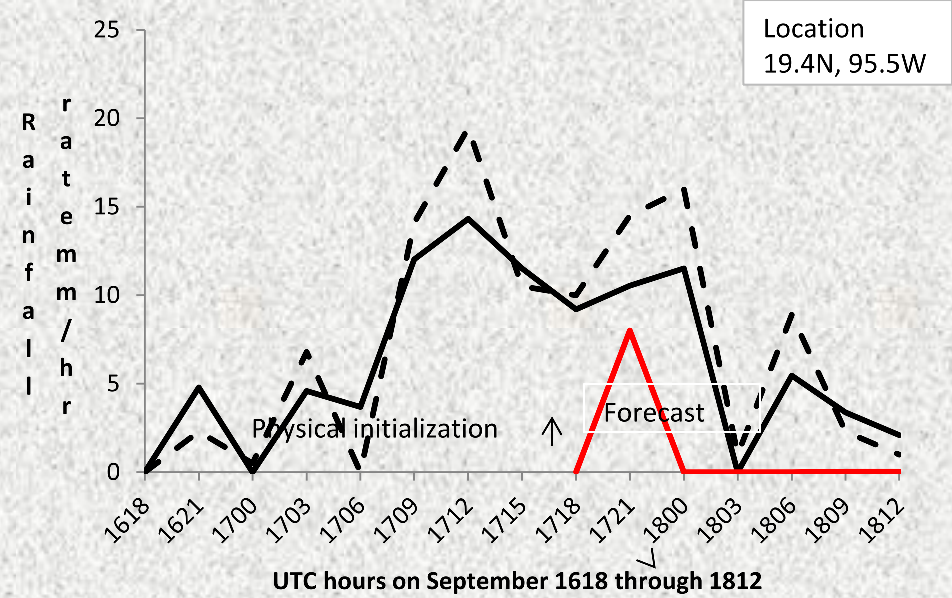


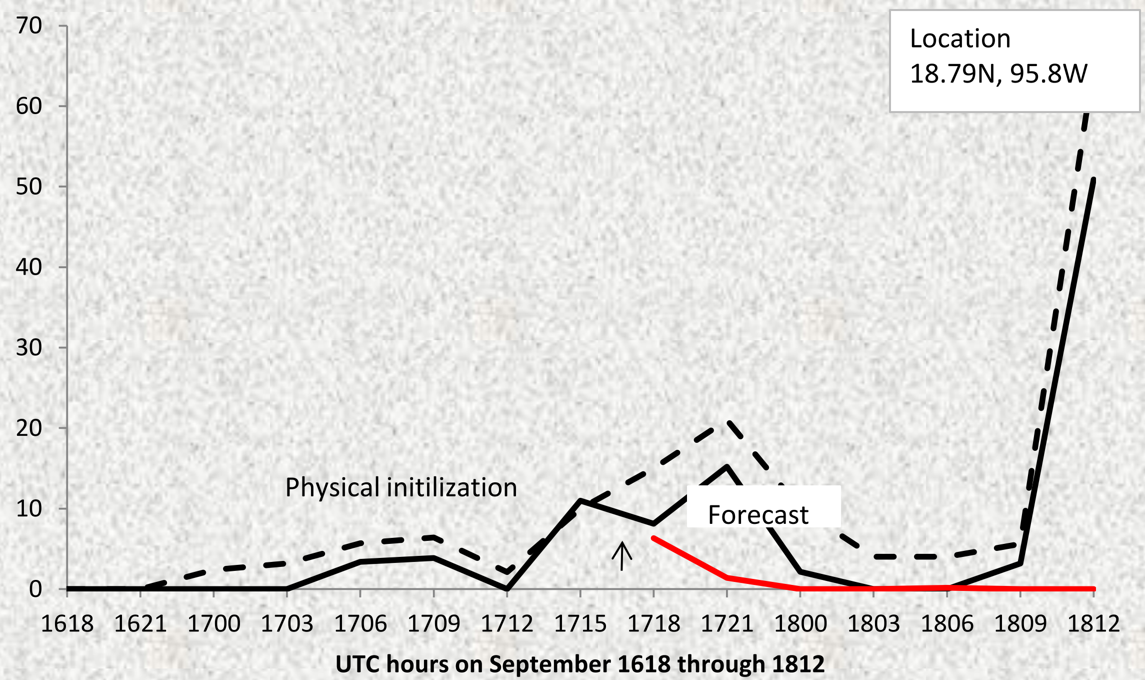




RMSE =5.24mm/hour
Corr. = 0.74



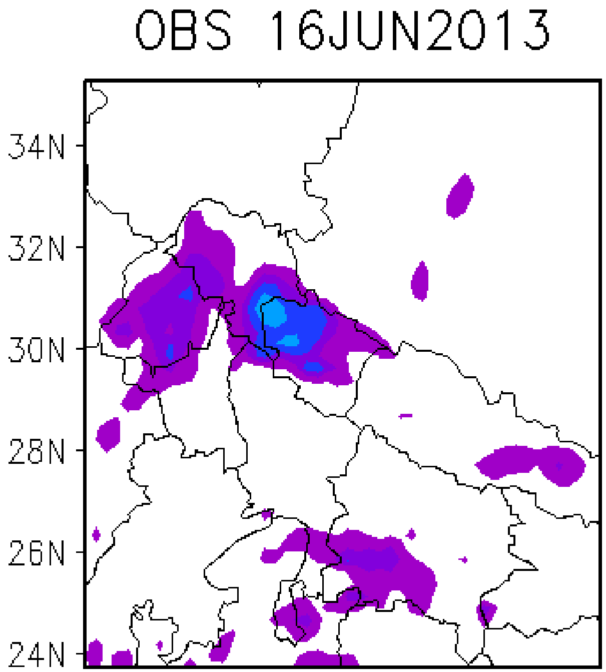



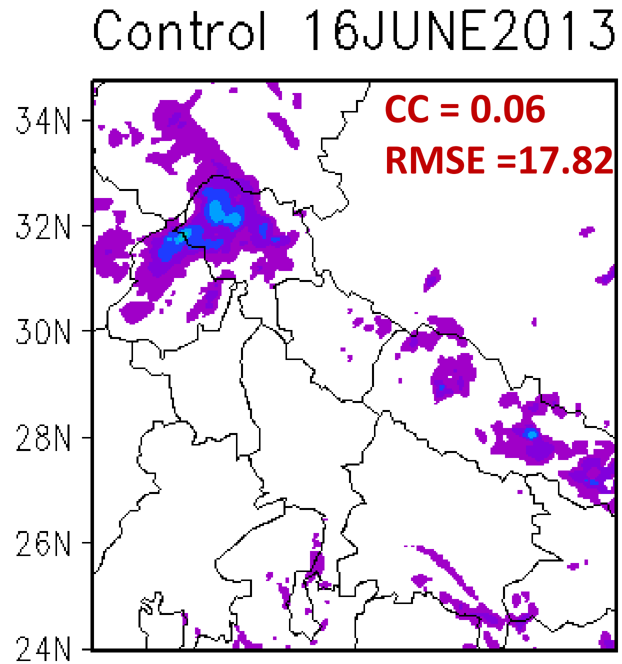

**THESE SHOW COMPARISONS OF THE TIME HISTORY OF OBSERVED, PHYSICALLY INITIALIZED AND FORECAST RAINS (mm/hour) AT SPECIFIC LOCATIONS**

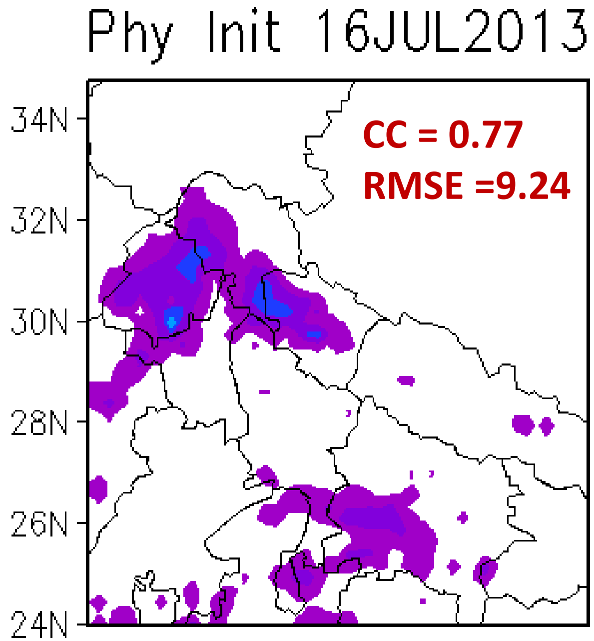


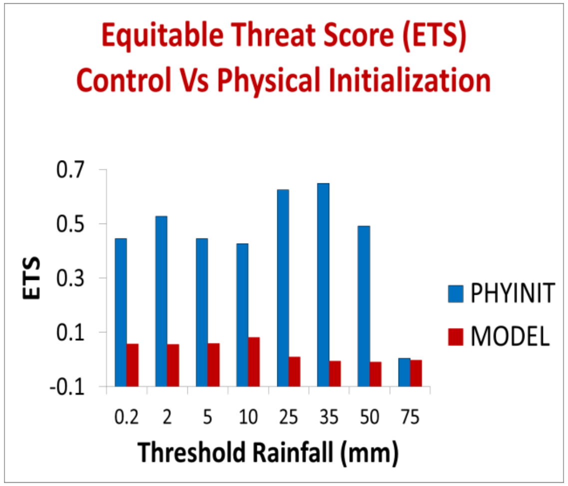

**Extreme rainfall of the order of 60mm/hour predicted from radar resolution physical initialization**

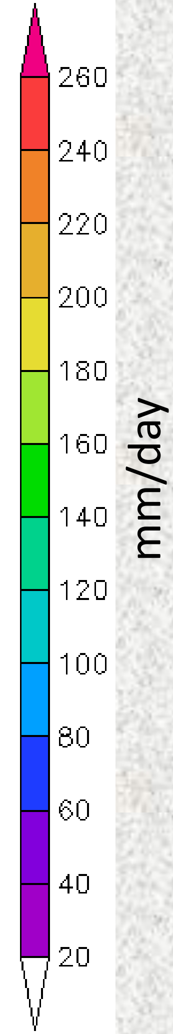
# Physical Initialization for Uttarakhand rains


OBS 16JUN2013
34N
32N
30N
28N
26N
24N

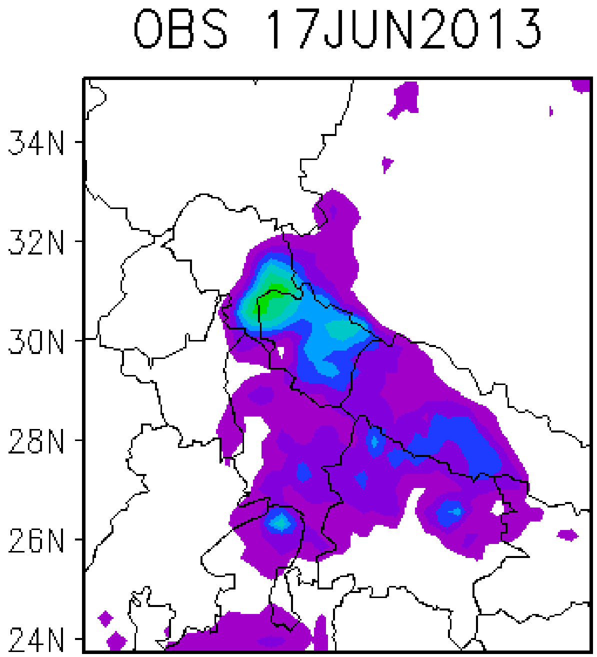

Control 16JUNE2013
CC = 0.06
RMSE =17.82
34N
32N
30N
28N
26N
24N

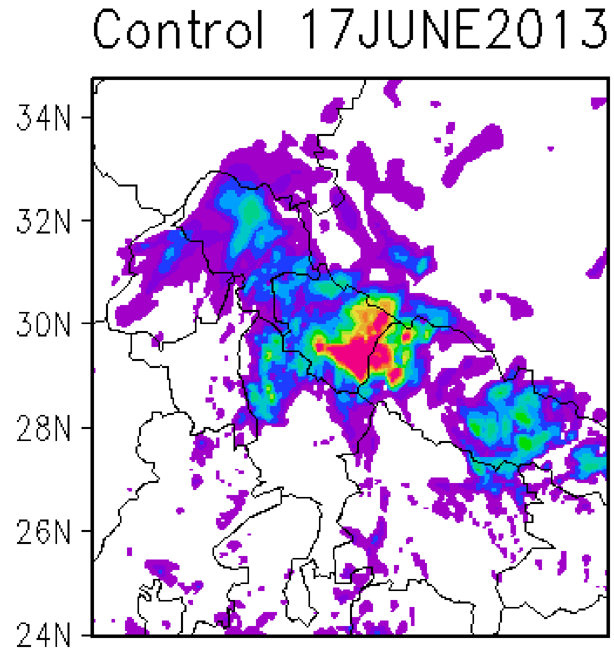

Phy Init 16JUL2013
CC = 0.77
RMSE =9.24
34N
32N
30N
28N
26N
24N

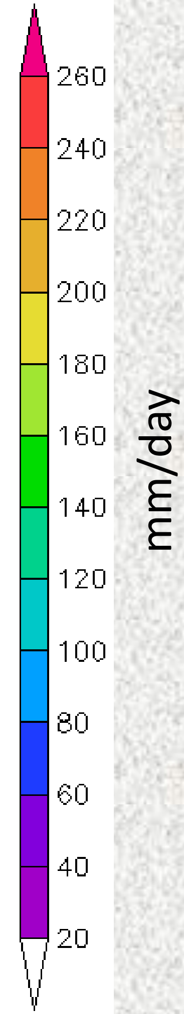

Equitable Threat Score (ETS)
Control Vs Physical Initialization
ETS
0.7
0.5
0.3
0.1
-0.1
0.2
2
5
10
25
35
50
75
Threshold Rainfall (mm)
PHYINIT
MODEL


260
240
220
200
180
160
140
120
100
80
60
40
20
mm/day

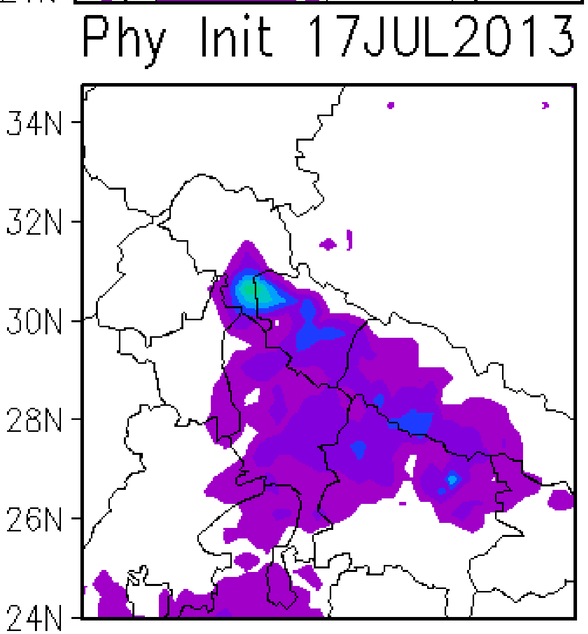
**Day 0**

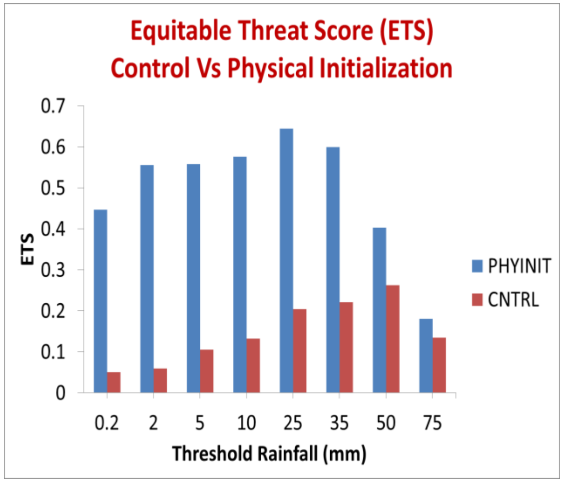



**CC = 0.25**
**RMSE = 40.66**



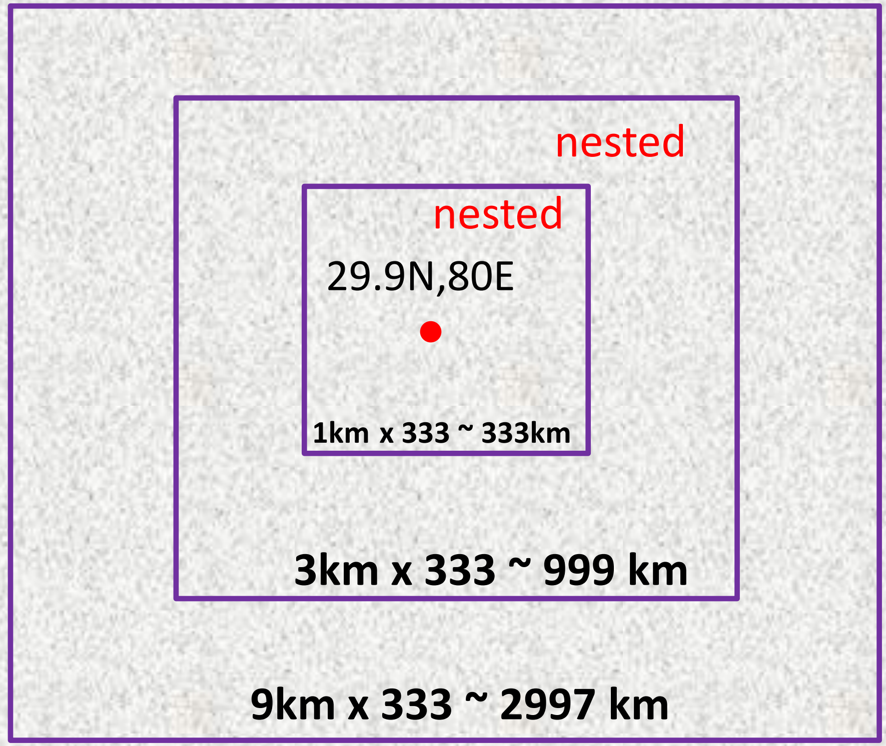




**Day 1** **CC = 0.79**
**RMSE = 10.13**

GrADS: COLA/IGES

# WRF-ARW OUTLINE

- 46 Vertical levels
- Microphysics : Goddard
- Longwave Radiation : rapid radiative transfer model
- Shortwave Radiation : Goddard
- Planetary boundary Physics : Yonsei Univerity Scheme
- Cumulus_parametrization : Explicit clouds (resolved)
- Initial Conditions : GFS ($1^0 x 1^0$)
- Lateral Boundary Conditions: GFS ($1^0 x 1^0$)
- Domain1/2/3: NIL/NIL/KF Scheme



# DATA SETS

**FOR THIS STUDY WE UTILIZED THE FOLLOWING DATA SETS.**

**1. 1 DEGREE BY 1 DEGREE (LATITUDE/LONGITUDE) GFS OPERATIONAL ANALYSIS AS WELL AS THE ERA INTERIM DATA (REANALYSIS) FROM ECMWF**

**2. TRMM PRECIPITATION ESTIMATES FROM NASA 3B42 DATA SETS AT 25 KM RESOLION AND 3 HOURLY INTERVALS. THIS STUDY HAS ALSO UTILIZED THE NCMRWF'S MERGED RAINFALL DATA SETS PRODUCED BY DR ASHIS MITRA.**

**3. CLOUDSAT/CALIPSO DATA SETS**

**4. WRF EXPERIMENTAL FORECAST DATA SETS AT 1KM HORIZONTAL RESOLUTION.**

**5. OLR DATA SETS FROM THE INDIA GEOSTATIONARY SATELLITE KALPANA PRODUCED BY IITM PUNE.**

# Buoyancy

# &

# CAPE

# BUOYANCY IS DEFINED BY THE RELATION

$$B = g\left(\frac{T'_v}{\overline{T}_v} - r_e\right)$$

where g is the acceleration of gravity,

$\overline{T}_v$ virtual temperature of the cloud environment ,

$T'_v$ virtual temperature inside a cloud ,

$r_e$ liquid water mixing ratio in the cloud (usually > 0.1 g/kg)

**Virtual Temperature** →

| Q | T | Tv | Tv-T |
|---|---|---|---|
| 0.018 | 300 | 303.294 | 3.294 |
| 0.019 | 300 | 303.477 | 3.477 |
| 0.02 | 300 | 303.66 | 3.66 |
| 0.021 | 300 | 303.843 | 3.843 |
| 0.022 | 300 | 304.026 | 4.026 |
| 0.023 | 300 | 304.209 | 4.209 |

***CAPE*- Convective Available Potential Energy(A measure of the amount of energy available for convection)**

**CAPE represents the amount of buoyant energy available to speed up a parcel vertically, or the amount of work a parcel does on the environment. Storms require high CAPE values; the higher the CAPE value, the more energy available to promote storm growth.**

**The acceleration (a) an air experiences due to density difference at a given level (buoyancy acceleration) can be related to the difference in the temperature of air parcel ($T_{ap}$) with respect to the temperature of the surrounding air ($T_e$ )**

$$\vec{a} = \frac{\left(T_{ap} - T_e\right)}{T_e}\vec{g}$$

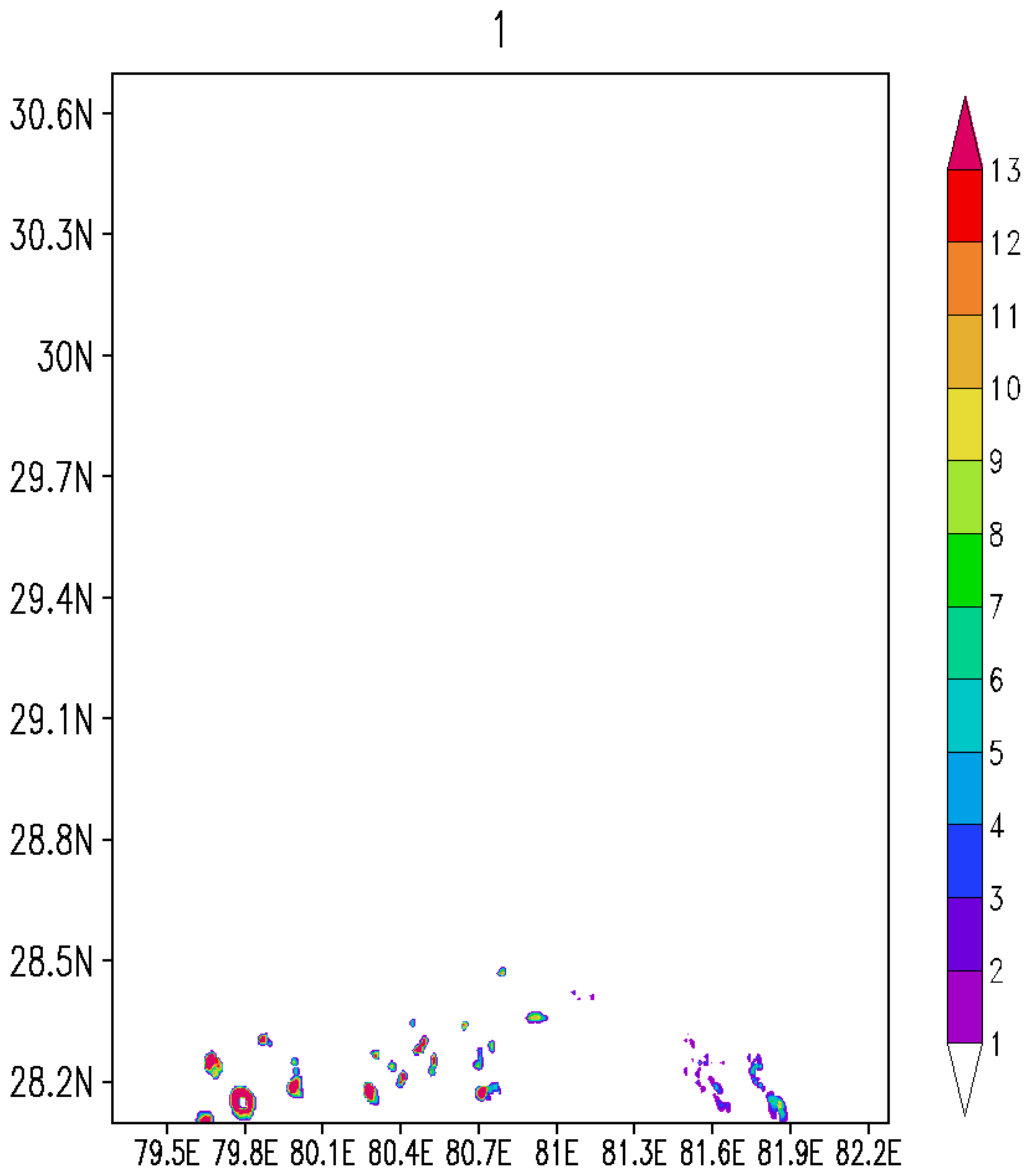
**Therefore CAPE or positive buoyancy can be represented as:-**

$$\text{CAPE} = \left(\sum_{LFC}^{EL}\left[\frac{\left(T_{ap} - T_e\right)}{T_e}\vec{g}\right]\right)\Delta z$$

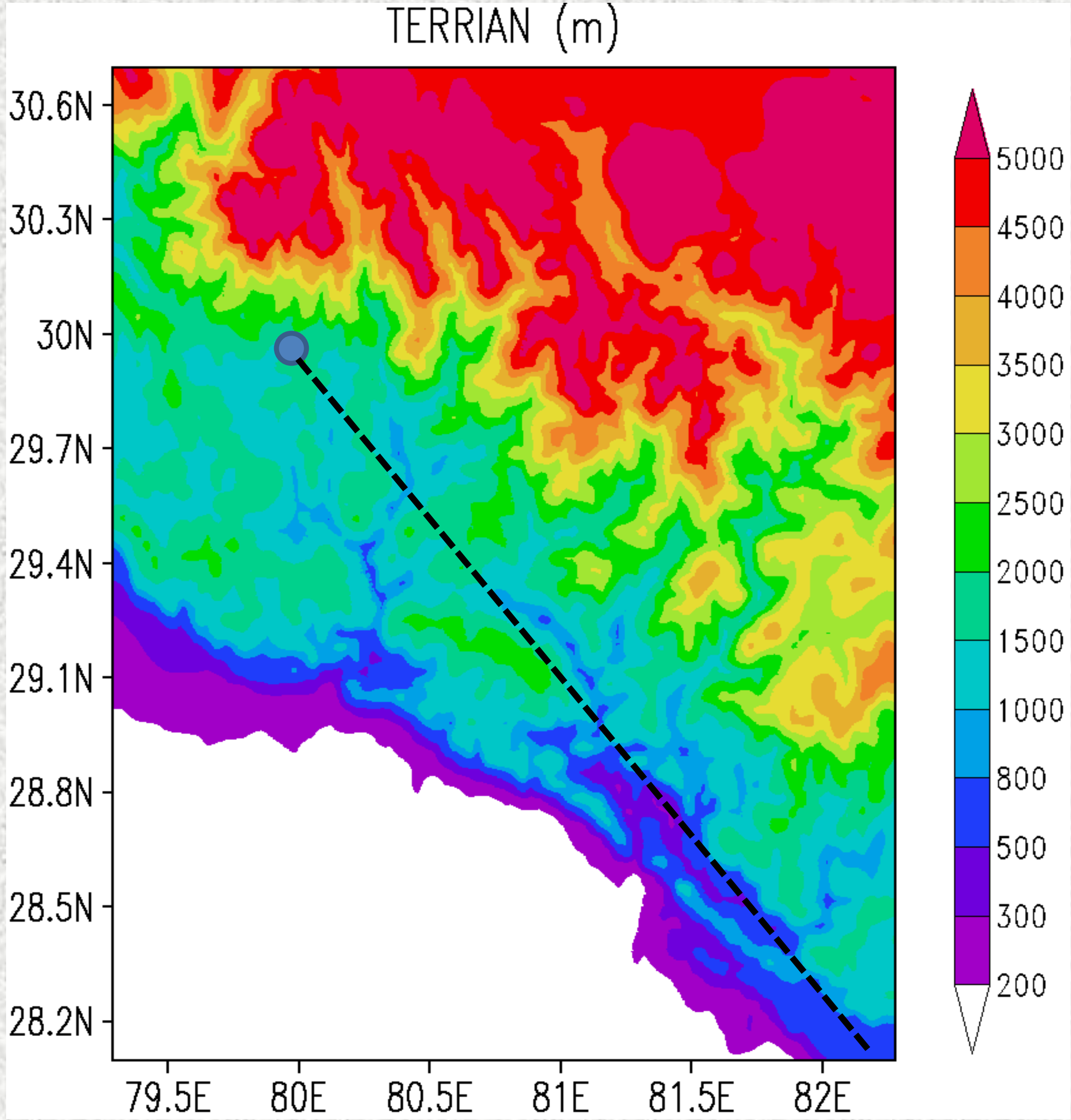
**CAPE is directly proportional to the total acceleration a parcel would experience due to buoyancy**

**Buoyancy (m $sec^{-2}$ ) for the CONTROL RUN**

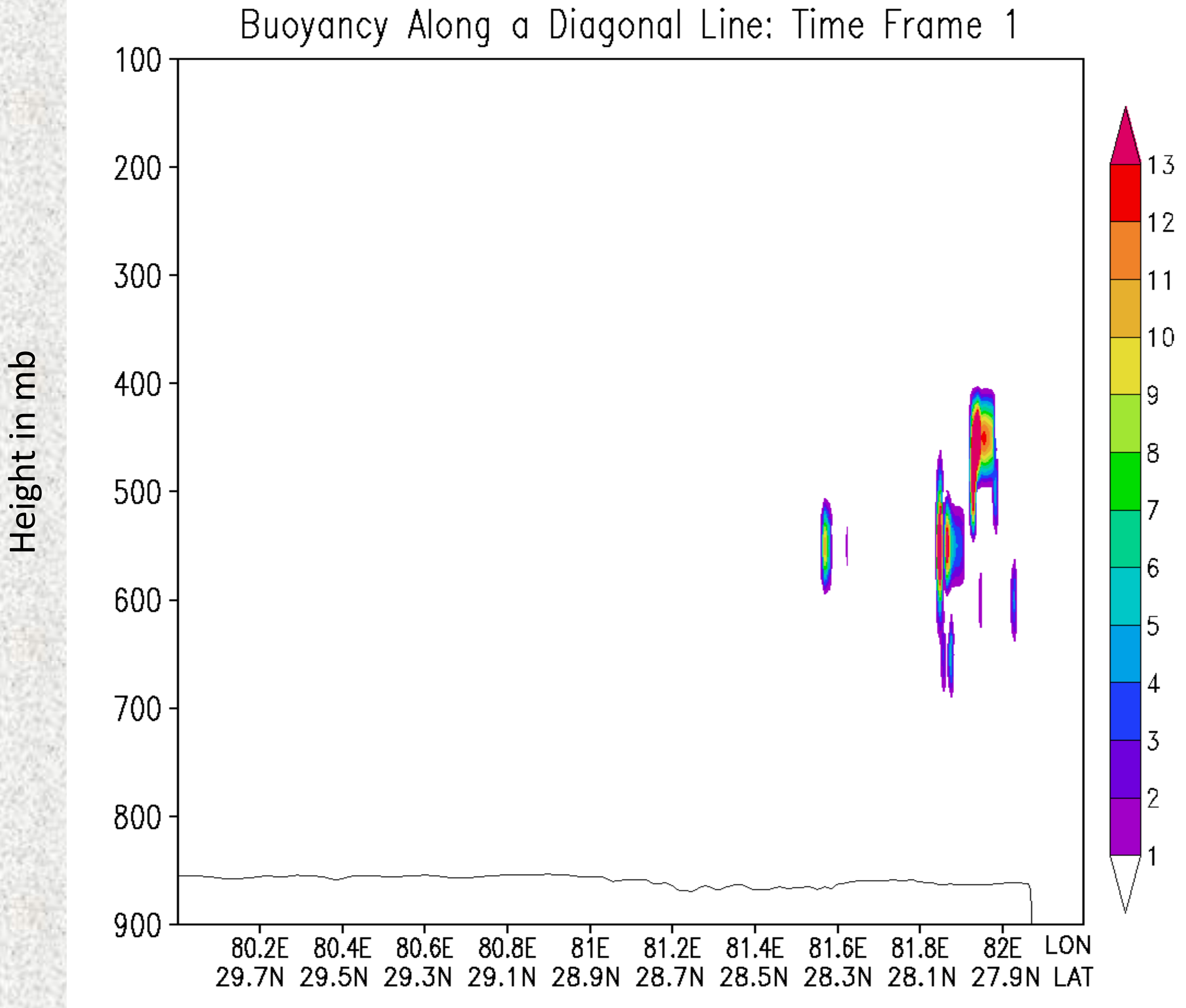
**00z16-16Z17 June 2013**

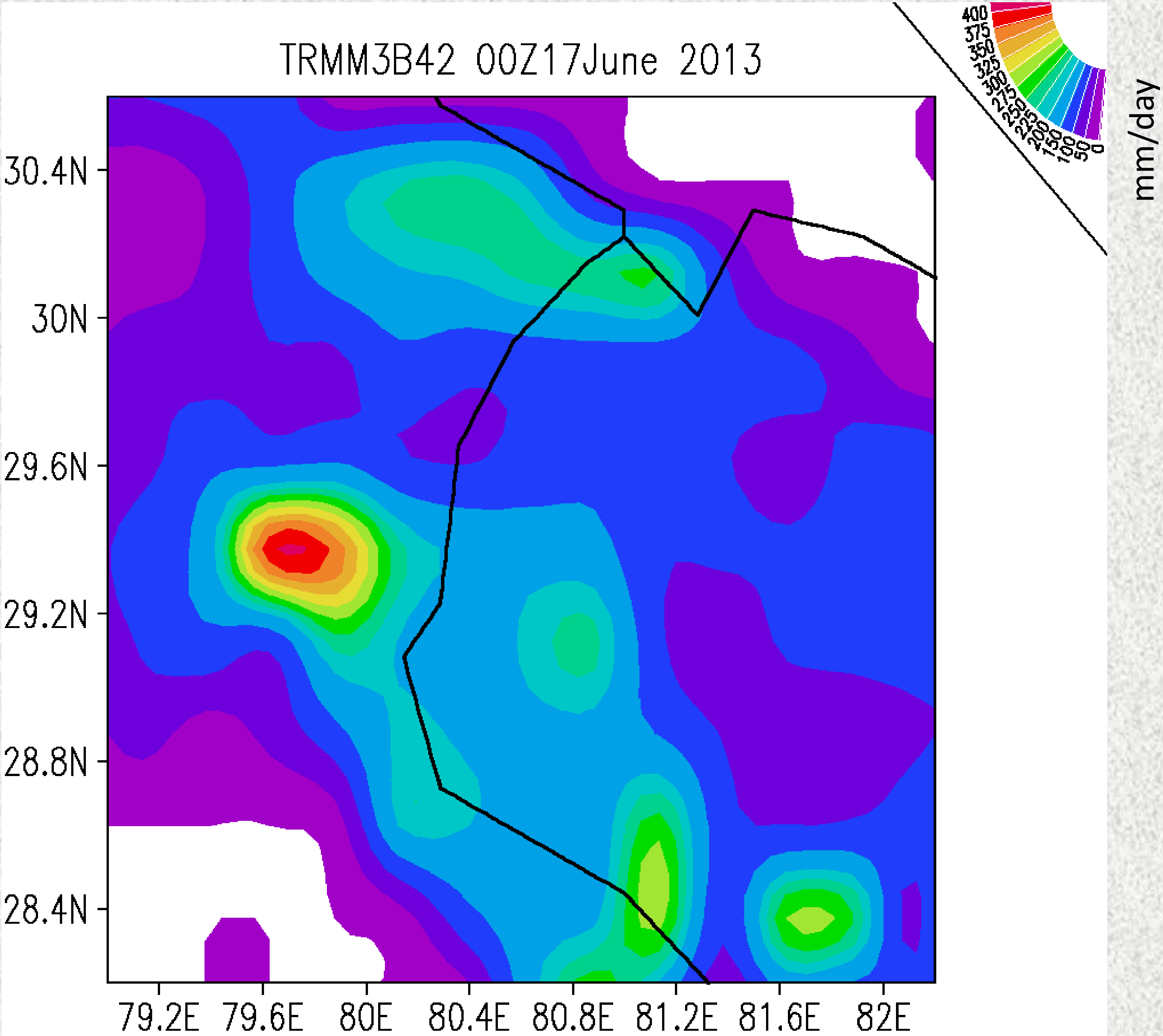


# Orography of Uttrakhand Region



# Passage of Buoyancy elements from South-East to the Uttrakhand mountain region of Heavy Rains

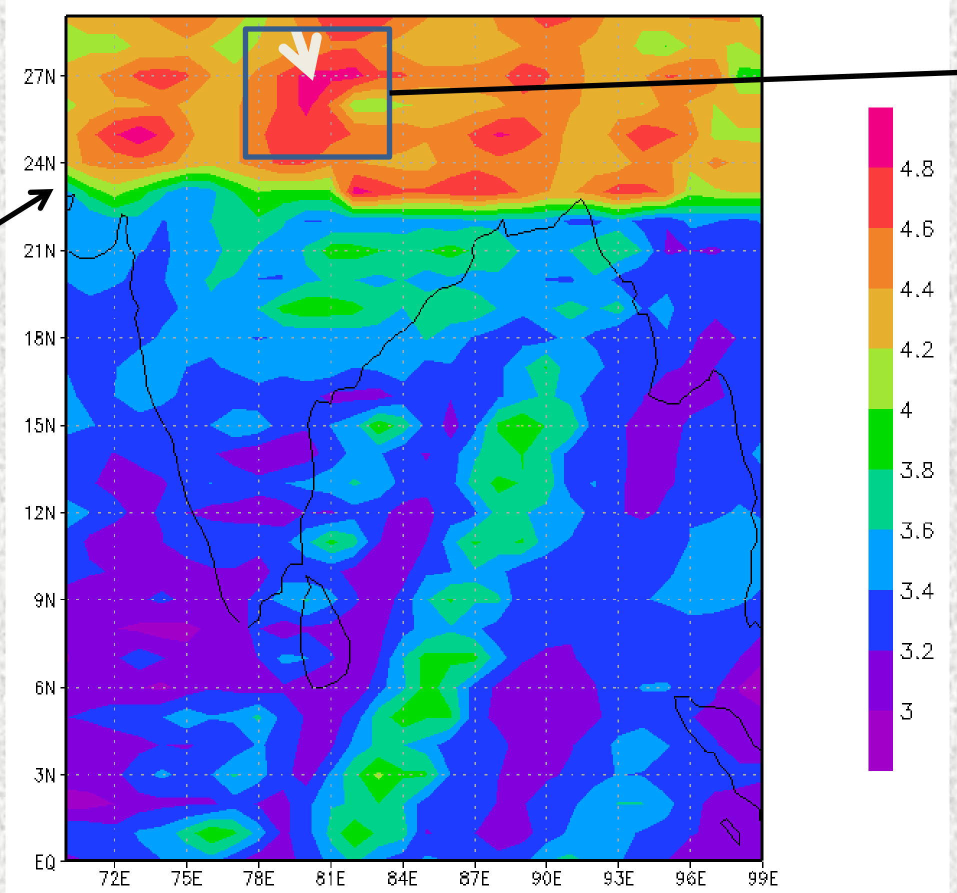




TRMM3B42 00Z17June 2013
30.4N
30N
29.6N
29.2N
28.8N
28.4N
79.2E
79.6E
80E
80.4E
80.8E
81.2E
81.6E
82E
400
375
350
325
300
275
250
225
200
150
100
50
0
mm/day

# ADAPTIVE OBSERVATIONAL STRATOGY

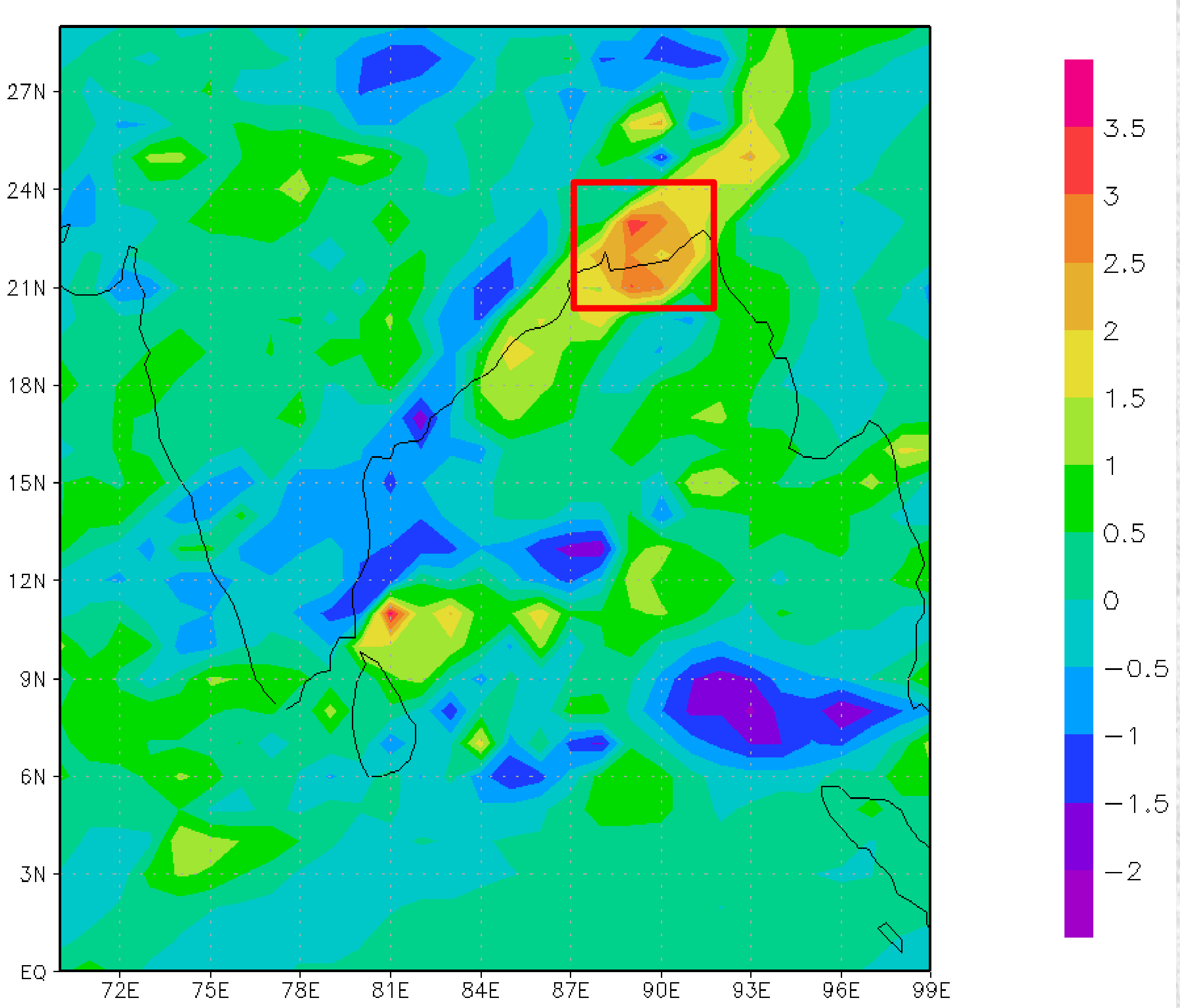
1. Run 20 forecast experiments using initial Monte Carlo type perturbations for specific humidity. Range of experiments from hours 0 to 48.
2. Take the specific humidity fields at hour 48, 850 hPa level and compute a field of standard deviation with respect to the forecast mean field of hour 48.
3. Find the 20 forecasted strings of specific humidity at the location of maximum standard deviation

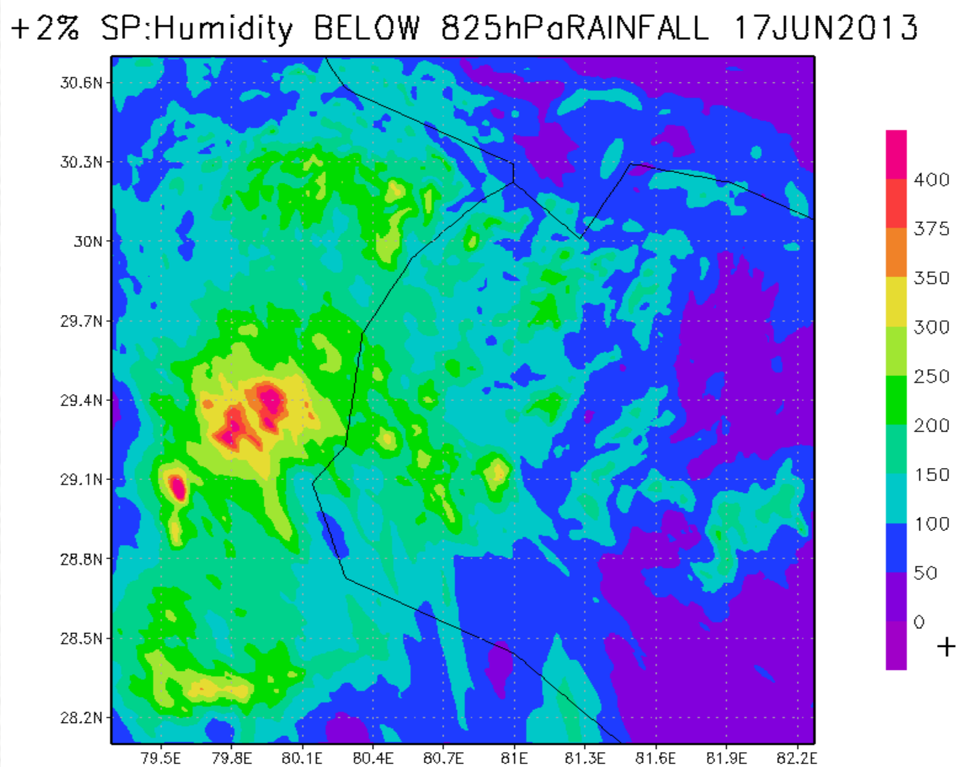



Uttaranchal region

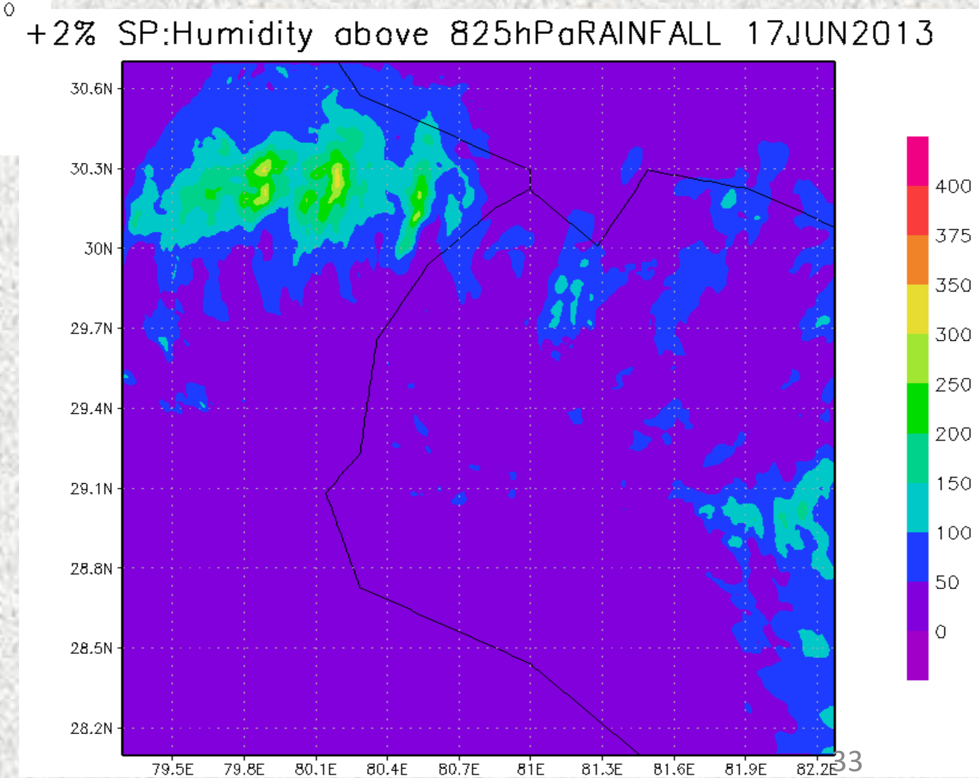
High contrast in color scheme is due to the large standard deviation among the forecast to the north of 22N

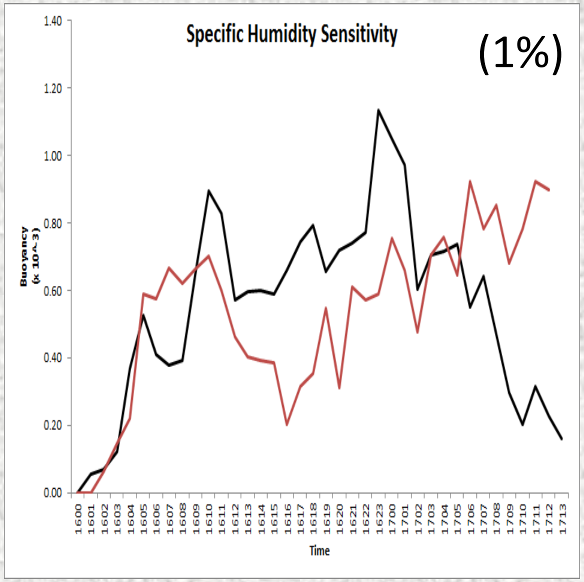
4. Back correlate the above string of 20 with all strings of 20 forecast value for the hour 12 forecast values.
5. Find the region of maximum back correlation.
6. This region is boxed below.

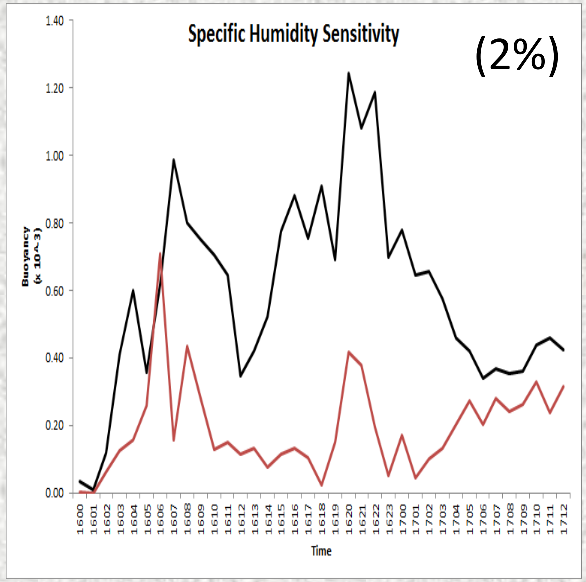



+2% SP:Humidity BELOW 825hPaRAINFALL 17JUN2013
30.6N
30.3N
30N
29.7N
29.4N
29.1N
28.8N
28.5N
28.2N
79.5E 79.8E 80.1E 80.4E 80.7E 81E 81.3E 81.6E 81.9E 82.2E
400
375
350
300
250
200
150
100
50
0

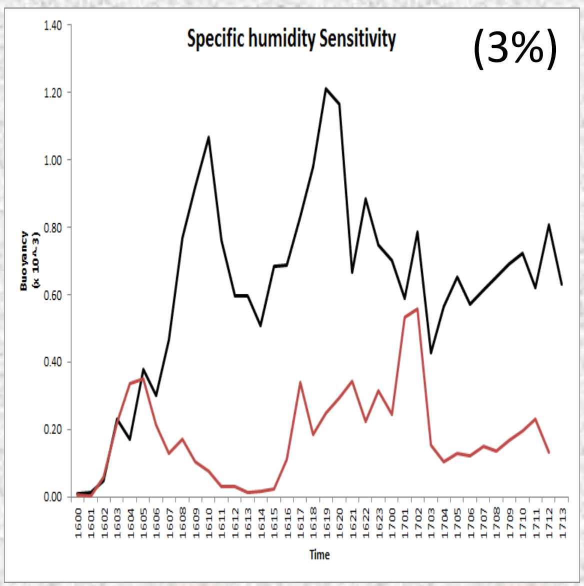
# RAINFALL

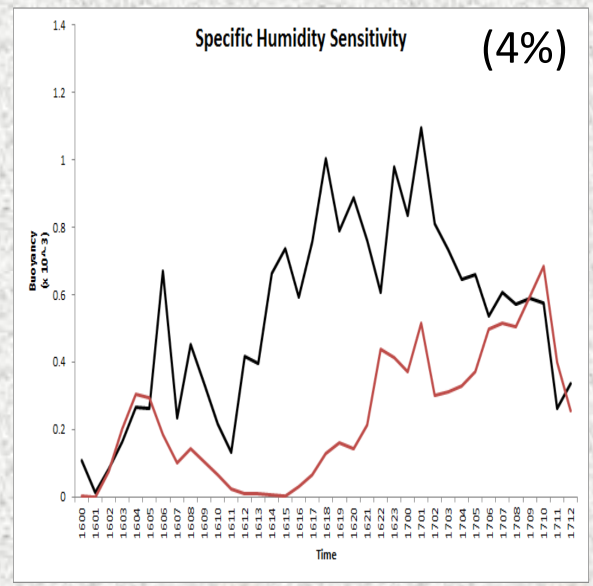

+2% SP:Humidity above 825hPaRAINFALL 17JUN2013
30.6N
30.3N
30N
29.7N
29.4N
29.1N
28.8N
28.5N
28.2N
79.5E 79.8E 80.1E 80.4E 80.7E 81E 81.3E 81.6E 81.9E 82.2E
400
375
350
300
250
200
150
100
50
0




# Area occupied by Buoyancy $(ms^{-2})$



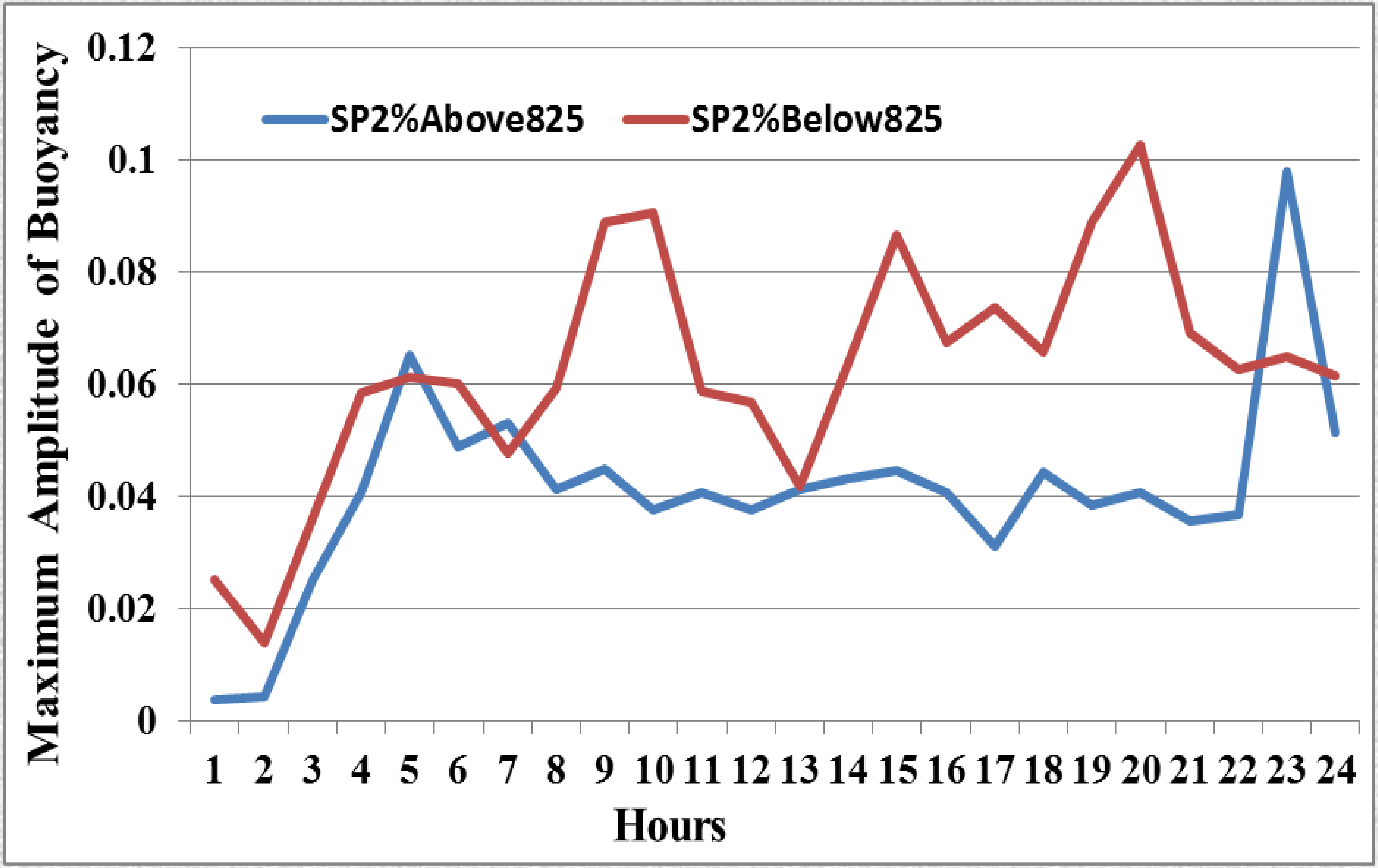




**Black solid line – Moisture enhanced by 1%,2%, 3% and 4% below 825hPa**

**Red solid line – Moisture enhanced by 1%,2%, 3% and 4% % above 825hPa**

# Maximum Amplitude of Buoyancy (m sec$^{-2}$)

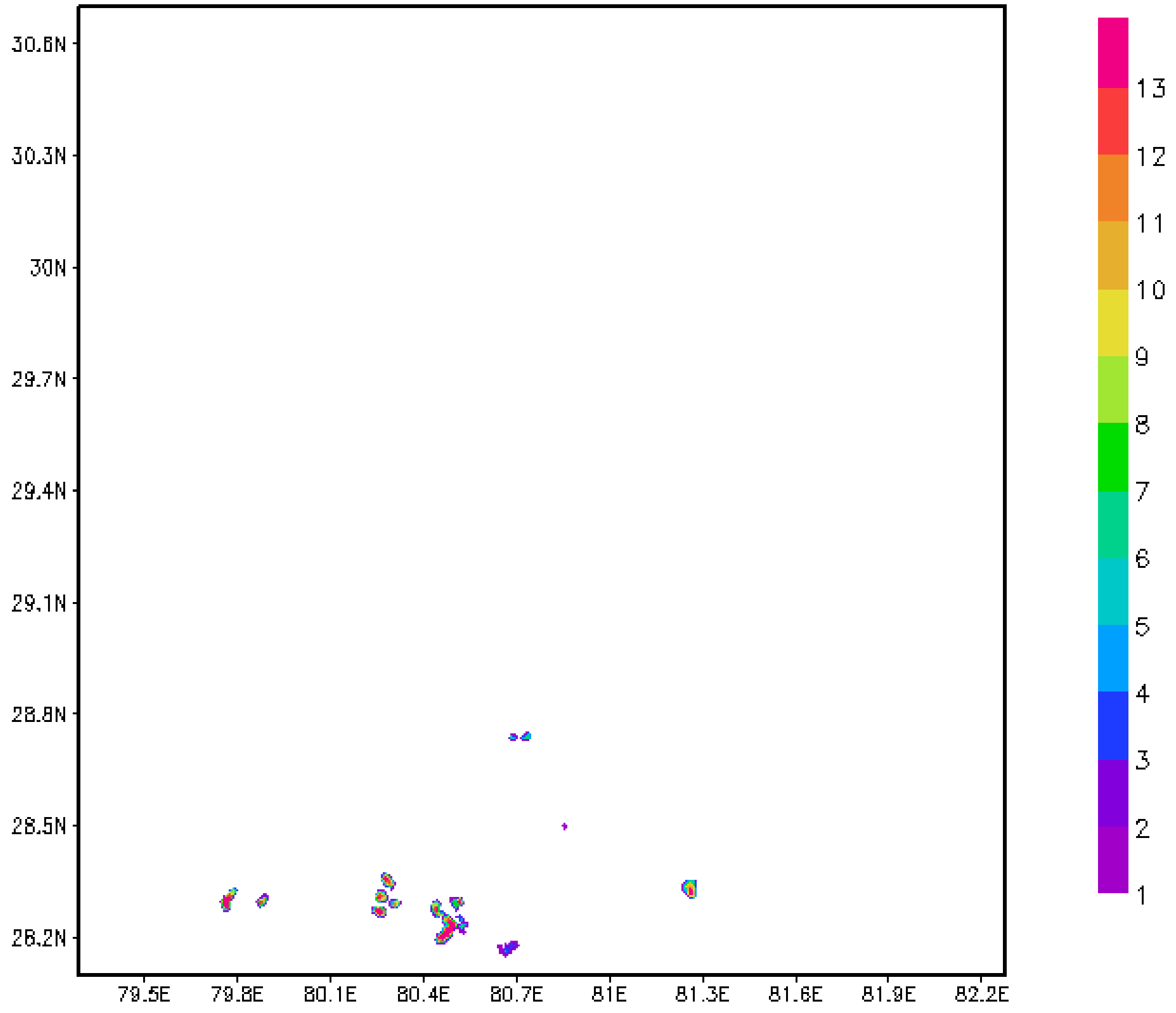
**(00Z16-00Z17 June 2013)**



# Buoyancy

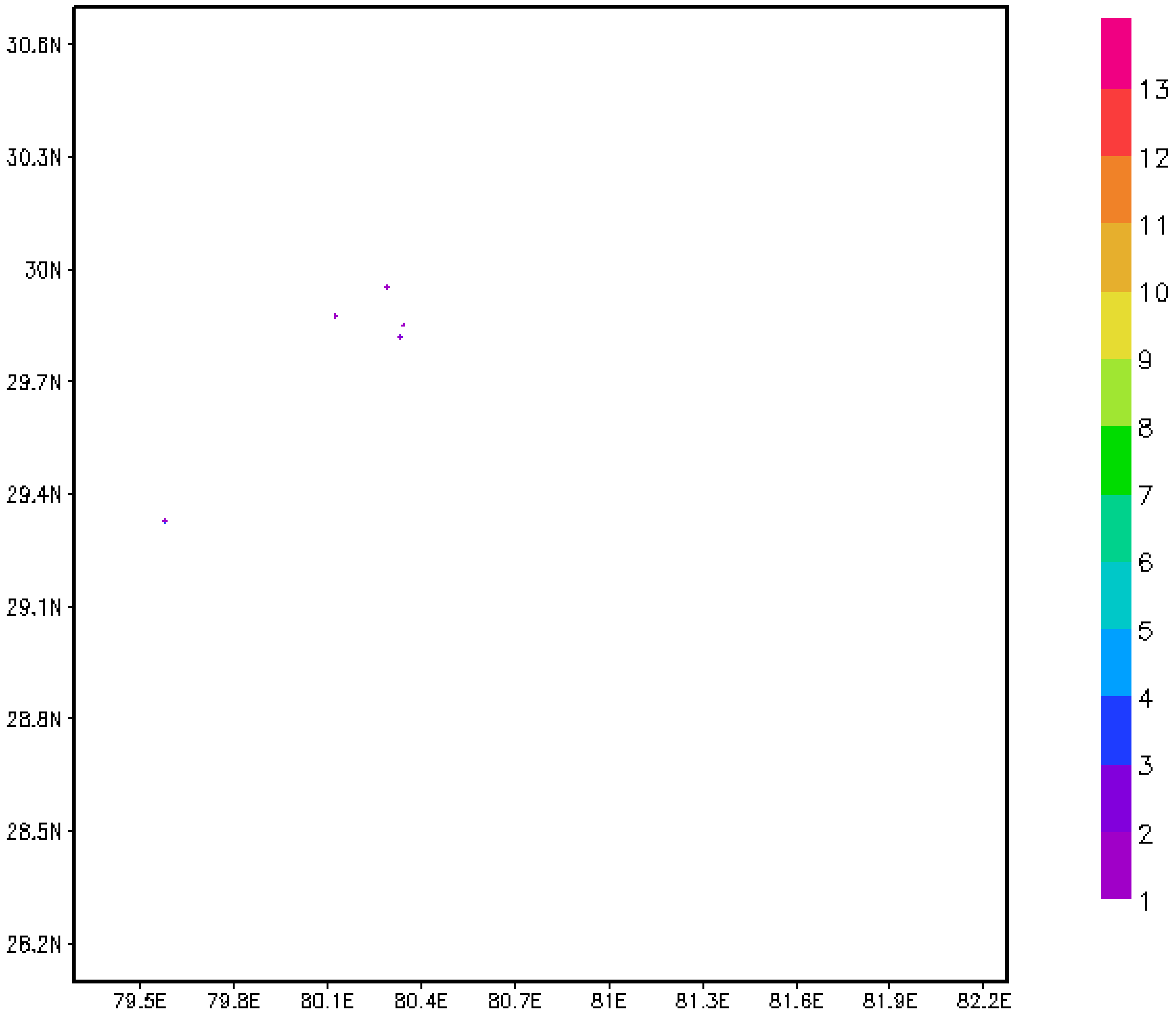
**Experiment:**

**SP2%below825**



# Buoyancy

**Experiment:**
**SP2%above825**



# RATE OF CHANGE OF BUOYANCY

$$\frac{\partial B}{\partial t} = -\nabla.VB - \frac{\partial}{\partial Z} wB + \frac{g}{\overline{T}_v}\{\frac{\partial T_v'}{\partial t} + V.\nabla T_v' + w\frac{\partial T_v'}{\partial z}\} - \frac{g}{\overline{T}_v^{\,2}} T_v' \frac{d\overline{T}_v}{dt} - g\frac{dr_e}{dt}$$

## Term on the right hand side denote:

1. Horizontal Convergence of Flux of Buoyancy
2. Vertical Convergence of Flux of Buoyancy
3. Local change of virtual temperature of cloud
4. Horizontal Advection of virtual temperature
5. Vertical Advection of virtual temperature
6. Change of virtual temperature of parcel of air in the environment
7. Change in Buoyancy from accumulation or depletion of parcels liquid water mixing ratio

Noting that $T_v = T(1 + 0.61q)$

$\frac{dT}{dt}$ is obtained from the WRF's use of the first law which is

**The thermal equation can be written as:**

$$\frac{\partial\theta}{\partial t} = -\vec{V}\,.\nabla\theta - w\frac{\partial\theta}{\partial z} - \frac{1}{\rho}\frac{\partial}{\partial z}\overline{\rho w'\theta'} + D_\theta + \frac{L_v}{C_P}(c - e_c - e_r) + \frac{L_f}{C_p}(f - m) + \frac{L_s}{C_p}(d - s) + Q_R$$

**The moisture equation is expressed by** :

$$\frac{\partial q_v}{\partial t} = -\vec{V}\,.\nabla q_v - \overline{W}\frac{\partial\bar{q}}{\partial z} - \frac{1}{\rho}\frac{\partial}{\partial z}\rho\overline{w'q_v'} + \overline{Dq_v} - (c - e_c - e_r) - (d - s)$$

**The liquid water mixing ratio is expressed by :**

$$\bar{\rho}\frac{\partial q_c}{\partial t} = -\frac{\partial}{\partial x}(\bar{\rho}\,uq_c) - \frac{\partial}{\partial y}(\bar{\rho}\,vq_c) - \frac{\partial}{\partial z}(\bar{\rho}\,wq_c) + \bar{\rho}(c - e_c) - T_{qc} + D_{qc}$$

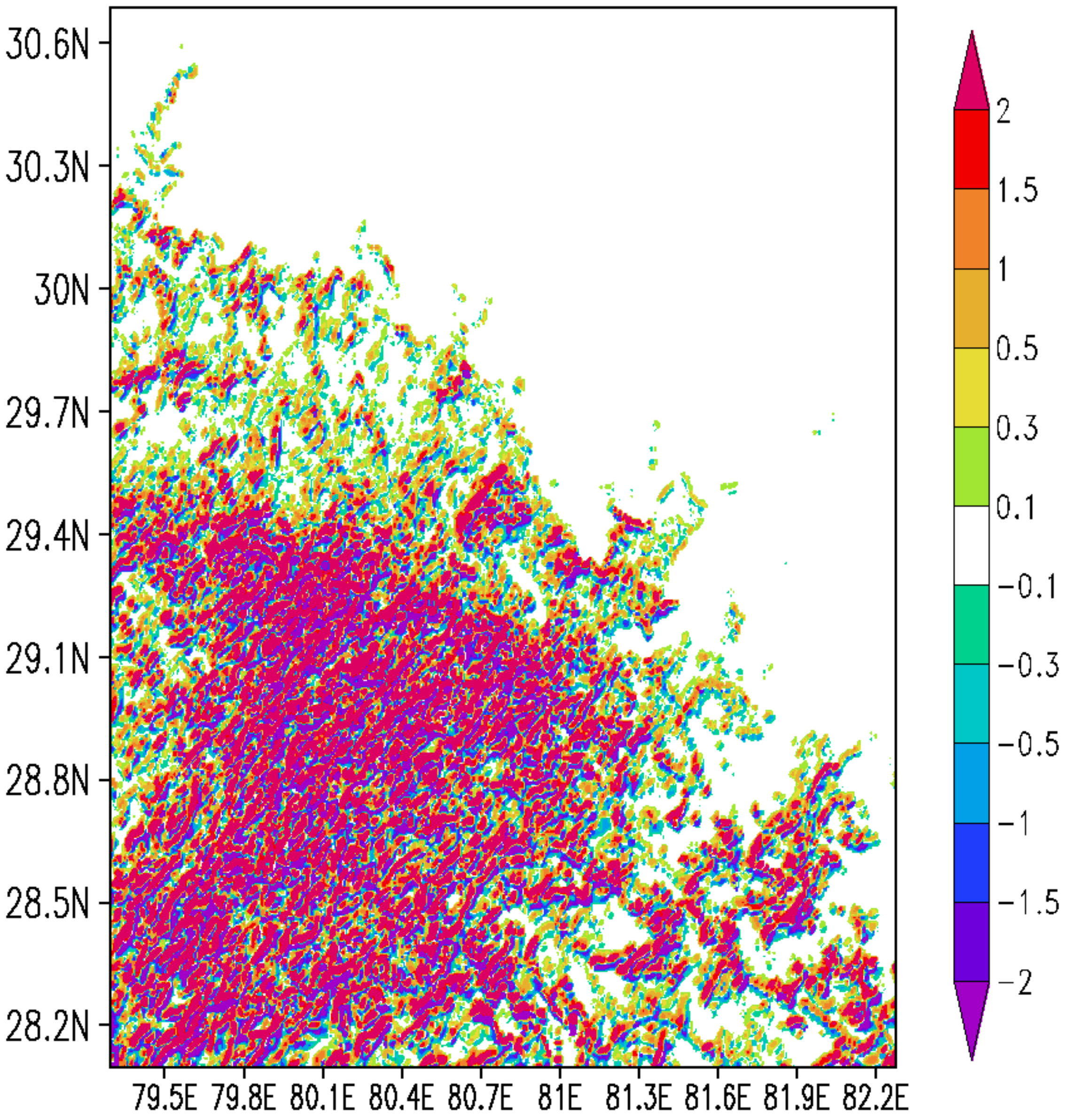
Experiment: SP2%below825

**HORIZONTAL CONVERFENCE OF FLUX OF BUOYANCY (*1E-6)**

$$-\nabla . BV$$

**averaged for 01Z16-22Z16 June at 2013 750mb**

**Unit: m sec$^{-3}$**



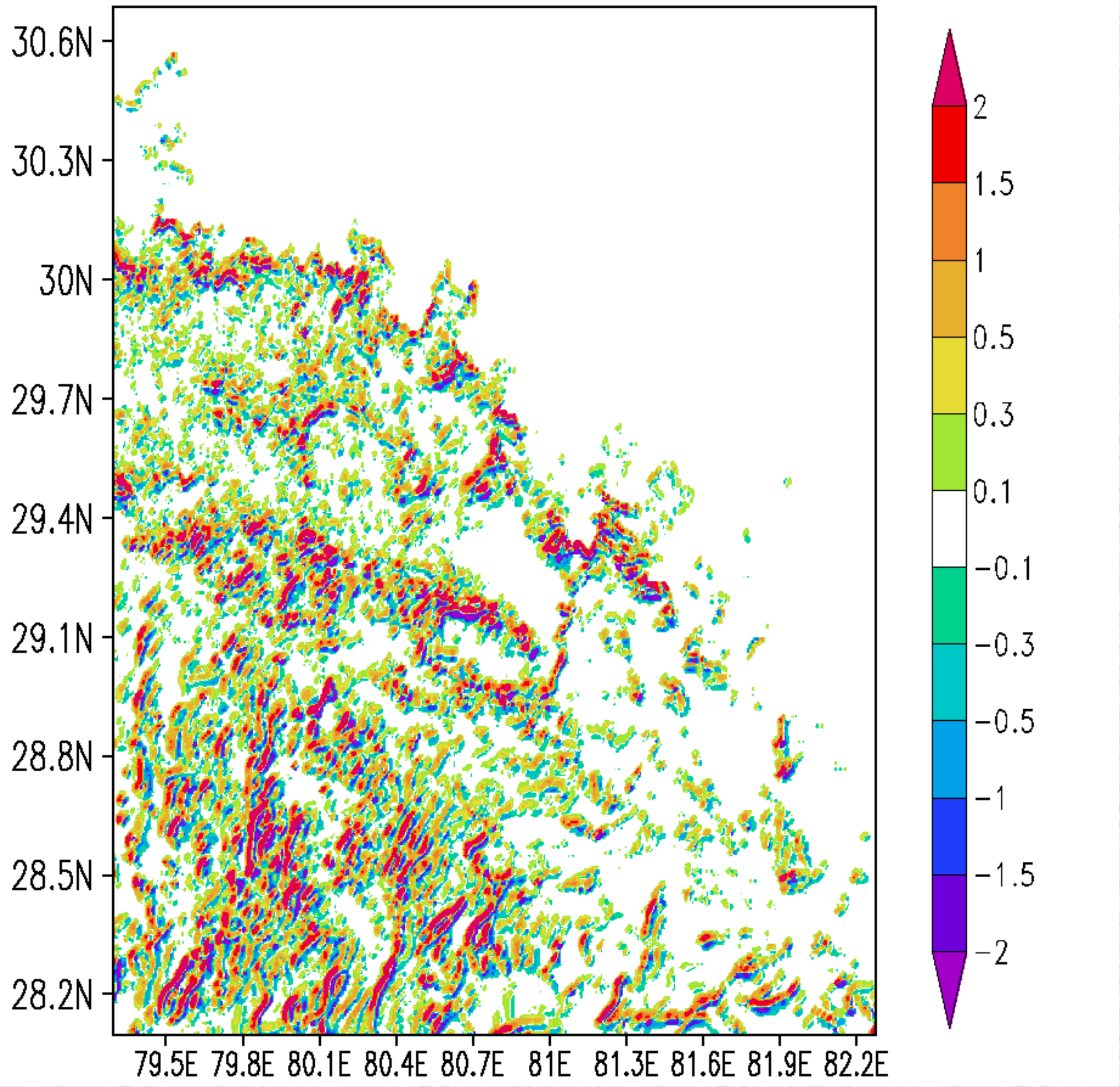
**HORIZONTAL CONVERFENCE OF FLUX OF BUOYANCY (*1E-6)**

$$-\nabla.BV$$

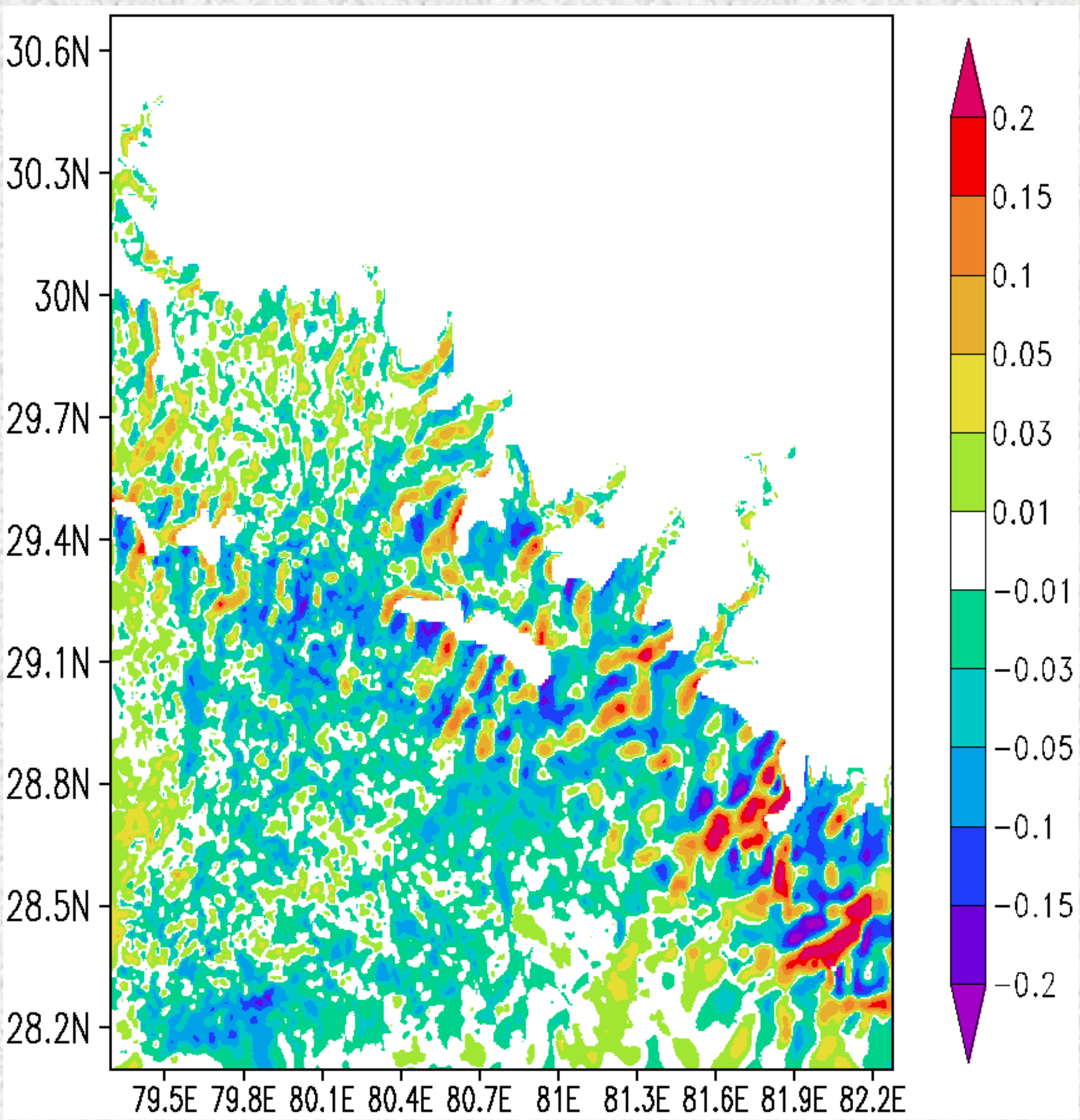
**averaged for 01Z16-22Z16 June at 2013 750mb**

**Unit: m sec$^{-3}$**

Experiment: SP2%above825



Experiment: SP2%below825




**Vertical advection of cloud's virtual temperature**

$$\frac{g}{\overline{\overline{T}}_v} w \frac{\partial T_v'}{\partial z}$$

**averaged for 01Z16-24Z16 June at 2013 750mb**

**Unit: m sec$^{-3}$**

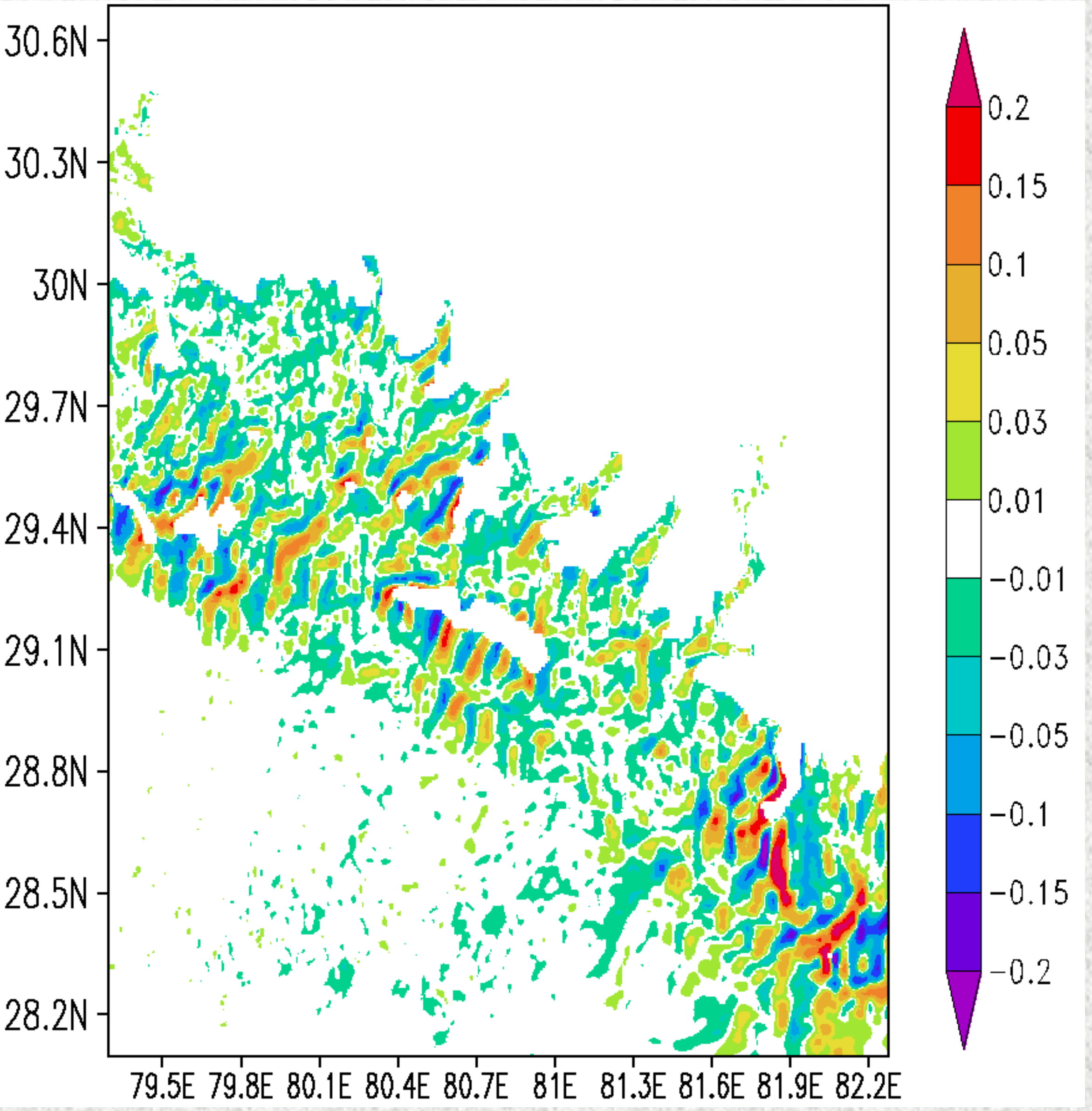
**Vertical advection of cloud's virtual temperature**

$$\frac{g}{\overline{\overline{T}}_v} w \frac{\partial T_v'}{\partial z}$$

**averaged for 01Z16-24Z16 June at 2013 750mb**

**Unit: m sec$^{-3}$**

**Experimet: SP2%above825**



Extreme rains in tropical depression seem to be very sensitive to moisture observations. We shall next examine similar features for two hurricanes Gabrielle and Ingrid of 2013.

# Hurricane Ingrid

# SYNOPTIC HISTORY

**The origin of Ingrid was complicated. One contributor was a tropical wave that moved westward from the coast of Africa on 28 August and showed little distinction through 1st 0f September. On 2nd September, shower activity increased near the northern end of the wave axis. This area of weather would eventually be absorbed into Tropical Storm Gabrielle, which was developing near and north of Puerto Rico during the 3rd – 7th September period. The southern part of the wave continued westward and eventually moved into a large area of low-level cyclonic flow extending from the western Caribbean Sea across Central America into the eastern north Pacific. The combination of this flow and the wave produced two areas of disturbed weather between 8-10 September. One, over the Pacific, moved westward and eventually helped spawn Hurricane Manuel. The second, which appeared over the northwestern Caribbean Sea on 9 September, became Ingrid. Slow development of the Caribbean disturbance led to formation of a low pressure area on 11 September. While the system showed signs of organization before moving over the Yucatan Peninsula later that day, surface observations indicate that it had not developed into a tropical cyclone. The low moved west-northwestward, with the center apparently reforming over the Bay of Campeche early on 12 September. Subsequent development led to the formation of a tropical depression around 1800 UTC that day about 150 n mi east-northeast of Veracruz, Mexico.**

**The best track positions and intensities are listed in Table 11 The depression initially moved westward, but turned toward the west-southwest on 13 September while the cyclone intensified into a tropical storm. Later that day, Ingrid made a hairpin turn when it was centered about 50 n mi east of Veracruz. On 14 September a combination of a mid/upper-level trough over northeastern Mexico and low/mid-level ridging over the southeastern United States steered Ingrid north-northeastward and then northward. Although the trough and upper-level outflow from Manuel caused moderate westerly vertical wind shear over Ingrid, the cyclone managed to intensify into a hurricane later on 14 September. Thereafter, it reached a peak intensity of 75 kt early on 15 September while centered about 215 n mi southeast of La Pesca, Mexico. The hurricane turned northwestward near the time of peak intensity, and this motion continued for the rest of the day. On 16 September, a mid-level ridge over Texas caused Ingrid to turn west-northwestward. Increasing vertical shear caused the cyclone to weaken below hurricane strength, and it is estimated that the maximum winds had decreased to 55 kt when the center made landfall just south of La Pesca around 1115 UTC that day. After landfall, Ingrid moved slowly westward until it dissipated over northeastern Mexico on 17 September.**

Single simulation domain 1 km resolution over Mexico Domain (98.635W-93.361W, 15.979N-20.988N).

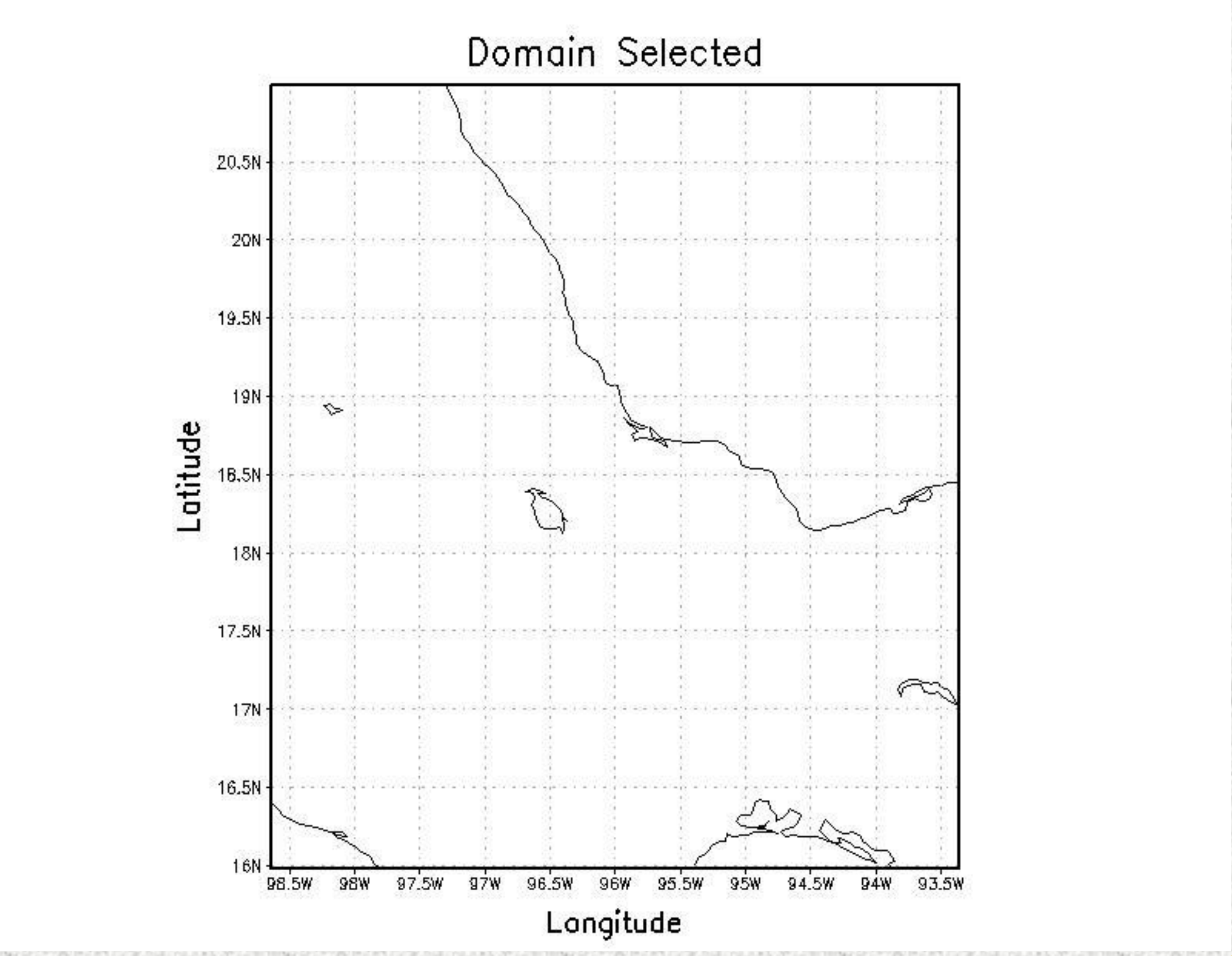


**Table 1a:** Model Configuration

| *Model* | *NCAR Mesoscale model WRF-ARW* |
| --- | --- |
| Dynamics | Non-hydrostatic with 3-D Coriolis force |
| No. of Vertical levels | 27 |
| Horizontal Resolution | 1 km |
| Domain of Integration | 98.635W-93.361W,15.979N-20.988N |
| Grid Points | 557×558 |
| Map Projection | Mercator |
| Integration Time-Step | 3 Sec |
| Initial and Boundary conditions | FNL $1^o \times 1^o$ Forecast |
| Boundary conditions updating | 12 hourly |

**Table 1b:** list of physical parameterization schemes used for model simulations

| ***Physics*** | |
| --- | --- |
| Microphysics (**MP**): | Surface: NOAH LSM (4 subsoil layers) |
| WRF Single Moment 5-class (WSM5) | PBL: YSU Scheme |
| Cumulus Parameterization (**CP**): | Surface layer: Monin-Obukhov Scheme |
| Kain-Fritsch Scheme | Radiation Parameterizations: |
| | 1. Short wave (Dudhia) |
| | 2. Long wave (RRTM) |

# HURRICANE INGRID TRACK

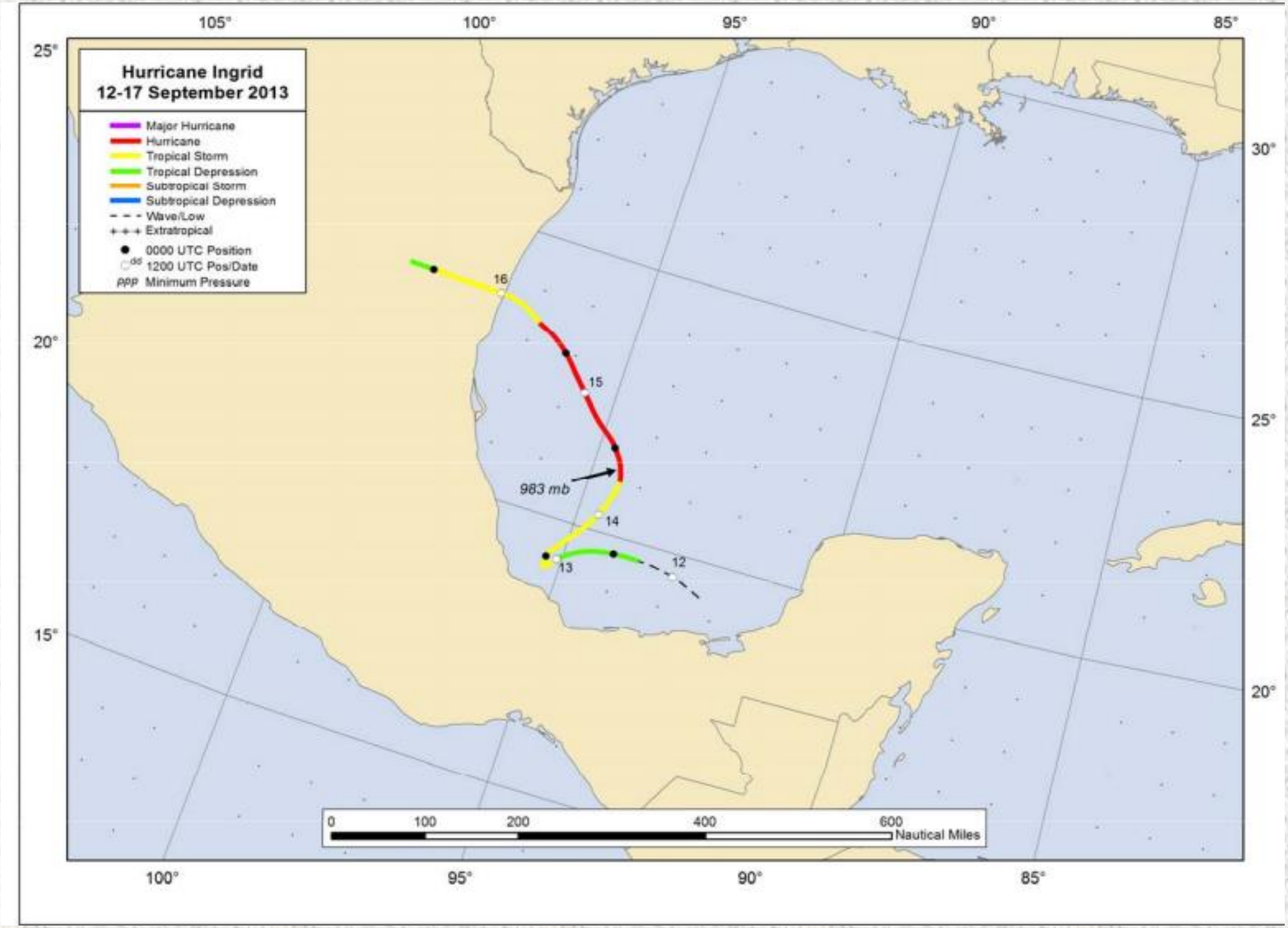



Image courtesy of the National Hurricane Center

# Hurricane Ingrid 2013 Sea Level Pressure

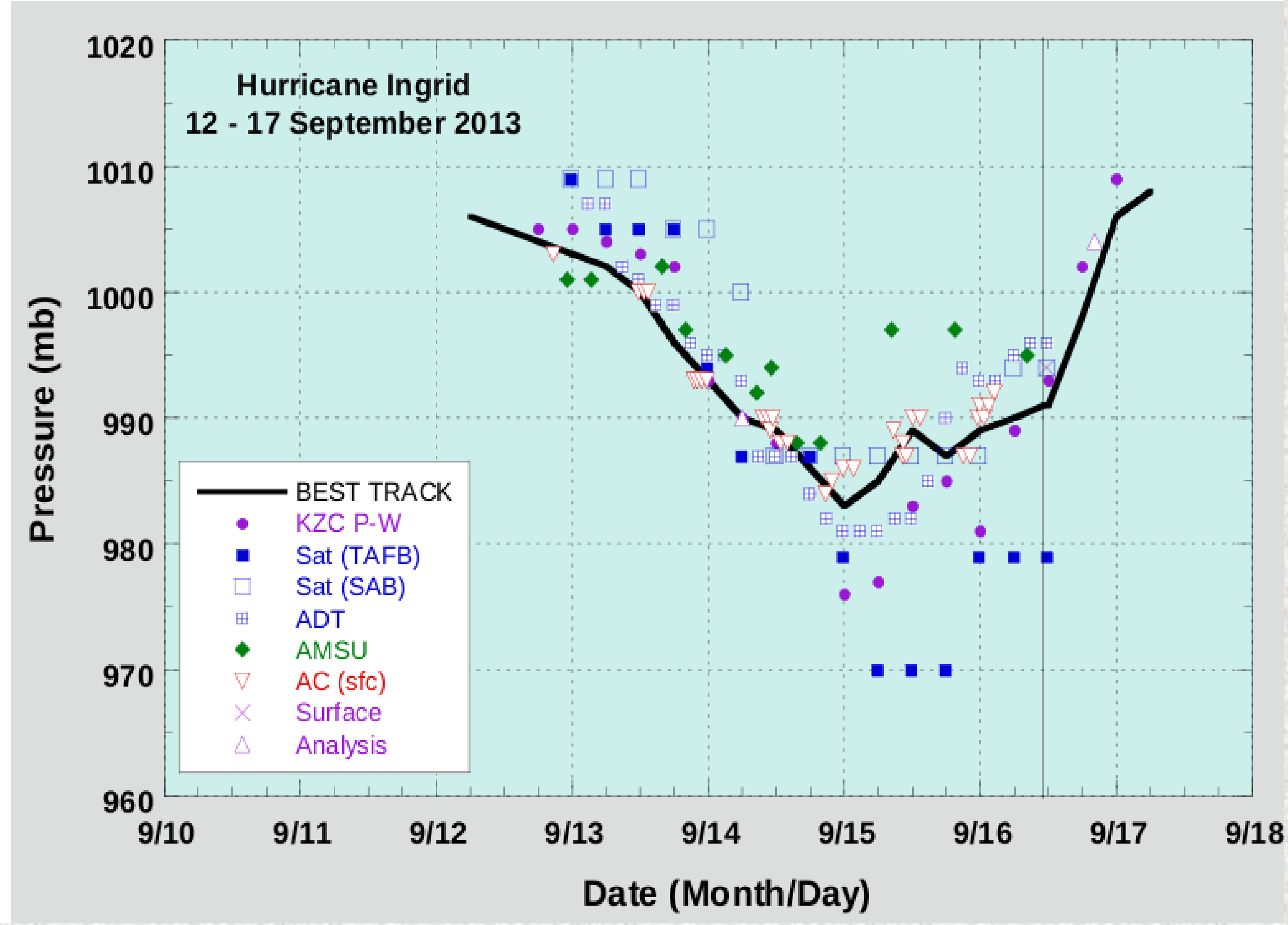



Image courtesy of the National Hurricane Center

# Hurricane Ingrid 2013 Wind Speed

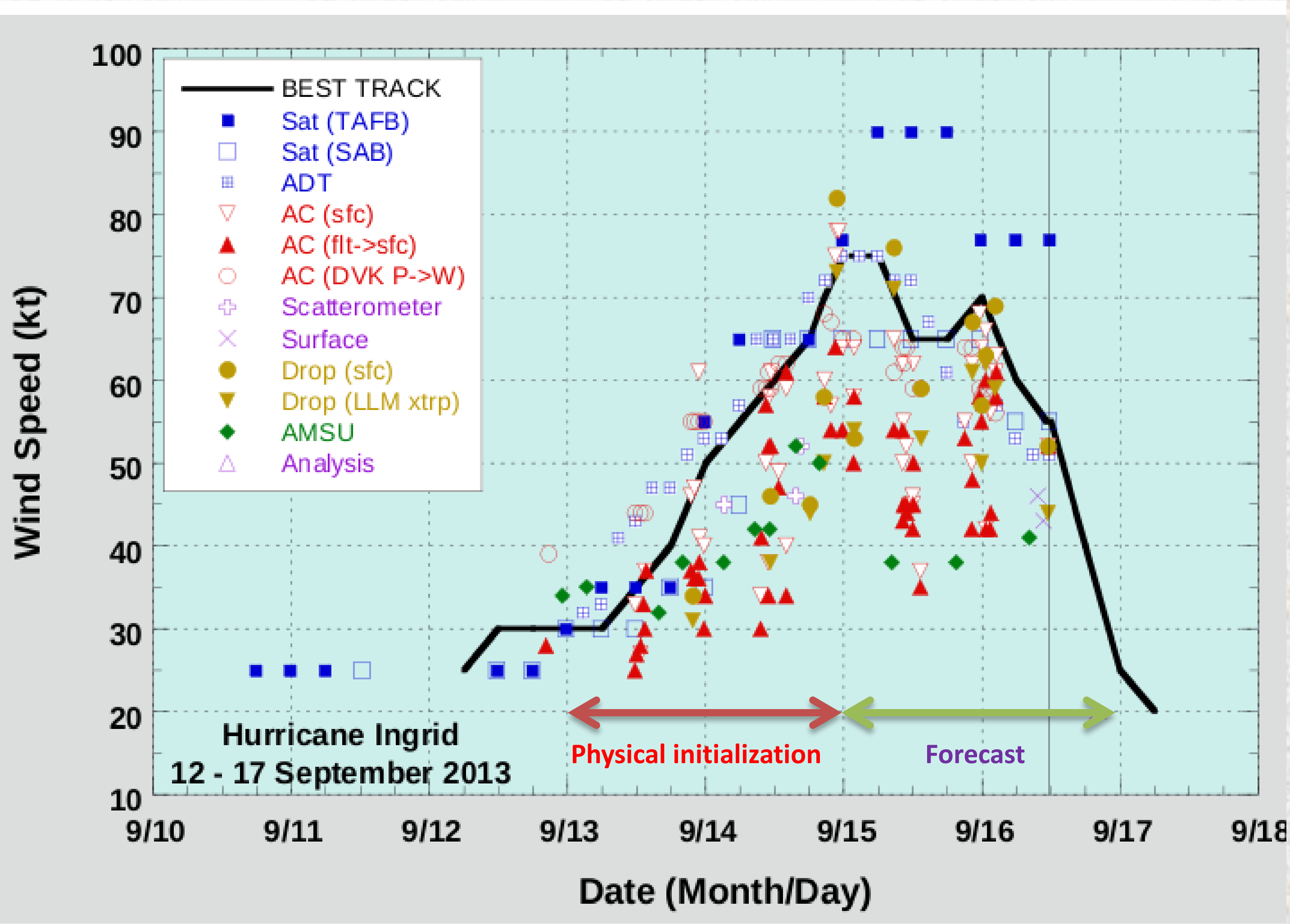
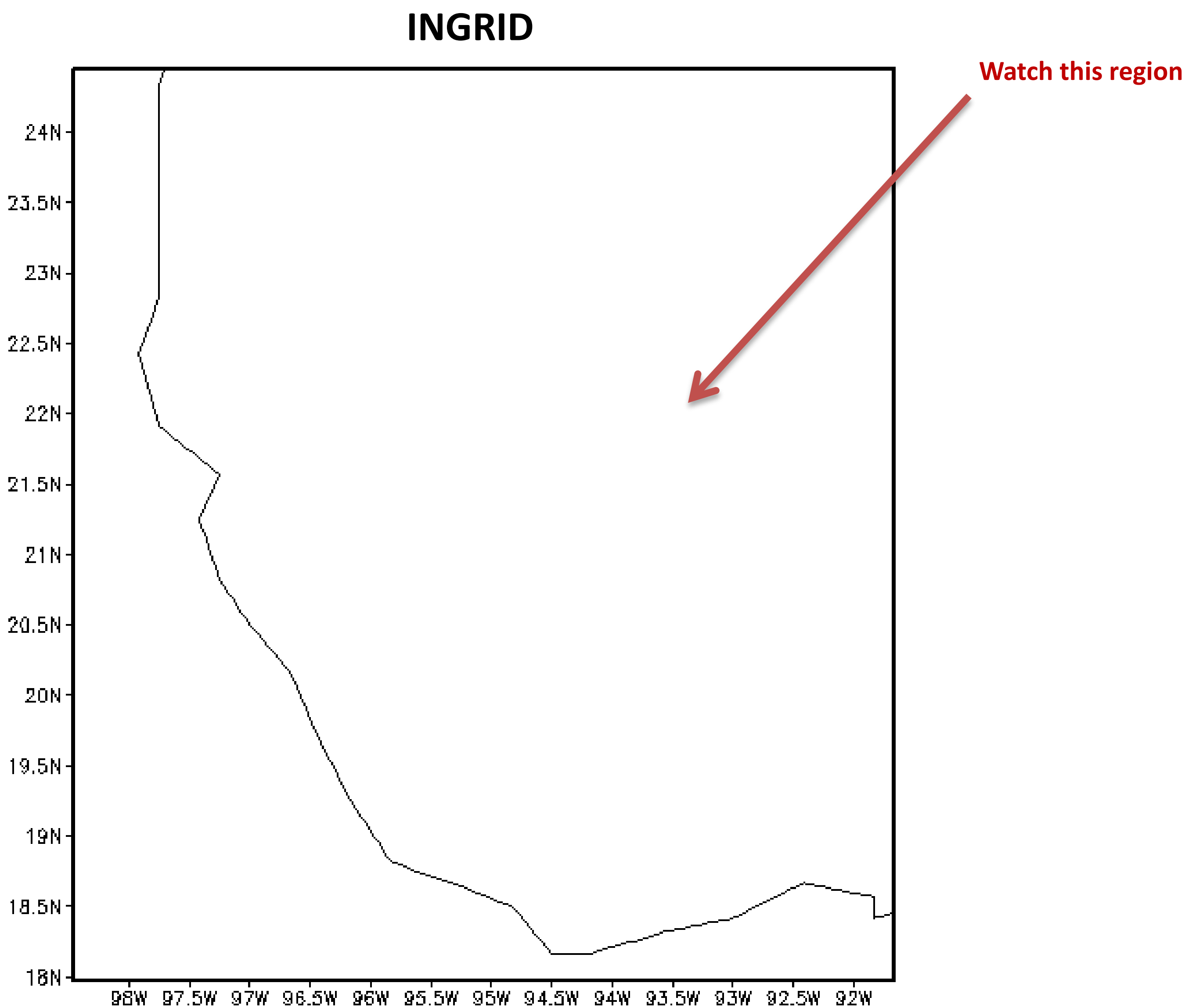
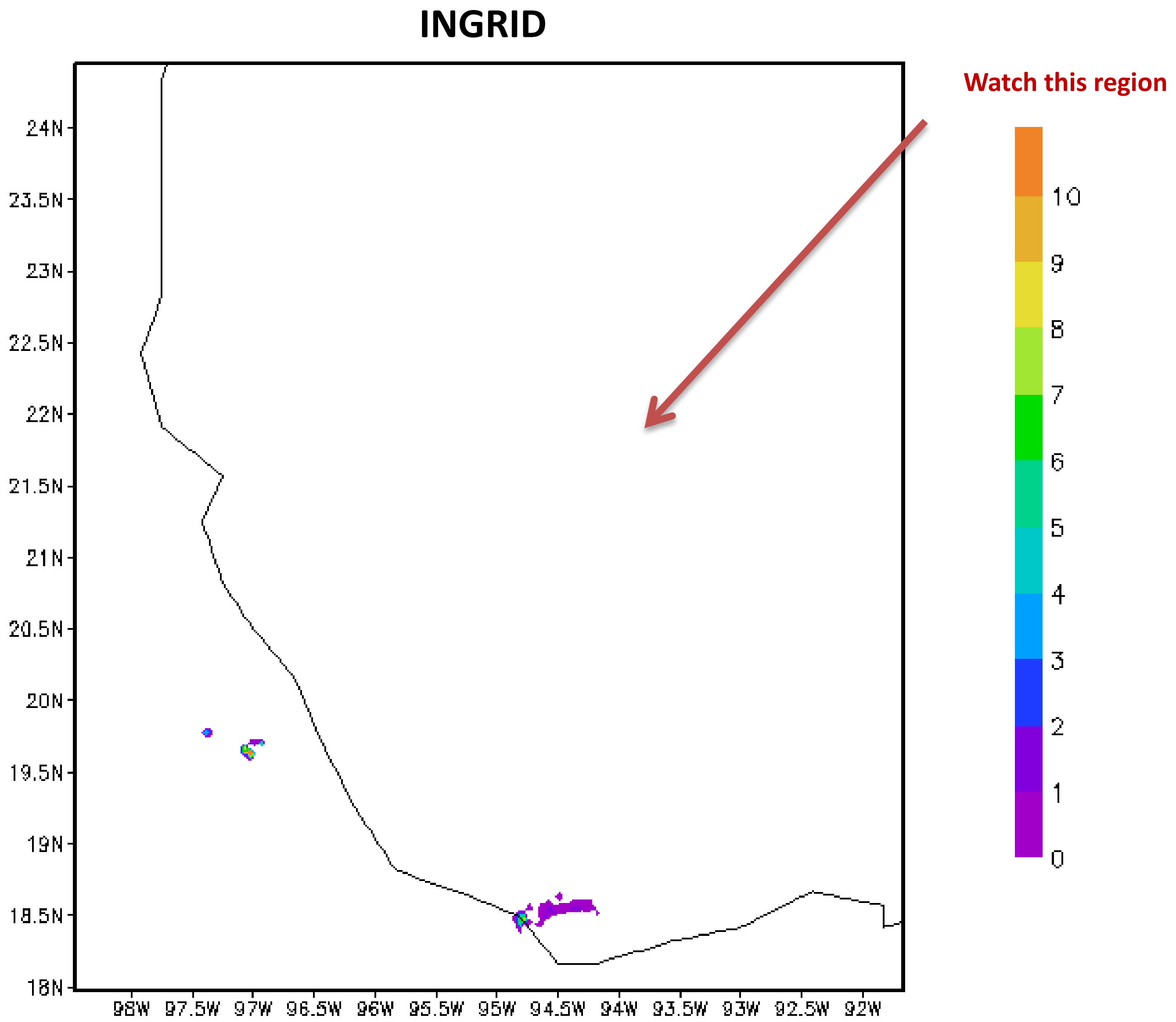



Image courtesy of the National Hurricane Center

# Buoyancy ($ms^{-2}$) INGRID CONTROL RUN

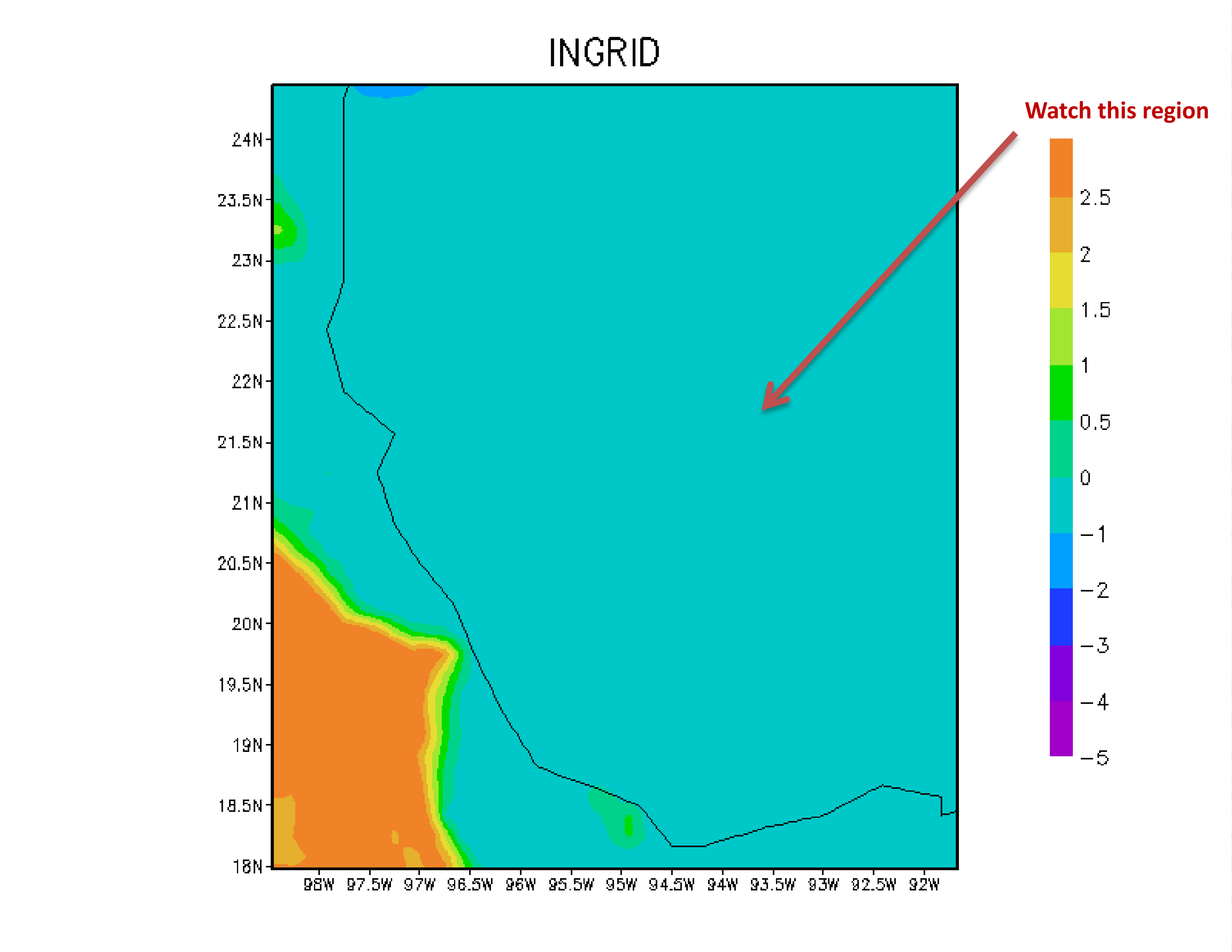


# Buoyancy ($ms^{-2}$) INGRID PHYSICAL INITIALIZATION



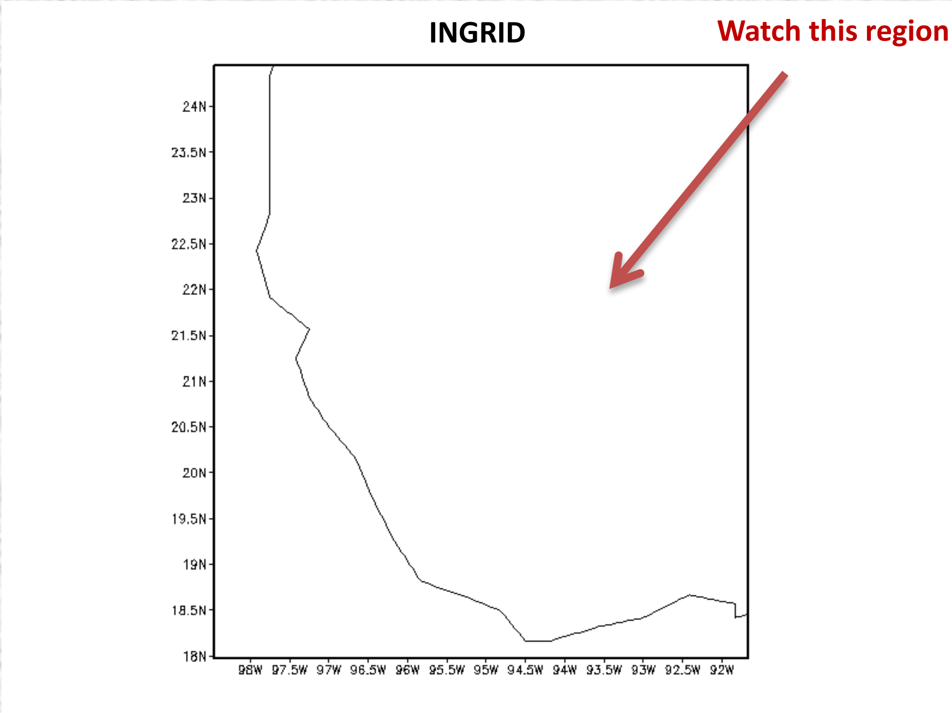
## Delta Q of Ingrid = Specific Humidity of Phy. init. - Specific Humidity of Control

Color scale g/kgm, moisture integrated between surface and 700 hPa

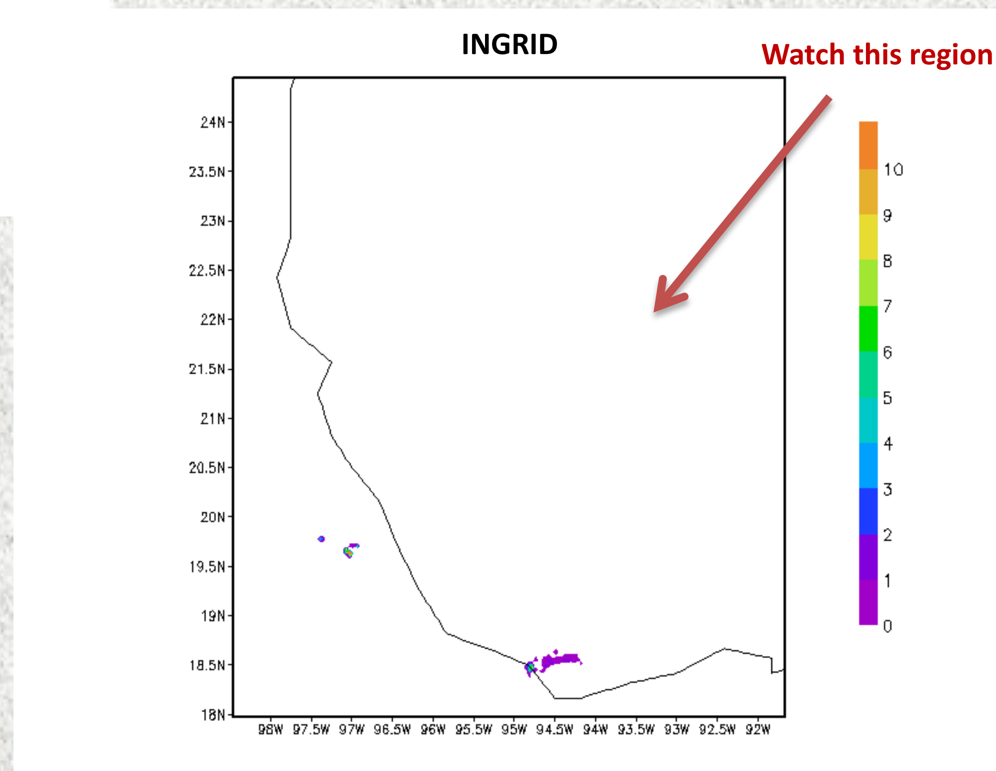



Click once on the image to start the animation

# Animation: Buoyancy $(m\ sec^{-2})$ for Ingrid Hurricane 15:00Z to 17:00Z Sept 2013 (Integrated, 950-500hPa)




Ingrid Control



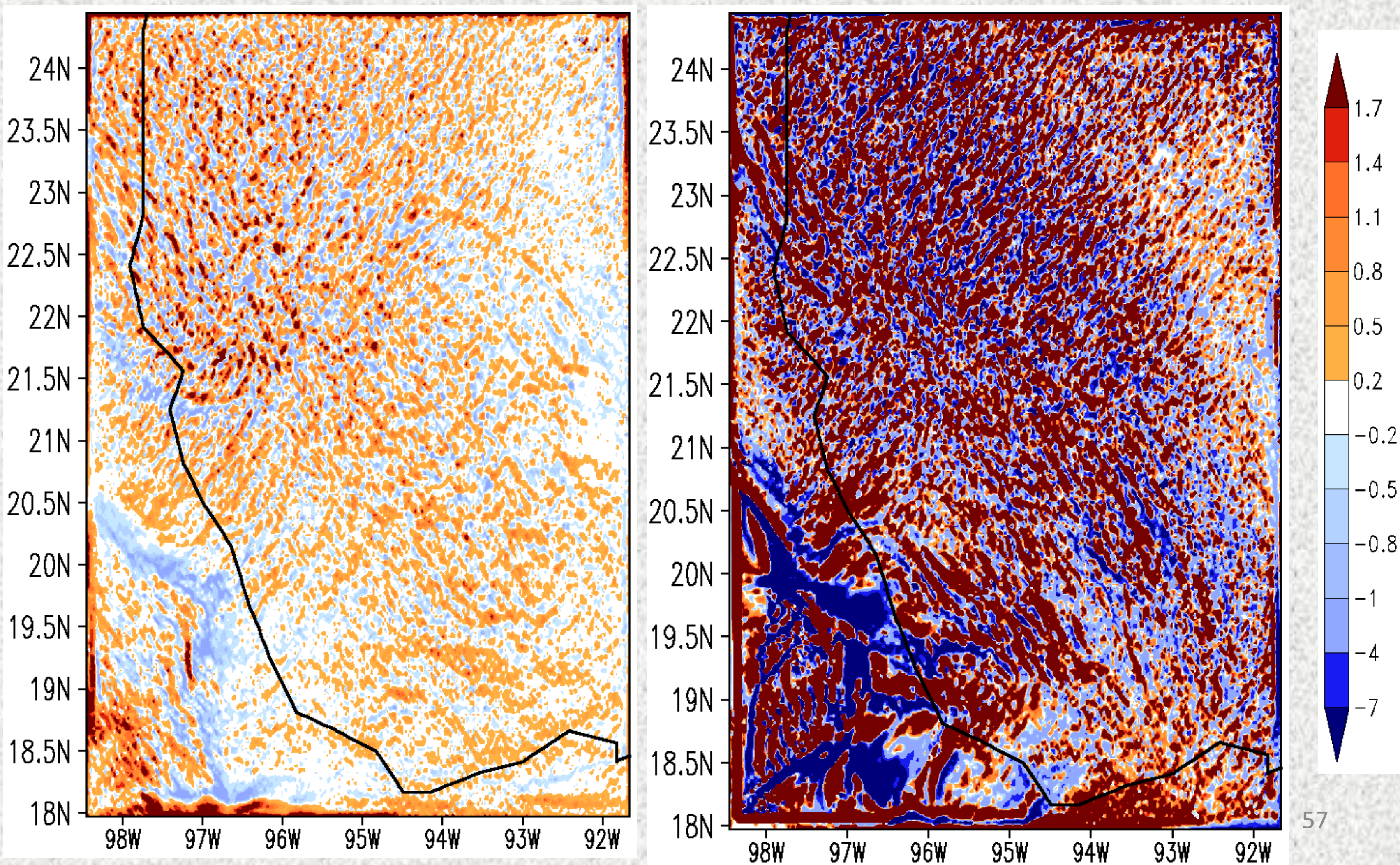

Ingrid Physical Init

Click once in the middle of picture to show animation

# HORIZONTAL CONVERFENCE OF FLUX OF BUOYANCY (*1E5) $-\nabla.BV$

**averaged for 15:00Z to 17:00Z Sept 2013 at 832mb : Unit: m sec$^{-3}$**

**Experiment** –> **Ingrid _Control** **Ingrid_Physical**

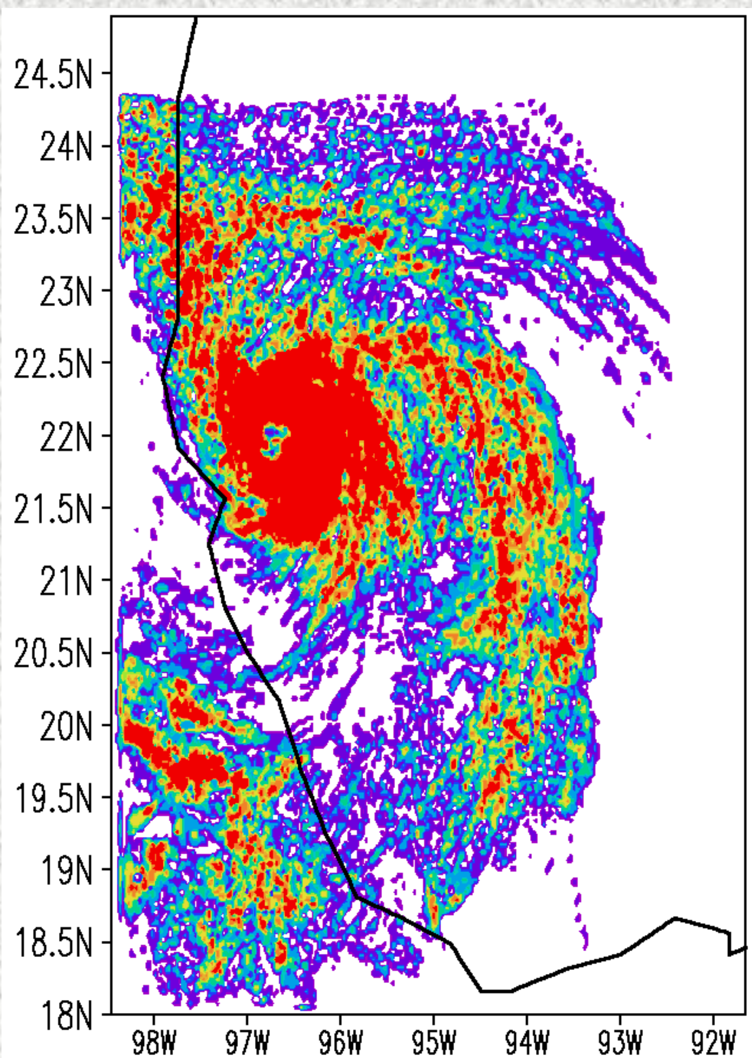


**Vertical advection of cloud's virtual temperature (*1E8)**

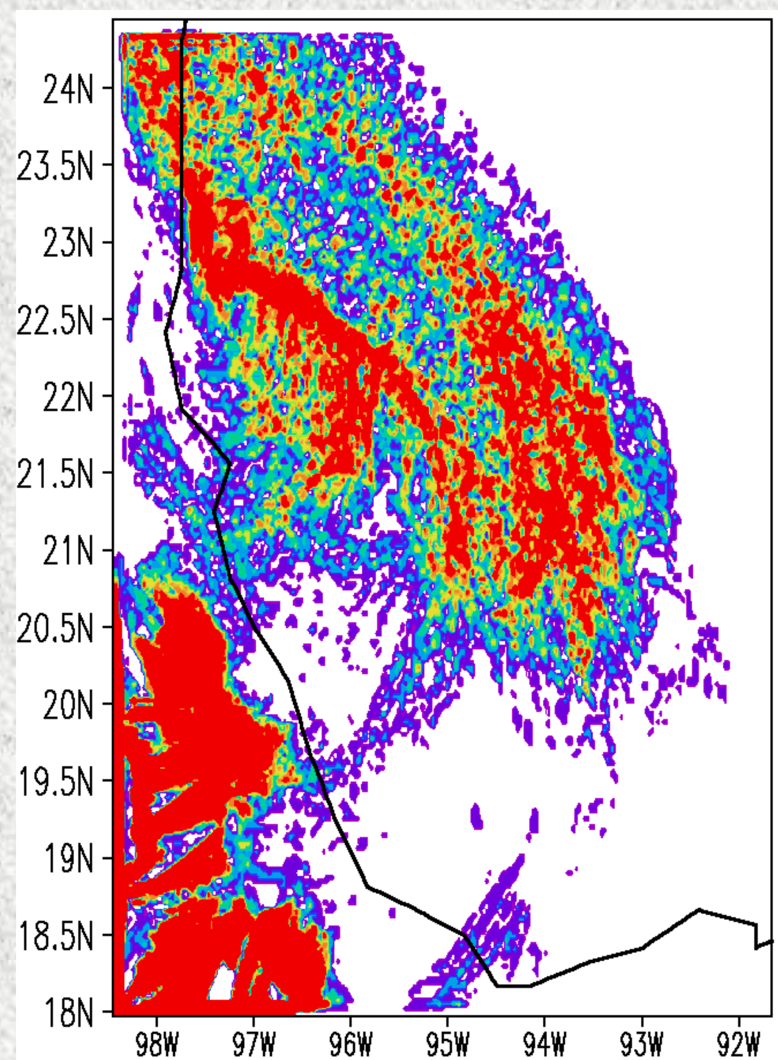
$$\frac{g}{\overline{T}_v} w \frac{\partial T_v'}{\partial z}$$

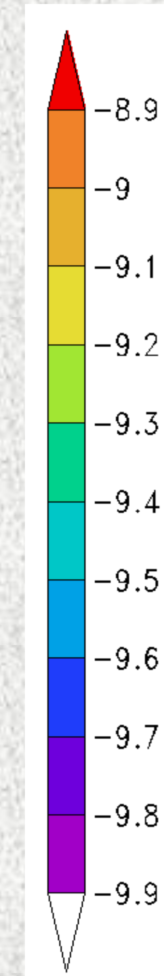
**averaged for 15:00Z to 17:00Z Sept 2013 at 832mb ;    Unit: m sec$^{-3}$**

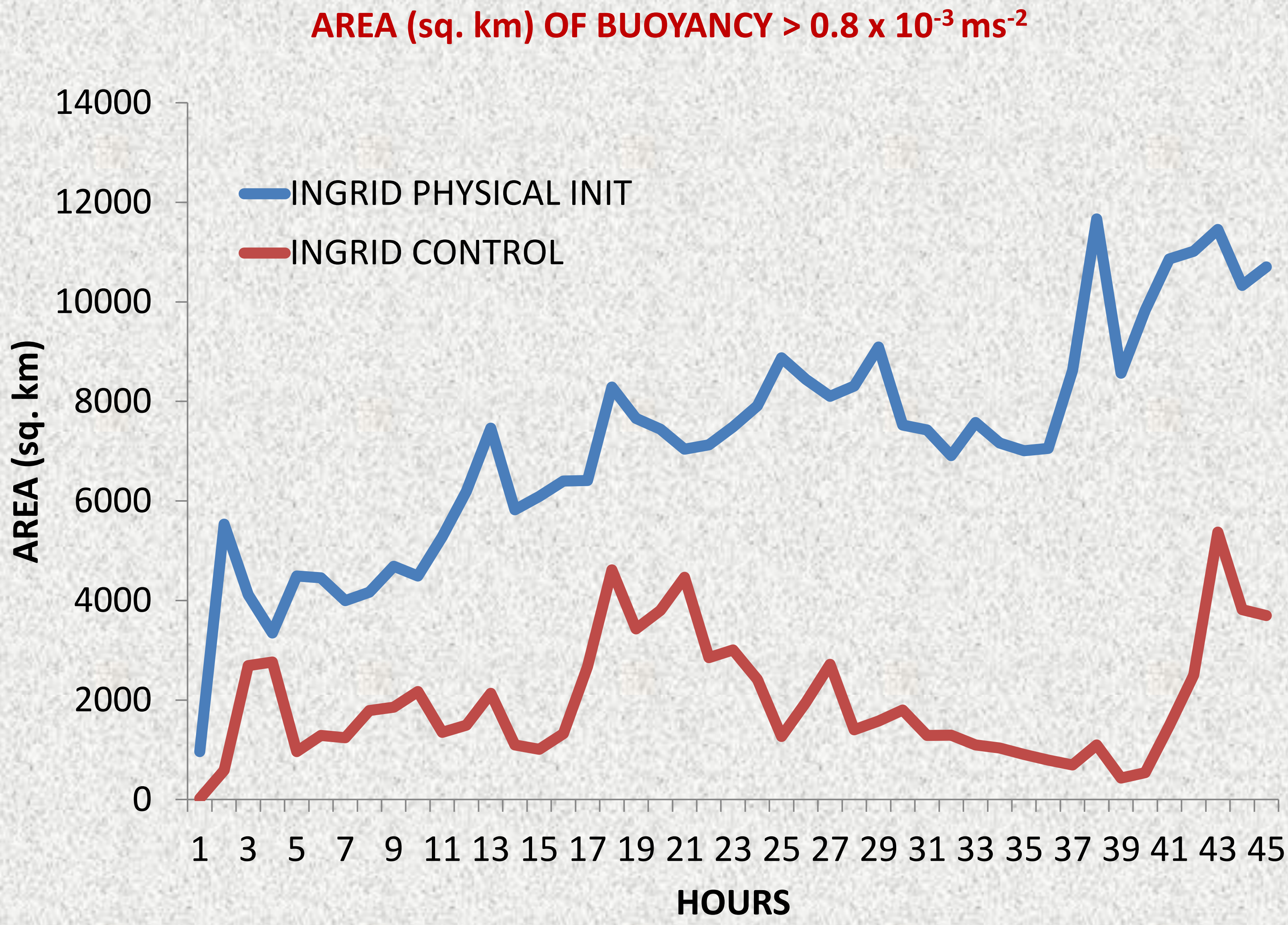
**Experiment → Ingrid_Control**




**Ingrid_Physical Init**




AREA (sq. km) OF BUOYANCY > 0.8 x 10-3 ms-2
14000
12000
10000
8000
6000
4000
2000
0
AREA (sq. km)
INGRID PHYSICAL INIT
INGRID CONTROL
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45
HOURS

# Hurricane Gabrielle

# TROPICAL STORM GABRIELLE TRACK

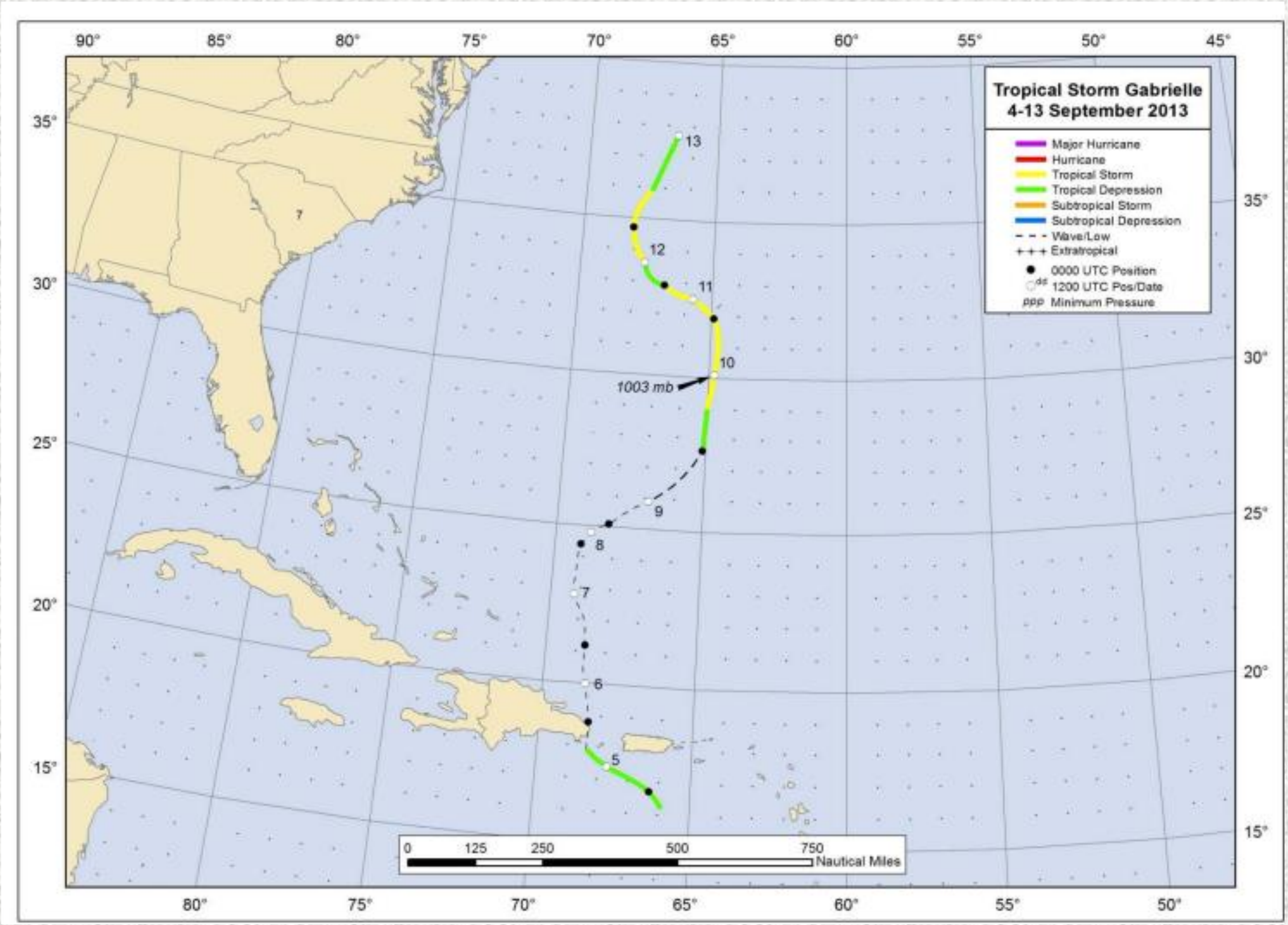



Image courtesy of the National Hurricane Center

# Tropical Storm Gabrielle Wind Speed

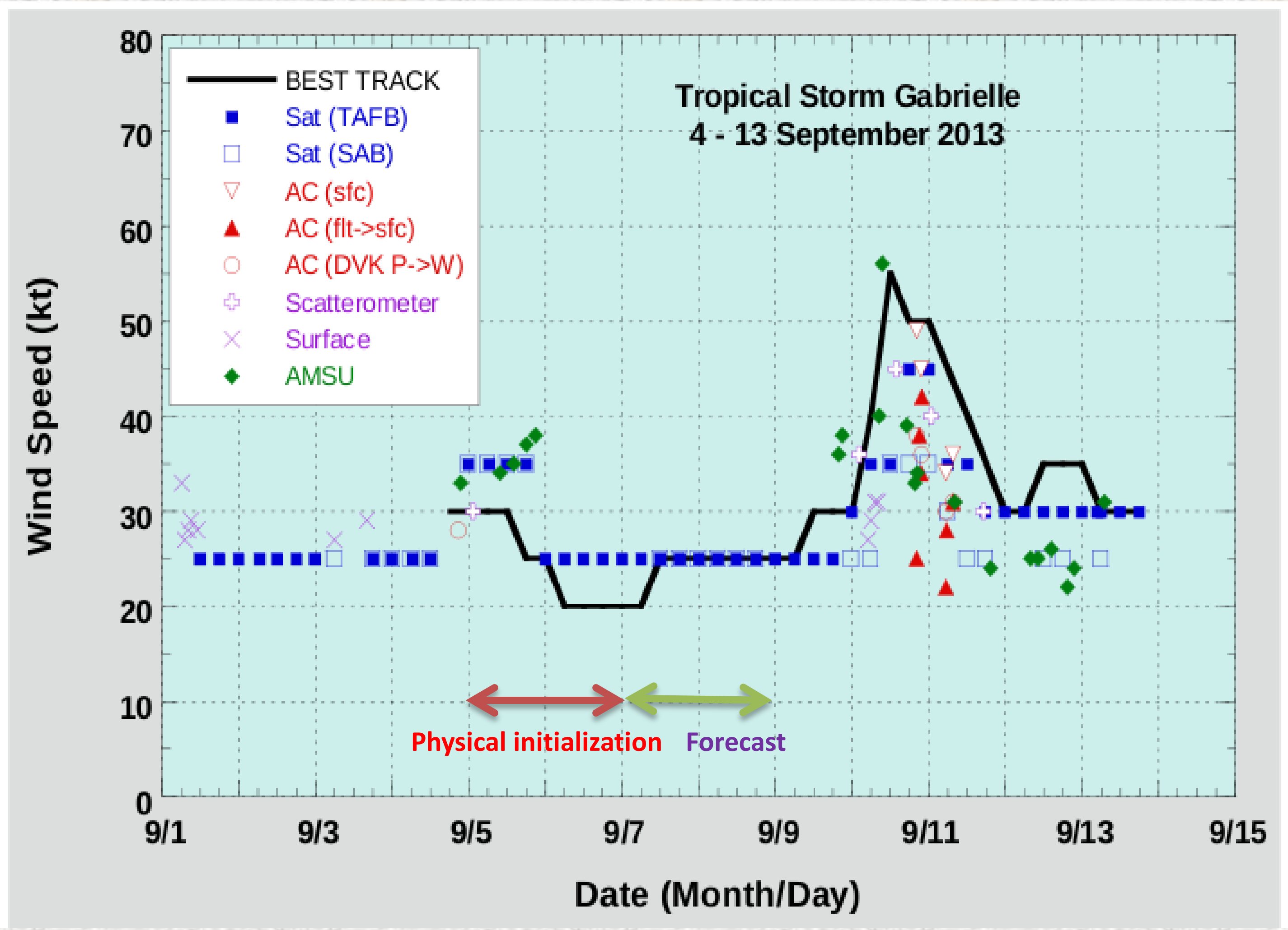



Image courtesy of the National Hurricane Center

# TROPICAL STORM GABRIELLE SEA LEVEL PRESSURE

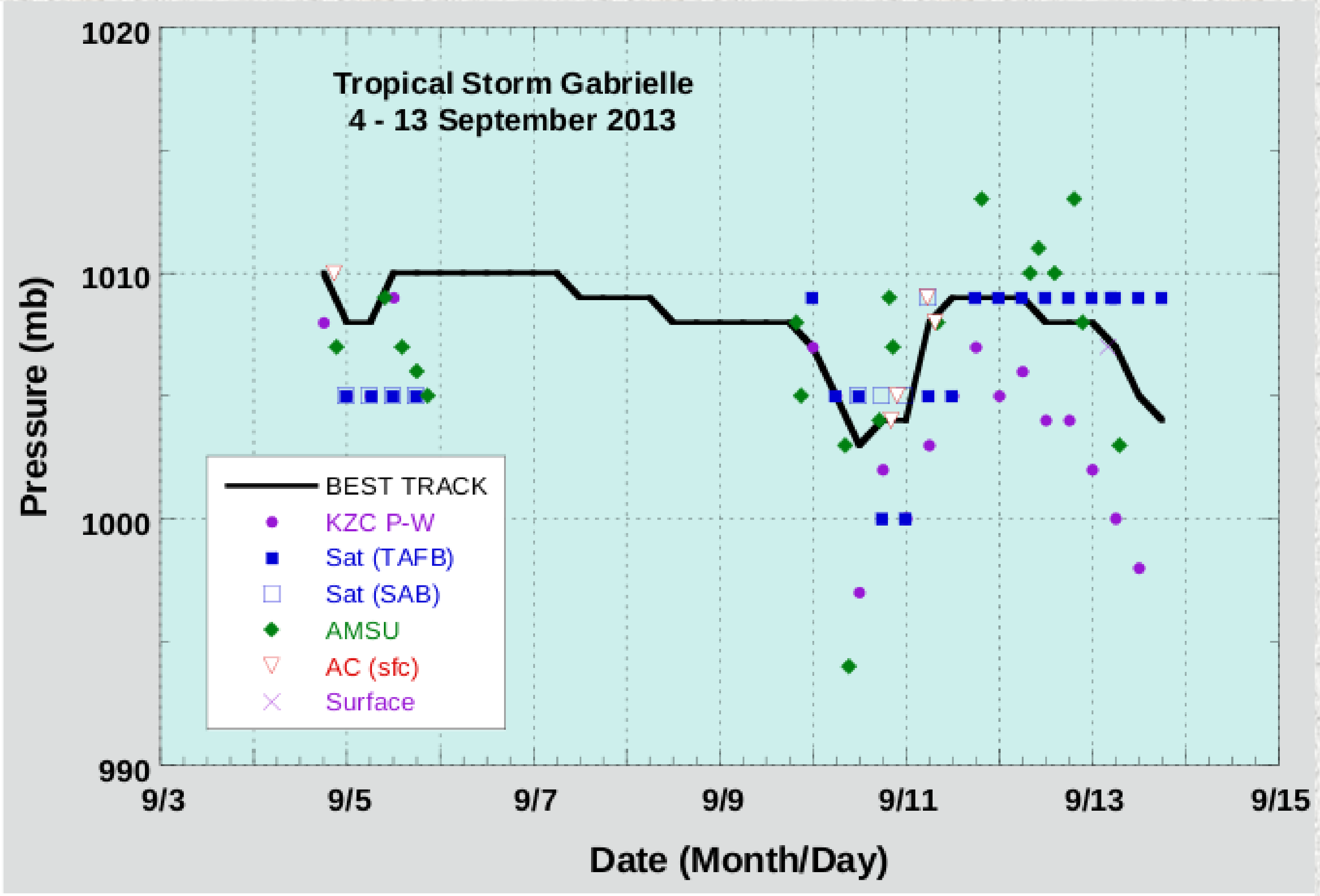
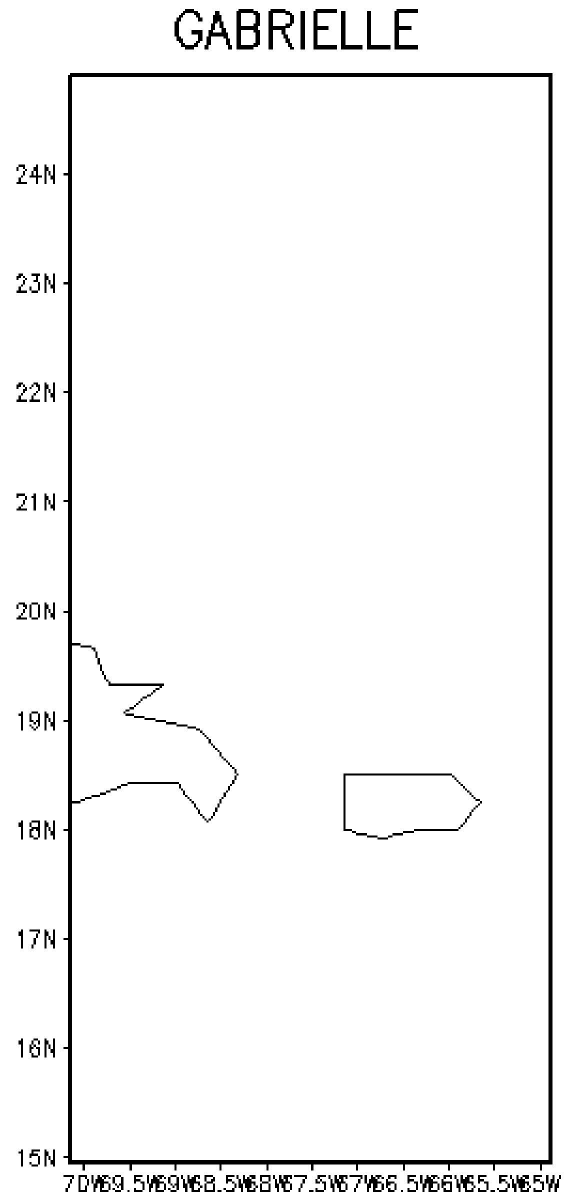
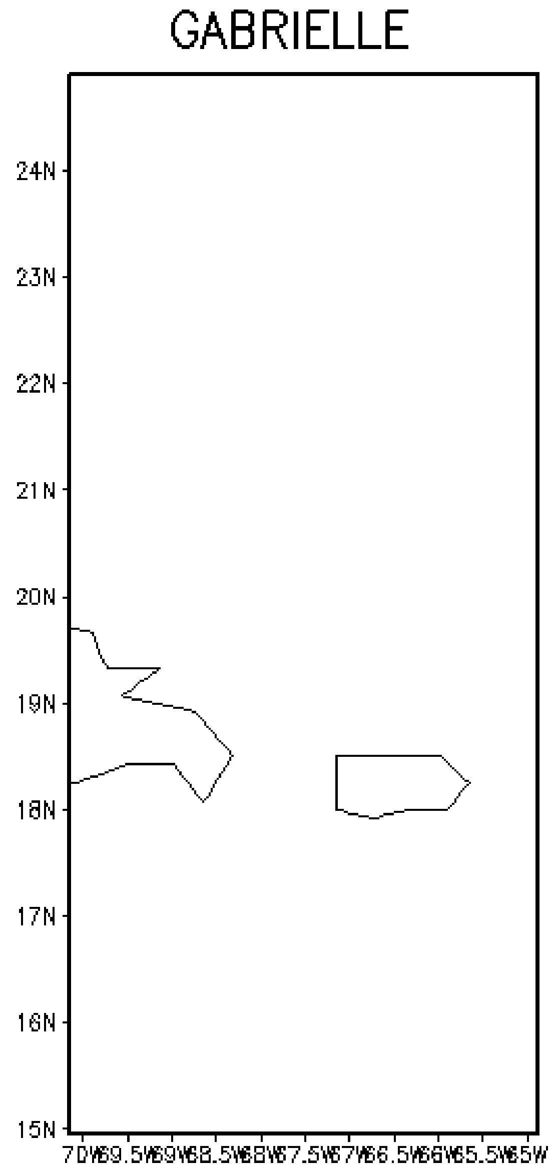



Image courtesy of the National Hurricane Center

# Buoyancy ($ms^{-2}$) GABRIELLE CONTROL RUN

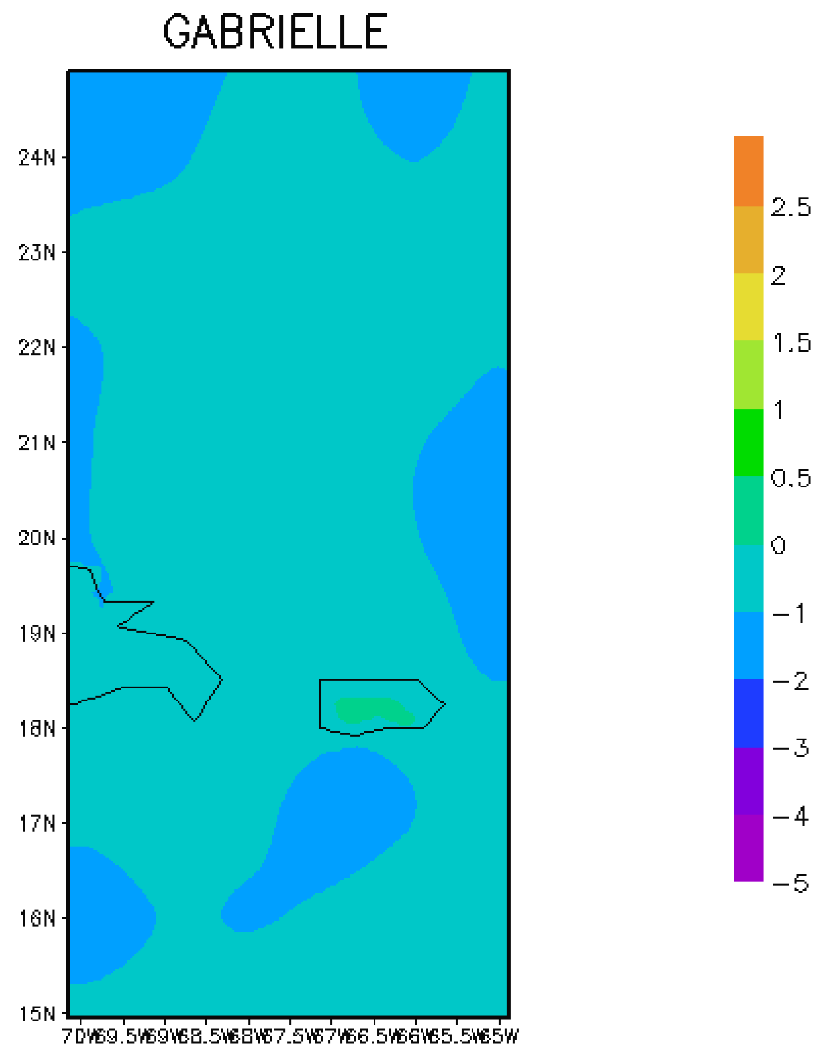


# Buoyancy ($ms^{-2}$) GABRIELLE PHYSICAL INITIALIZATION



# Delta Q of Gabrielle = Specific Humidity of Phy. init. - Specific Humidity of Control

**Color scale g/kgm, moisture integrated between surface and 700 hPa**

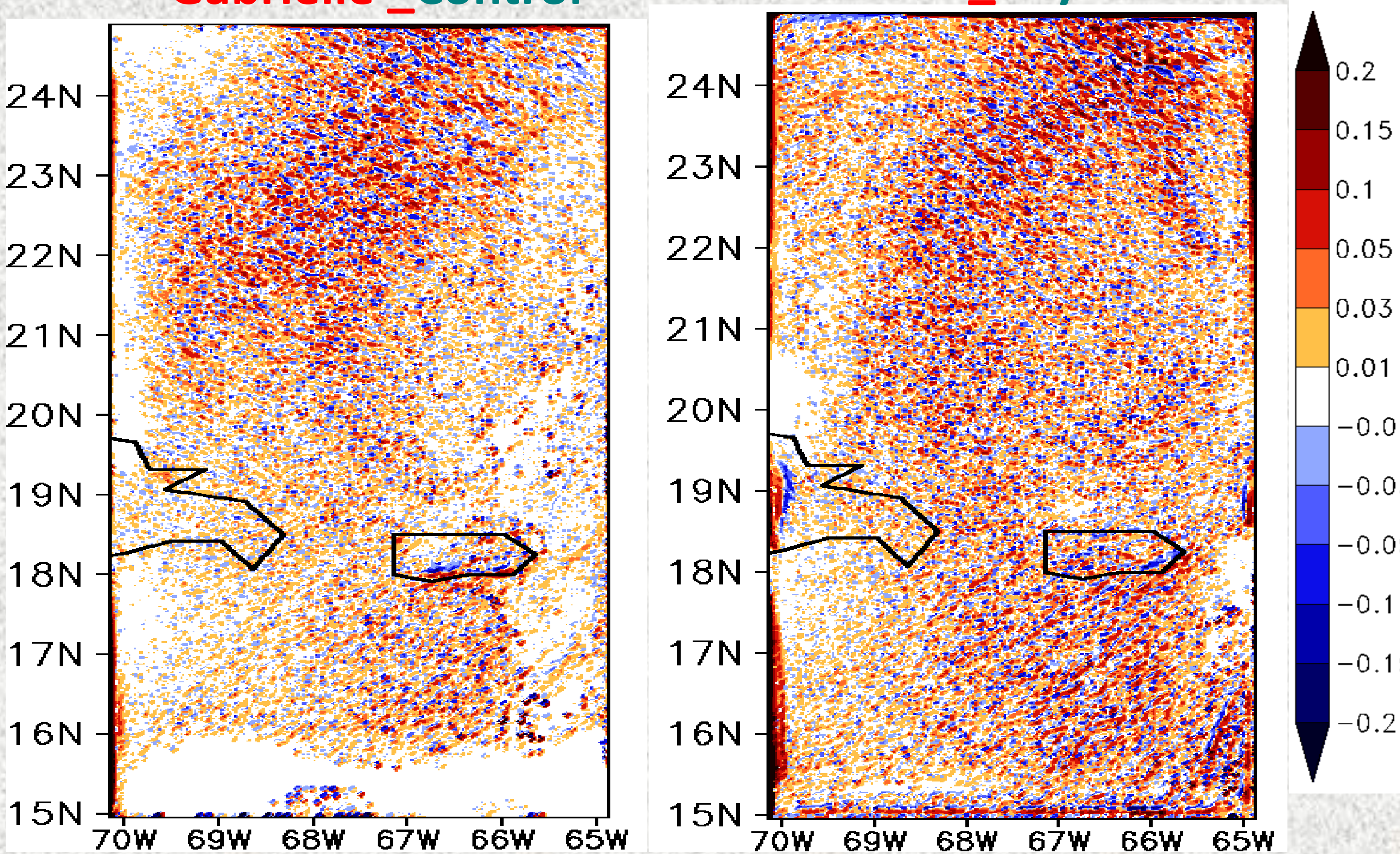



**Click once on the image to start the animation**

## HORIZONTAL CONVERFENCE OF FLUX OF BUOYANCY (*1E6) $-\nabla.BV$

**averaged for 7:00Z to 9:00Z Sept 2013 at 832mb; Unit: m sec$^{-3}$**

**Experiment** → **Gabrielle _Control** **Gabrielle _Physical Init**

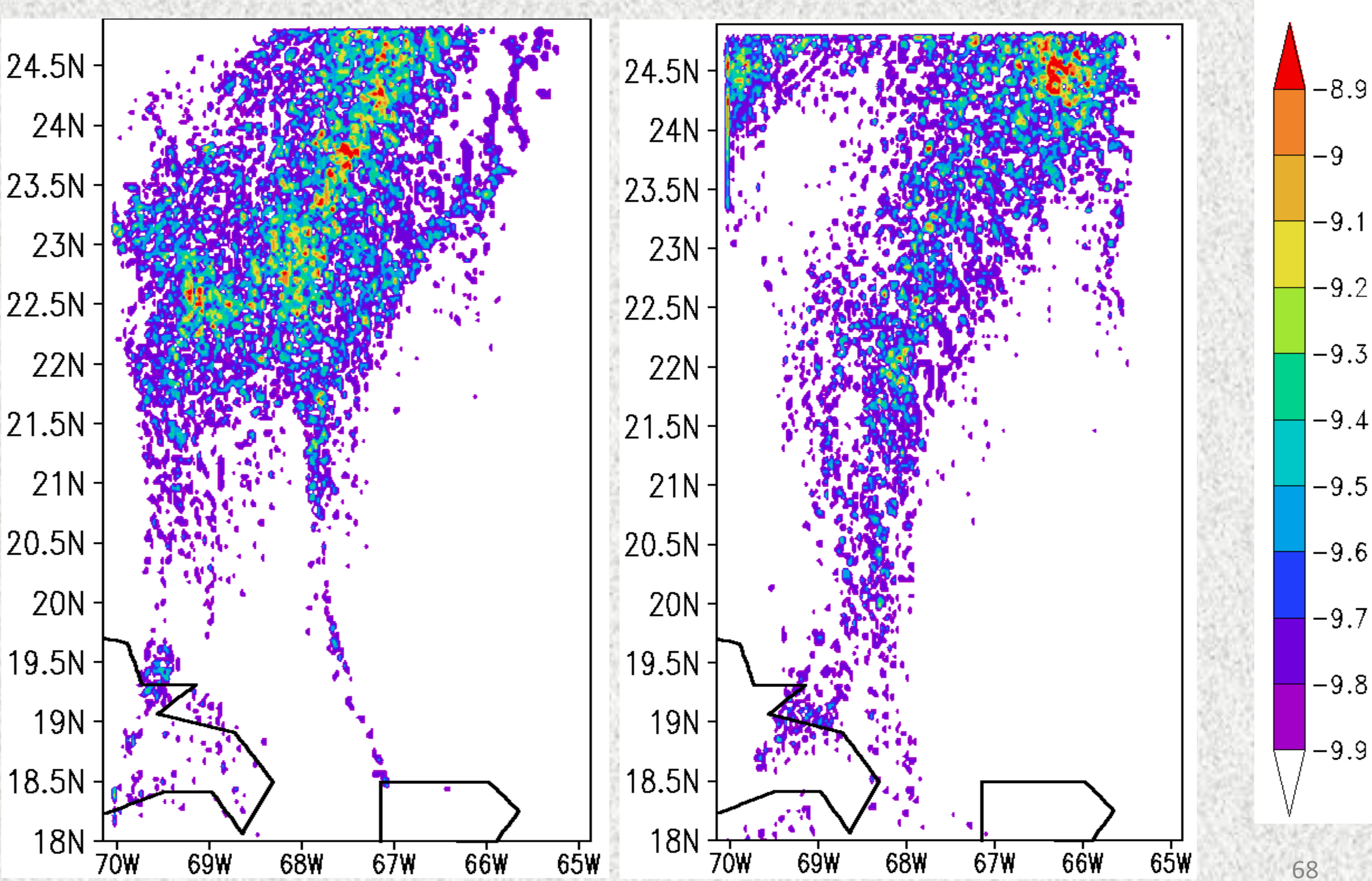


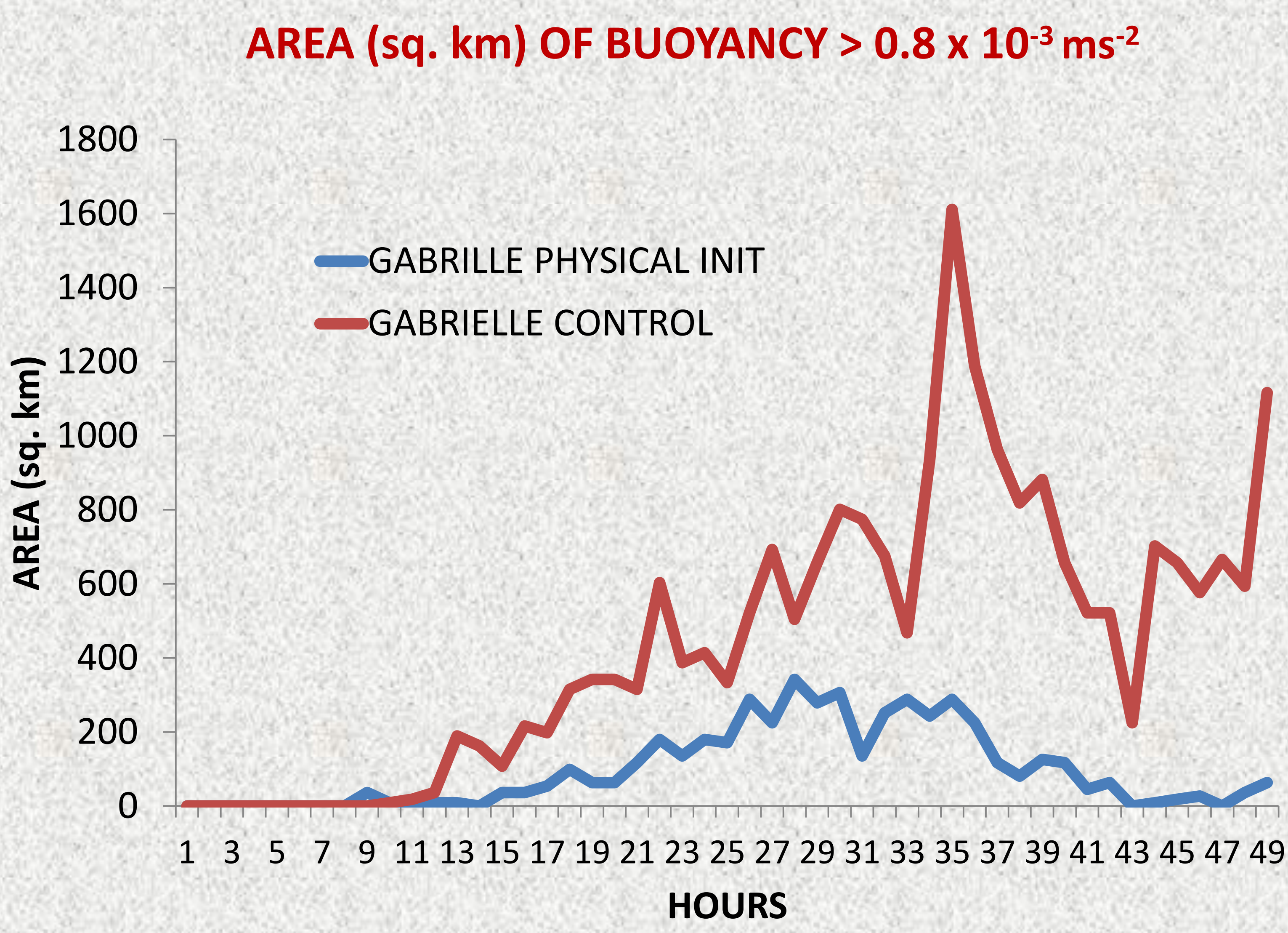
**Vertical advection of cloud's virtual temperature (*1E8)**

$$\frac{g}{\overline{\overline{T}}_v} w \frac{\partial T_v'}{\partial z}$$

**averaged for 7:00Z to 9:00Z Sept 2013 at 832mb; Unit: m sec$^{-3}$**

**Experiment** → **Gabrielle _Control** **Gabrielle _Physical Init**




AREA (sq. km) OF BUOYANCY > 0.8 x 10-3 ms-2
GABRILLE PHYSICAL INIT
GABRIELLE CONTROL
AREA (sq. km)
HOURS
0
200
400
600
800
1000
1200
1400
1600
1800
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 41 43 45 47 49

# CONCLUDING REMARKS

1. THIS RESEARCH STEMS FROM PREVIOUS WORK WE HAVE COMPLETED ON PHYSICAL INITIALIZATION AND LASE DATA IMPACTS ON HURRICANE FORECASTS IN REFERENCE TO THE SENSITIVITY TO THE MOISTURE FIELD.

2. THIS WORK STARTED WITH THE STUDIES OF MONSOON DEPRESSIONS WHERE WE IMPLEMENTED A NEAR RADAR RESOLUTION PHYSICAL INITIALIZATION. MAJOR IMPROVEMENTS .

3. FOR HURRICANES MAKING LANDFALL WE FOUND THAT RAIN RATE INITIALIZATION (VIA PHYSICAL INITIALIZATION) NEAR RADAR RESOLUTION RAINS, IMPROVES THE NOWCASTING AND ESPECIALLY THE DAY 1 FORECAST SKILLS. ( THIS WAS SHOWN FOR GRIP HURRICANE KARL, TROPICAL CYCLONE THANE OF 2011 OVER NORTH INDIAN OCEAN, HURRICANE IRENE OVER THE NEW ENGLAND COASTAL AREA ,2011). PHYSICAL INITIALIZATION HELPS TO IMPROVE SKILLS OF DAY 2$^{nd}$ AND 3$^{rd}$ FOR HURRICANE FORECASTS.

4. THIS SAME WORK WAS FOLLOWED FOR AN EXTREME RAIN EVENT ( 370 MM/DAY RAINS) OVER UTTARAKAND NEAR HIMALAYAS IN INDIA. THAT WORK SUPPORTED BY ADAPTIVE OBSERVATIONAL STRATEGY SUGGESTED THE NEED FOR MOISTURE OBSERVATIONS. THAT STUDY SHOWED A GREAT SENSITIVITY TO MOISTURE FOR THE EVOLVING HISTORY OF CLOUDS, RAINS AND ESPECIALLY THE LIQUID WATER MIXING RATIOS AND BUOYANCY. BUOYANCY CAN BE REGARDED AS A FIELD VARIABLE.IF MOISTURE DATA ARE IMPROVED THEN THE FORECASTS SHOW AN ARMY OF BUOYANCY ELEMENTS COVERING A LARGER AREA MOVE TOWARDS THE HIMALAYAS AND GIVING RISE TO EXTREME RAINS ( AROUND 370 MM/DAY) FOR THE EXPERIMENT WITH PHYSICAL INITIALIZATION.

5. THE SAME IDEA WAS EXTENDED TO TWO HS3  STORMS, NAMED INGRID AND Gabrielle OF 2013.

6. INGRID STRENGTHENED INTO A HURRICANE OF CATAGORY XX PRIOR TO LANDFALL. WHEREAS GABRIEL REMAINED A WEAK STORK AND WEAKENED DURING OUR FORECAST PERIODS.

7 PHYSICAL INITIALIZATION REVEALED MAJOR DEFICIENCIES IN MOISTURE ANALYSIS OF THE INITIAL STATES FOR INGRID AND GABRIEL. PHYSICAL INITIALIZATION IMPROVED THE MOISTURE ANALYSIS SOMEWHAT.

8. THAT IMPROVEMENT CALLED FOR AN ENHANCEMENT OF BOUNDARY LAYER MOISTURE, ESPECIALLY ON A SOUTHEASTERN RAINBAND OF INGRID  AND RESULTING IN IMPROVED FORECASTS OF INTENSITY AND RAINS .HOWEVER IN GABRIEL THE OPPOSITE TYPE OF ERROR WAS NOTED  THIS RESULTED INA REDUCTION OF BOUNDARY LAYER MOISTURE  BY THE PHYSICAL INITIALIZATION THAT KEPT  GABRIEL AS A WEAK STORM DURING ITS FORECAST PERIOD.

9. ADAPTIVE OBSERVATIONAL STRATEGIES IN  HURRICANES FOR OBSERVATIONS AND MODELING MAY STILL BE WORTH EXPLORING ESPECIALLY FOR MOITURE DISTRIBUTIONS THAT HAVE A GREAT IMPACT ON THE BUOYANCY DISTRIBUTIONS.