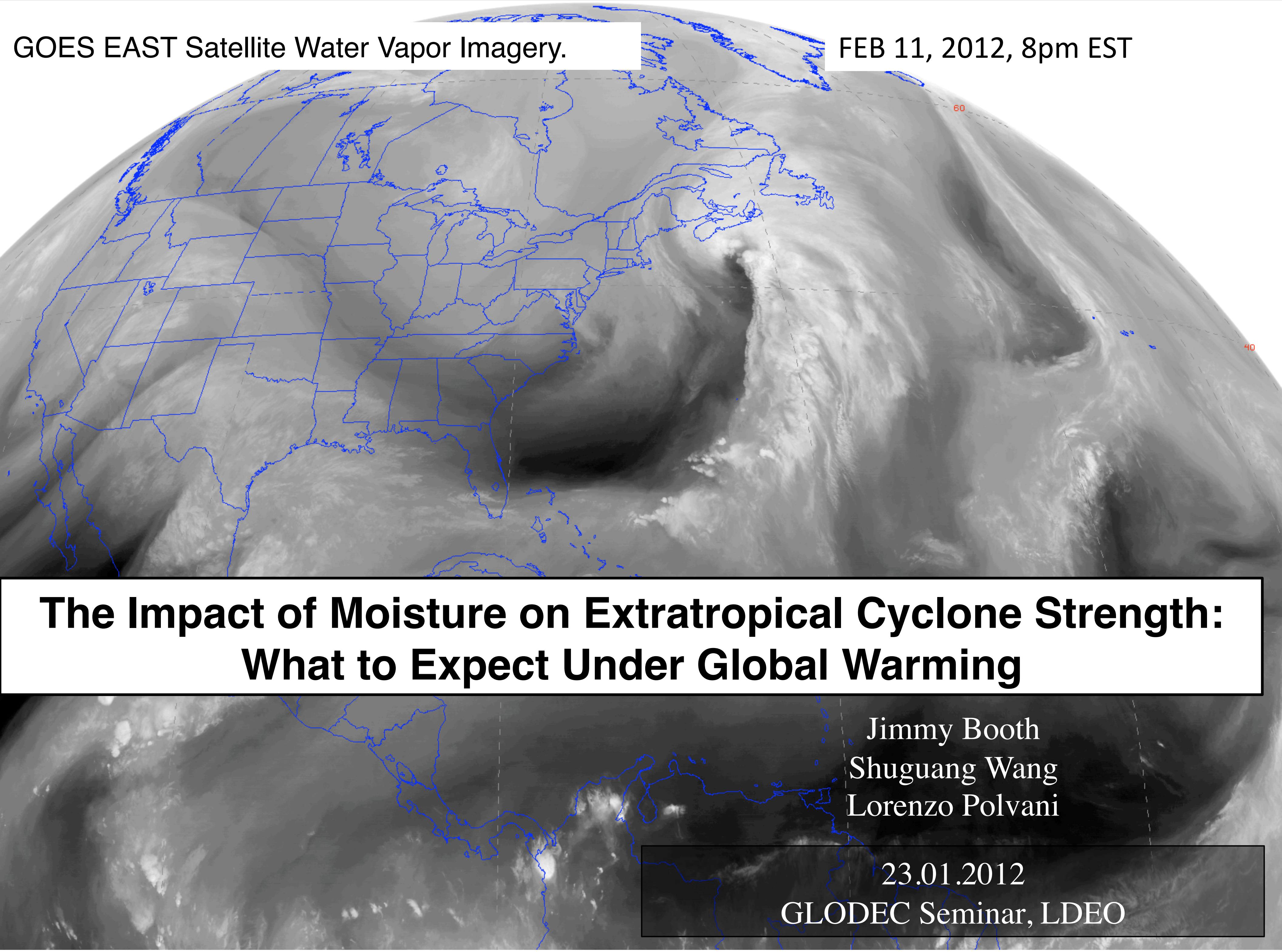
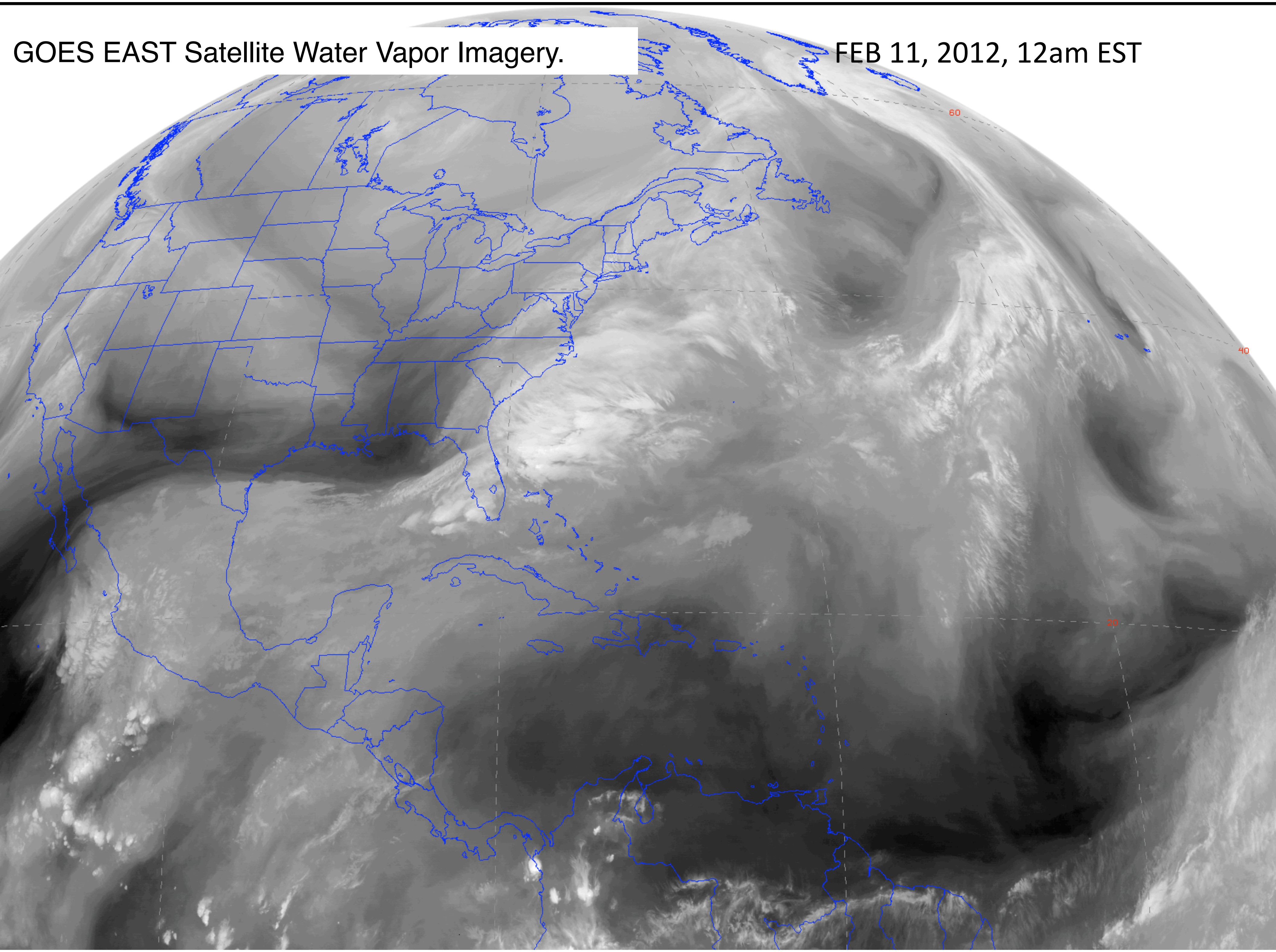


GOES EAST Satellite Water Vapor Imagery. FEB 11, 2012, 8pm EST

The Impact of Moisture on Extratropical Cyclone Strength: What to Expect Under Global Warming

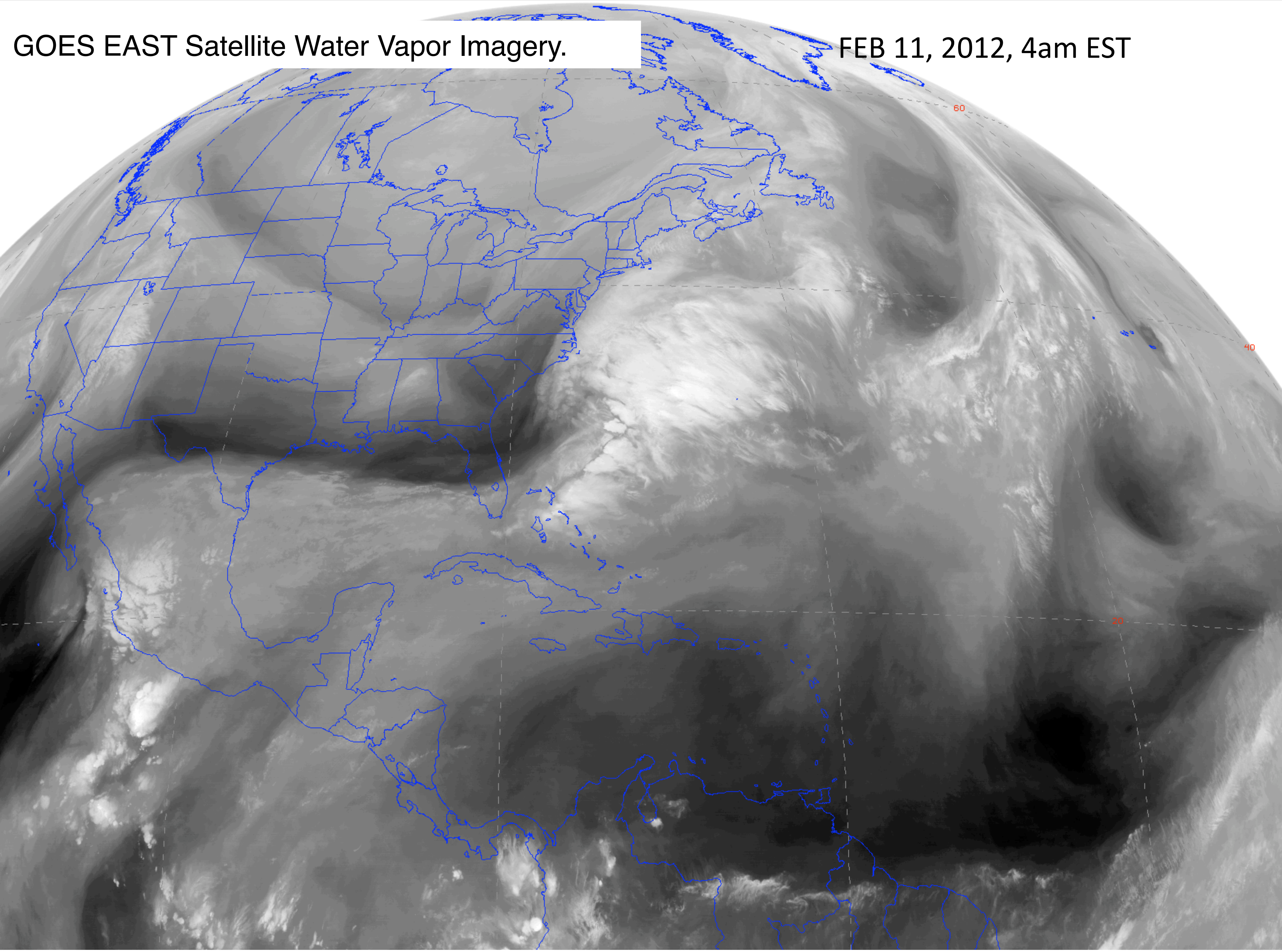
Jimmy Booth
Shuguang Wang
Lorenzo Polvani

23.01.2012
GLODEC Seminar, LDEO


GOES EAST Satellite Water Vapor Imagery.
FEB 11, 2012, 12am EST

GOES EAST Satellite Water Vapor Imagery.

FEB 11, 2012, 4am EST



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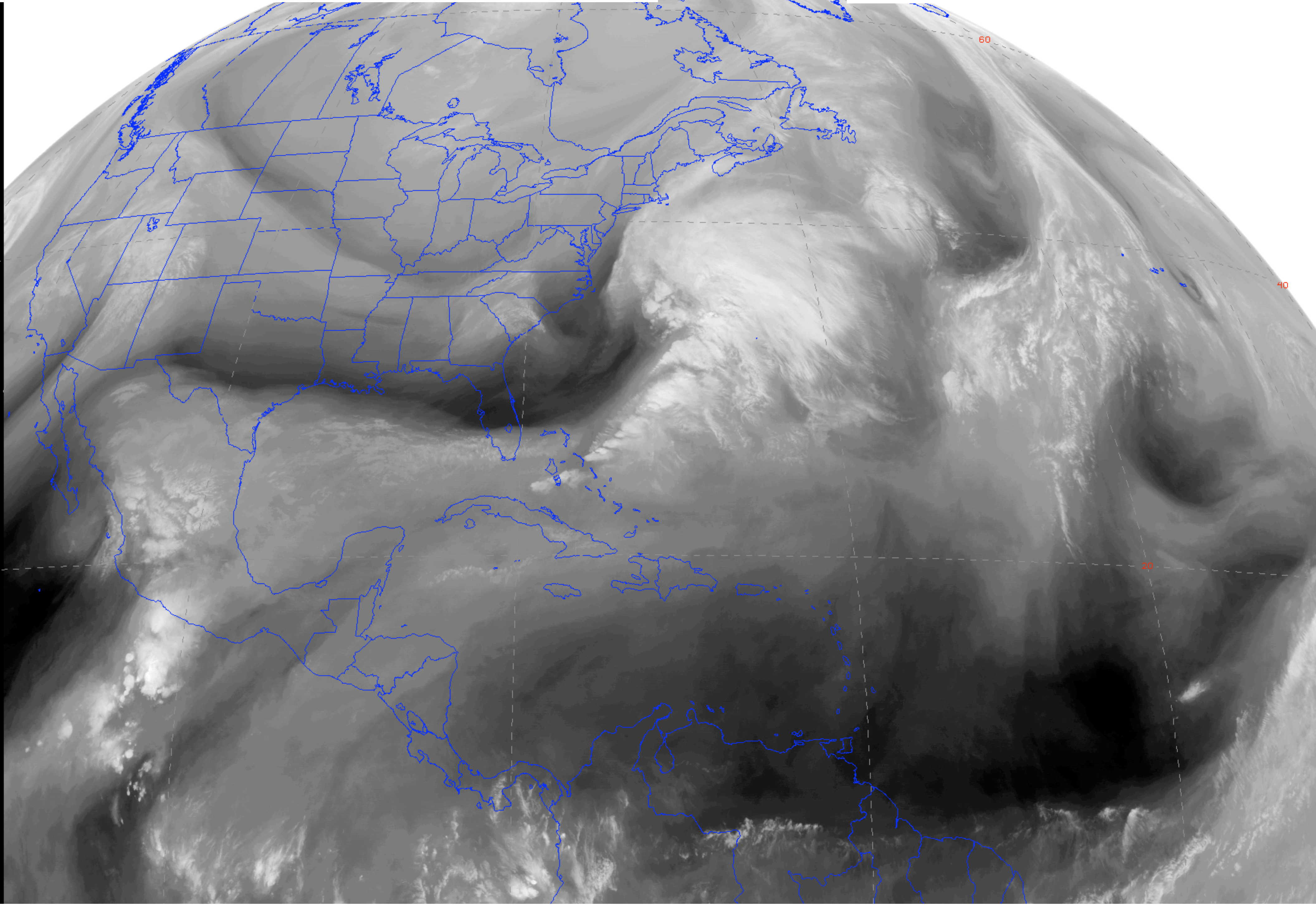

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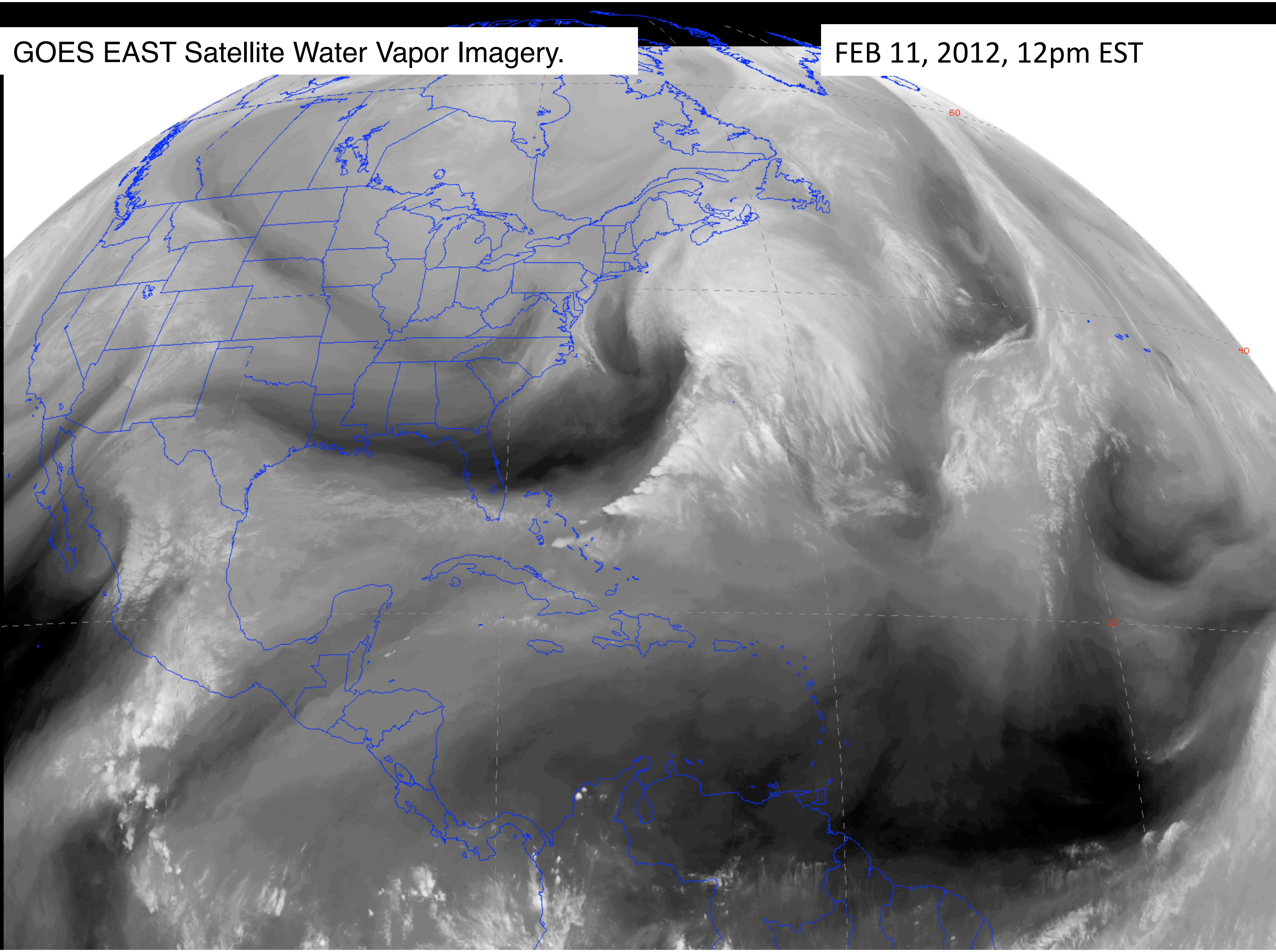

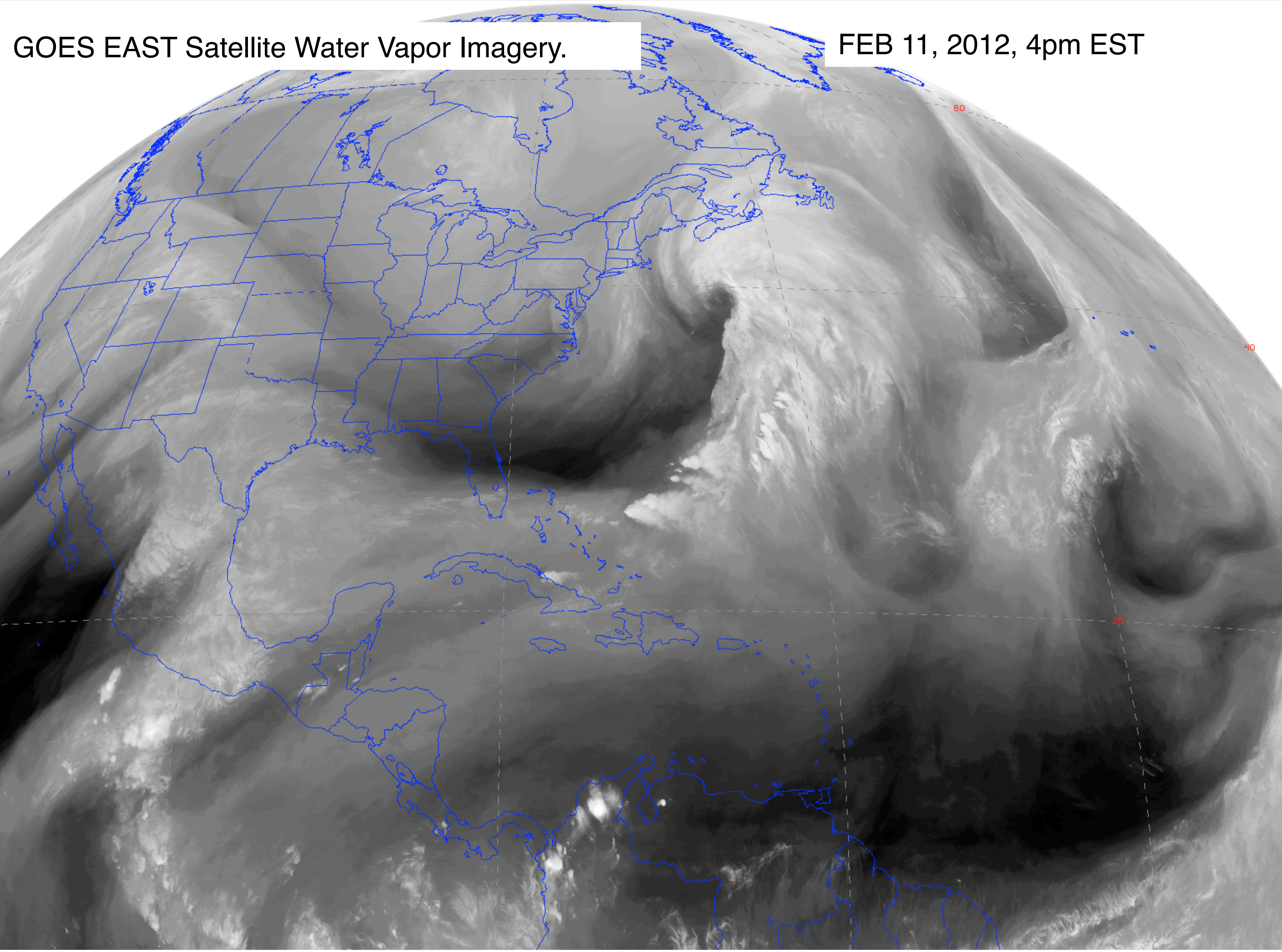
GOES EAST Satellite Water Vapor Imagery.
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GOES EAST Satellite Water Vapor Imagery.

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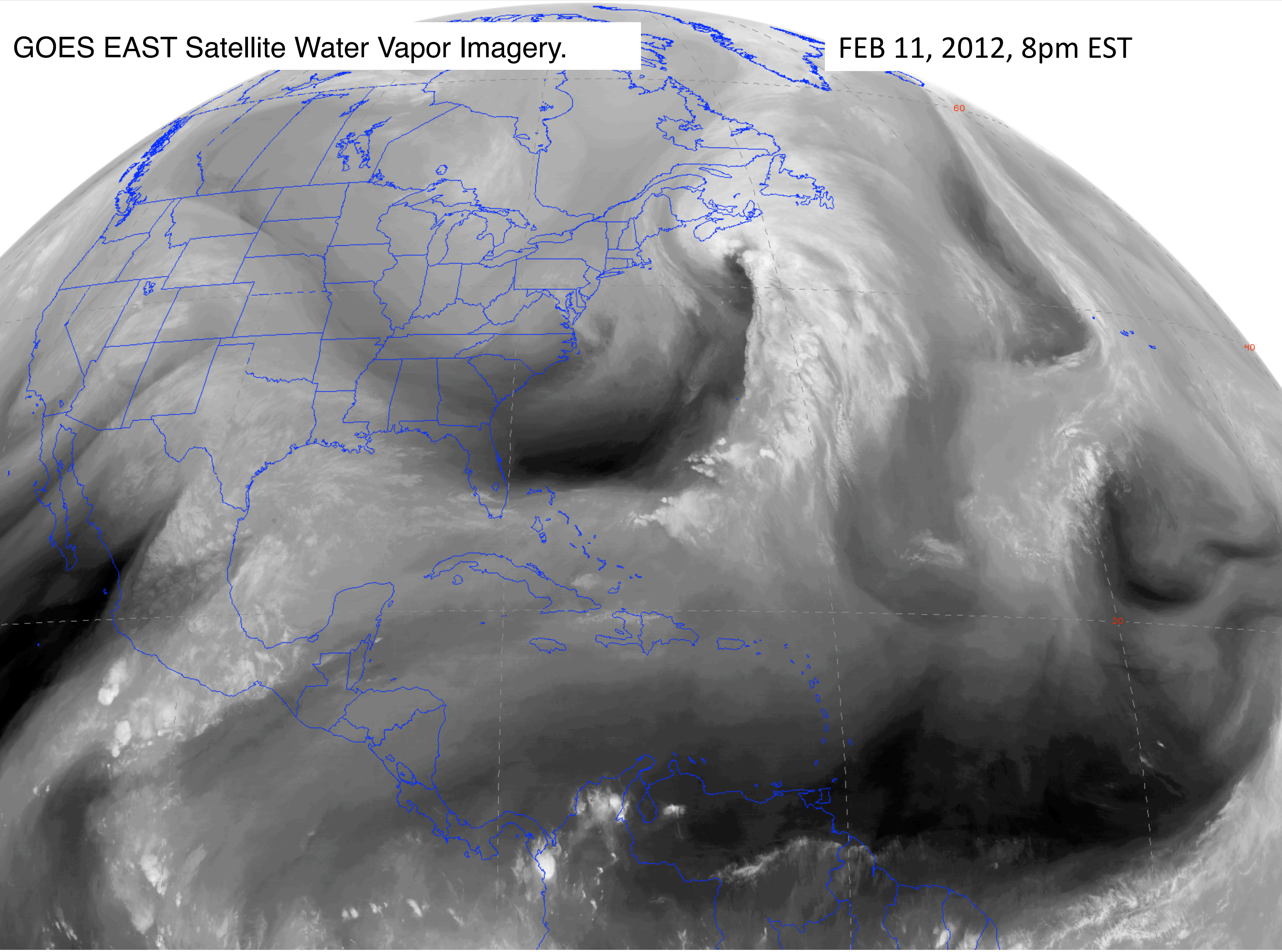


What is an extratropical cyclone?

From Personal Experience:

Wintertime storms in the Northeast.

Characteristics:

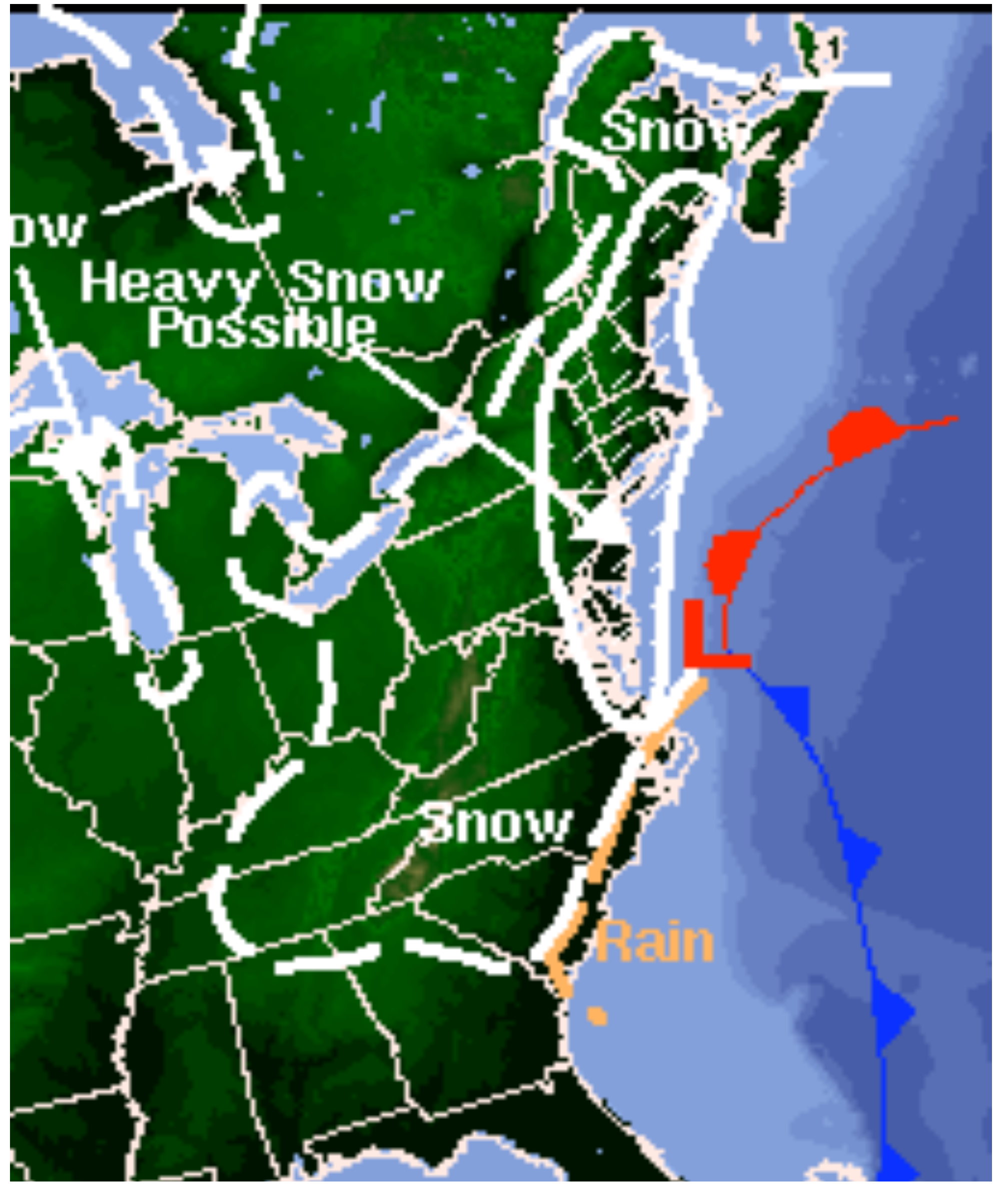
- low pressure center
- warm and cold front
- abundance of rain and/or snow

From Theory:

Circulation response to *baroclinic instability* (*Meridional Temperature Gradient*).

hence: baroclinic life cycles.

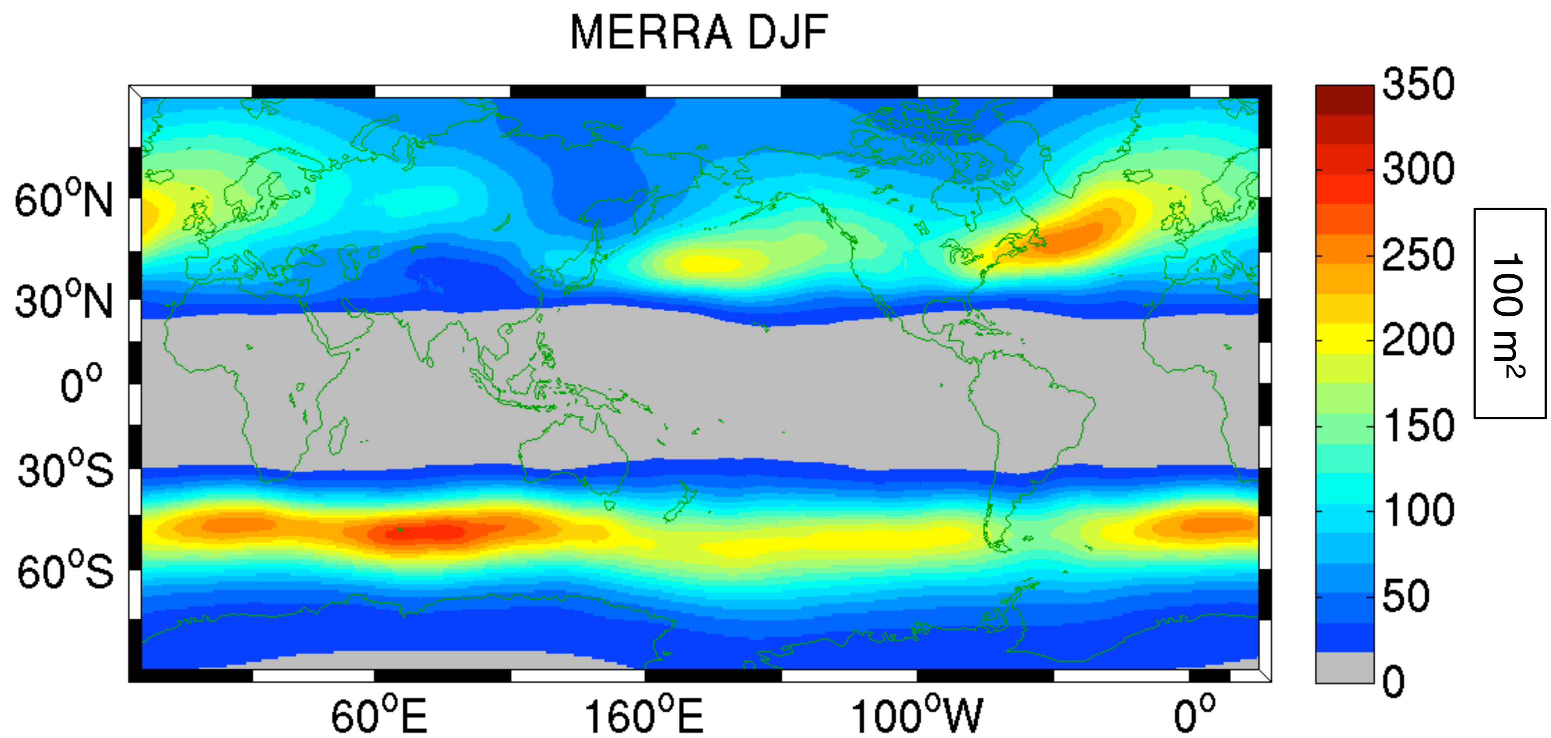
Forecast for Dec. 26, 2010



http://www.hpc.ncep.noaa.gov/noaa/noaa_archive.php

Introduction: Extratropical Cyclones and Climate

Climatological Storms Tracks, i.e., Baroclinic Wave Activity



Variance of time-filtered 250 hPa Geopotential Height
(time filtered to isolate synoptic variability)

Storm Track Analysis examines the cumulative affect of storms.

Today I will focus on the individual storms.

What will happen to midlatitude storms in a warmer world?

How will components of the atmosphere that influence storms change with global warming?

(1) dT_{SURF}/dy decreases :: less low-level baroclinicity.

**Wu et al., 2011: upper-level baroclinicity increases.*

(2) Low-level atmospheric water vapor increases.

Using PV thinking to understand the influence of moisture

$$\text{(1)}\quad PV = -g(\zeta_\theta + f)\left(\frac{\partial\theta}{\partial p}\right)$$

Potential Vorticity = (local rotation + global rotation)*(vertical stability)

$$\text{(2)}\quad \frac{d(PV)}{dt} \approx -g(\zeta_\theta + f)\frac{\partial\dot{\theta}}{\partial p}$$

$\dot{\theta} =$ *diabatic heating rate*

Potential Vorticity Tendency ≈ (rotation)*(vertical derivative of diabatic heating rate)

<u>PV inversion offers a useful estimation of midlatitude storm dynamics.</u>

A positive PV anomaly generates <u>cyclonic circulation</u> at all points (lat, lon, p).
The strength of the circulation induced decreases radially away from the PV anomaly.

Dynamics of midlatitude storms

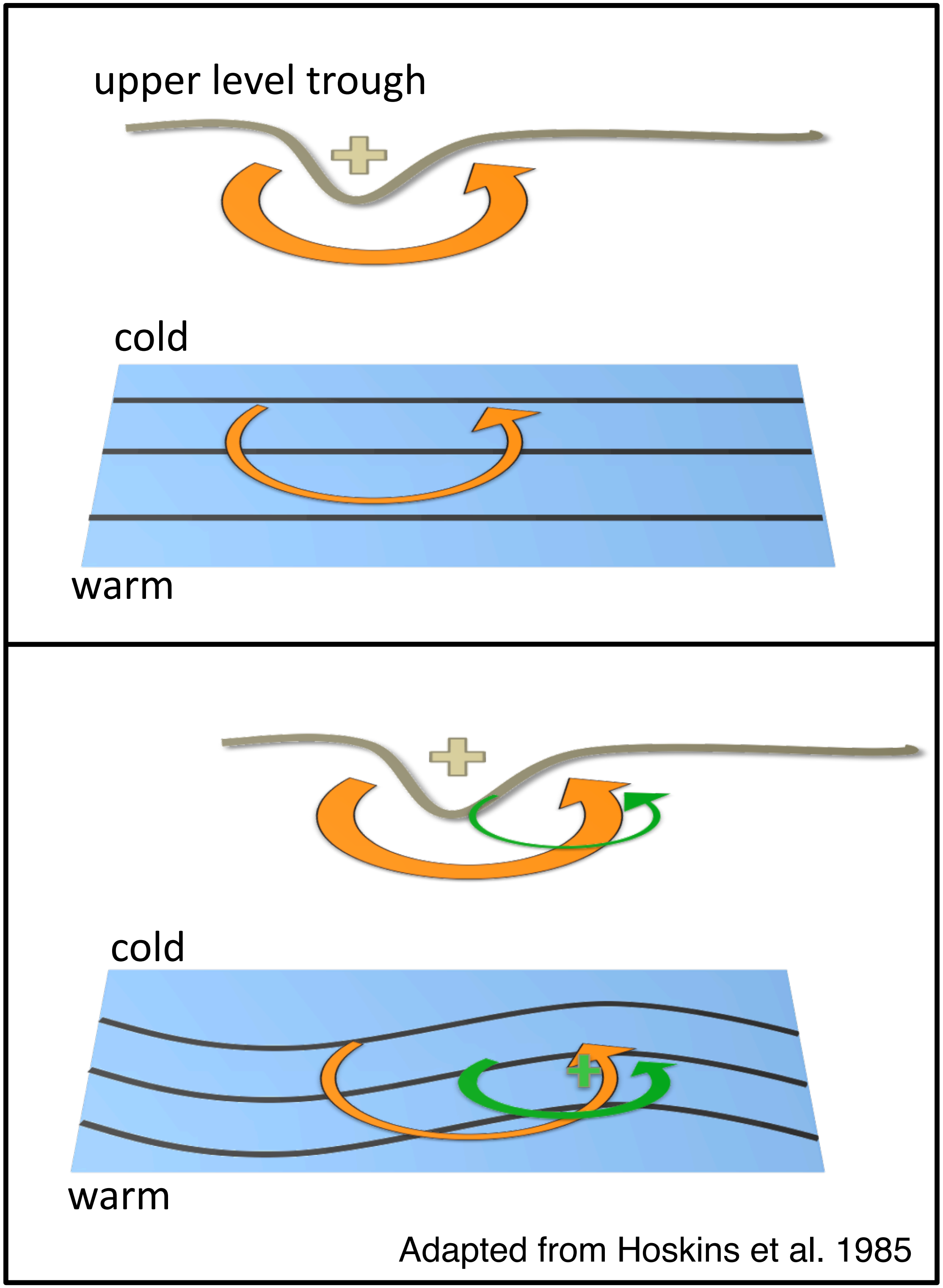
Classic Dry Schematic:
STEP 1: upper-level trough induces a circulation: warm air poleward and cold air equatorward.

orange: circulation associated with upper level PV

black lines: surface isotherms

STEP 2: upper-level and surface PV anomalies interact

green: circulation related to surface PV created by poleward advection of warm air.



Dynamics of midlatitude storms

Classic Dry Schematic + MOISTURE:

STEP 1: upper-level trough induces a circulation: warm air poleward and cold air equatorward.

orange: circulation associated with upper level PV

black lines: surface isotherms

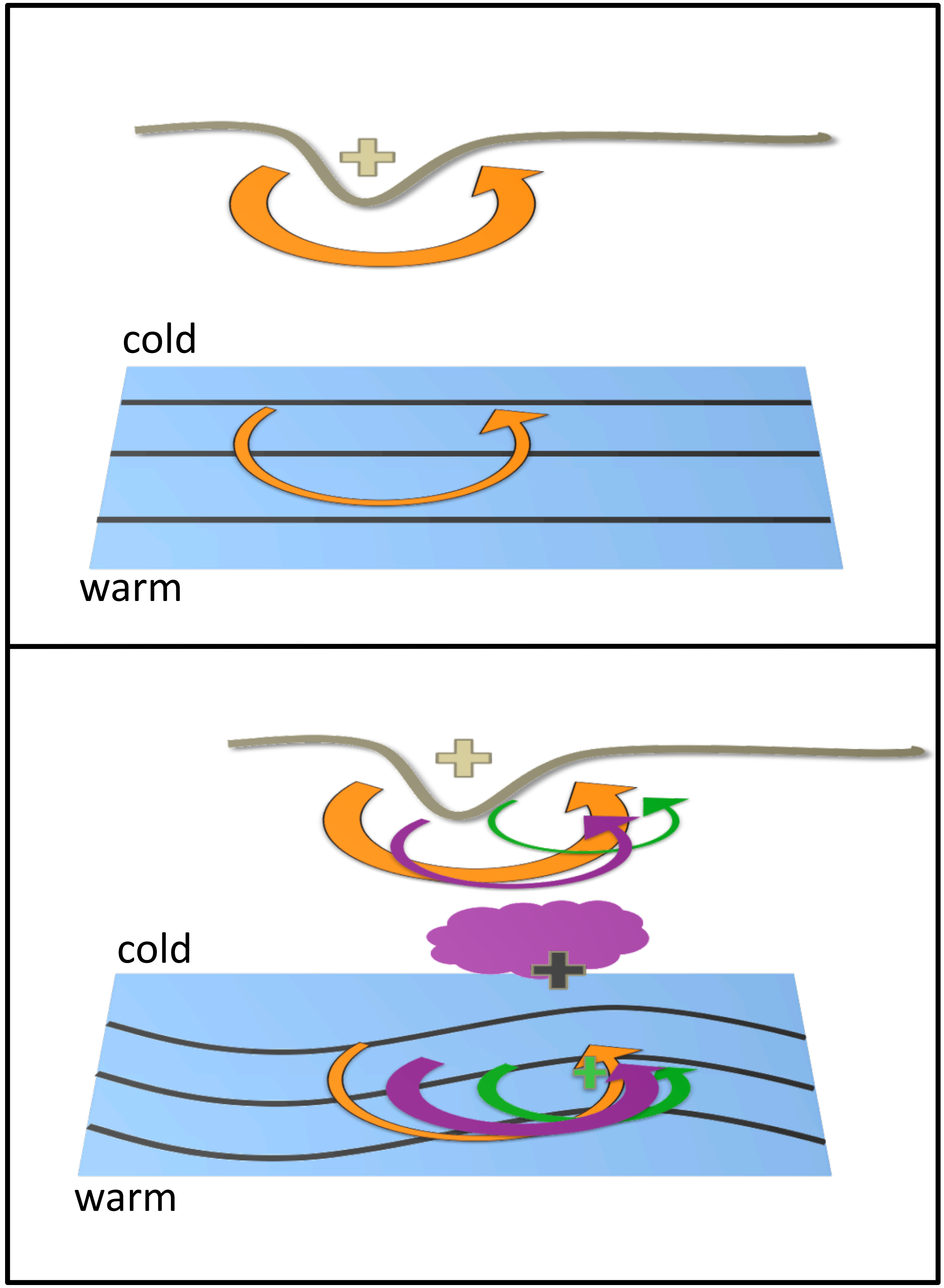
STEP 2: upper-level and surface PV anomalies interact

Circulation strengthened by moist +PV.

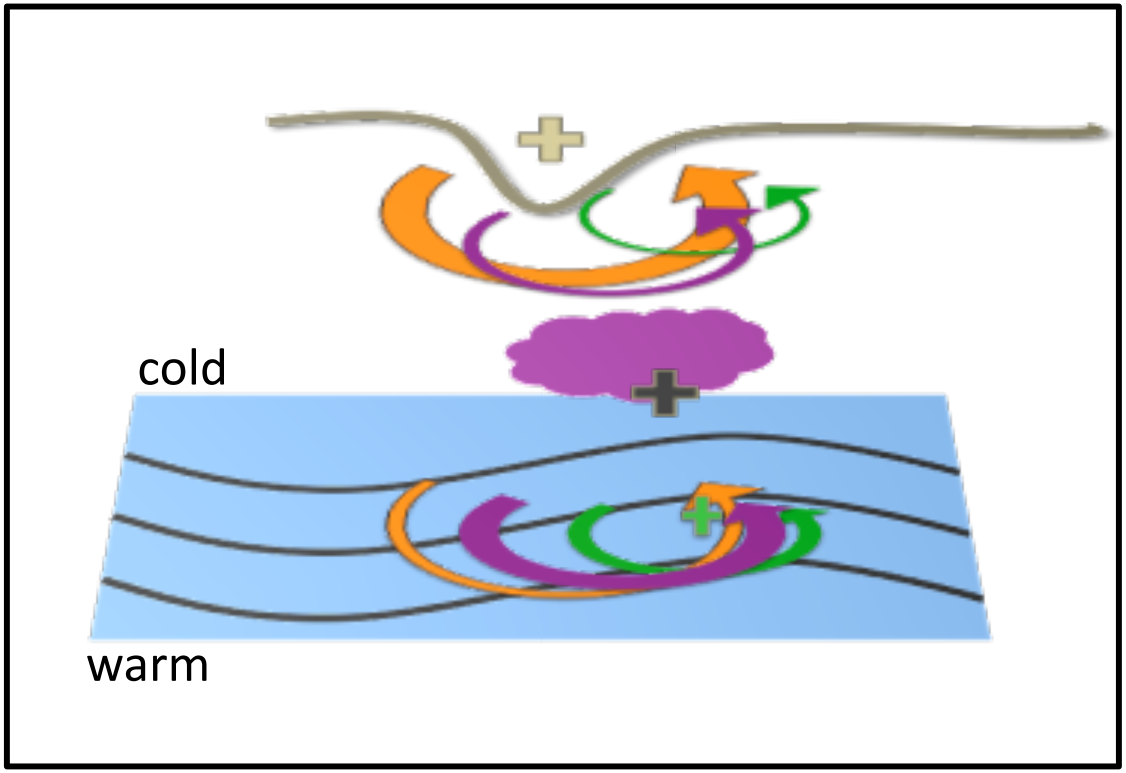
green: circulation related to surface PV created by poleward advection of warm air.

purple: PV created by condensational heating and its circulation

Kleinschmidt 1957
Stoelinga 1996



Moisture forcing of midlatitude storms



Emanuel et al. 1987
moist processes → faster development, scale collapse in semigeostrophic system.

Kuo et al. 1992
numerical weather model case studies: moisture strengthens storms

Warm Conveyor Belt (WCB)

- Filaments of vertical and horizontal transport within storms
  e.g. Browning 1971.

- Strengthens storm circulation.

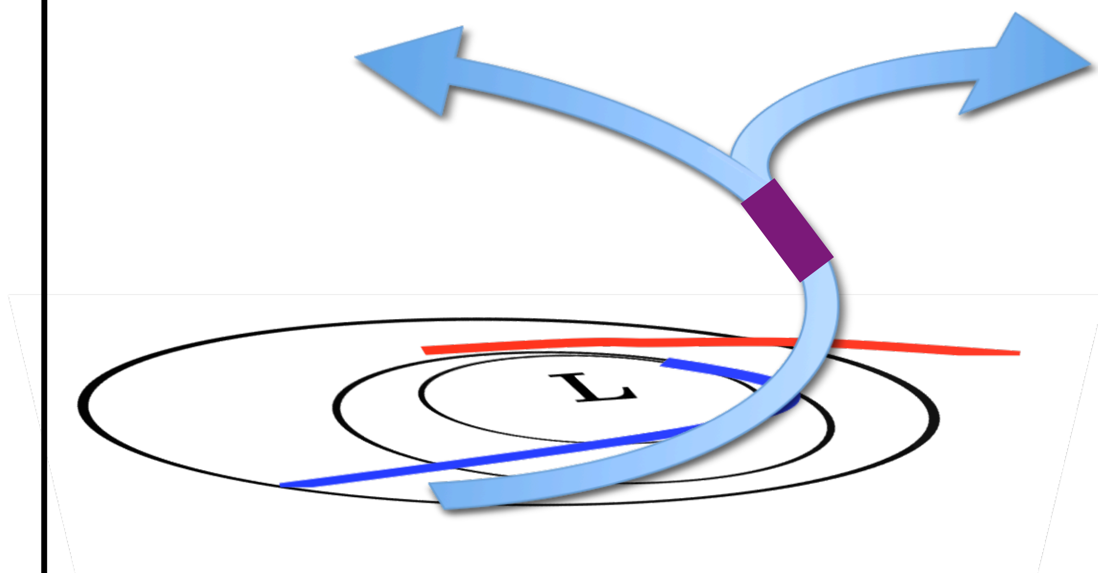
Boutle et al. 2011

Changing initial relative humidity in idealized model

→changes in WCB ventilation

→changes in storm strength

3-D Schematic of Warm Conveyor Belt



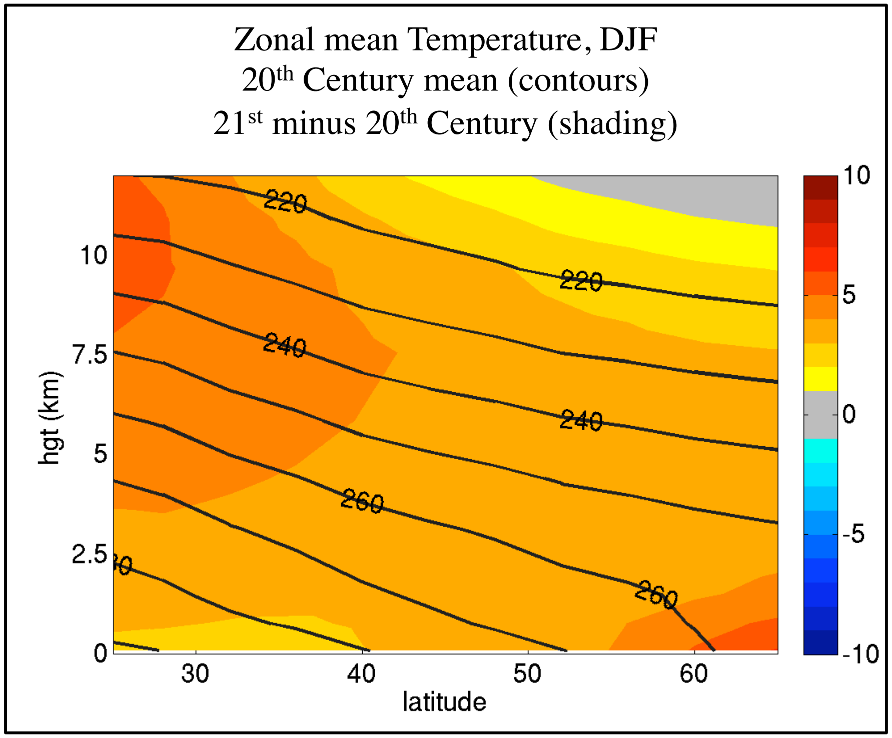
- SLP: black
- Temperature Fronts: blue, red
- Blue/White: Warm Conveyor Belt
- Purple: +PV from diabatic heating

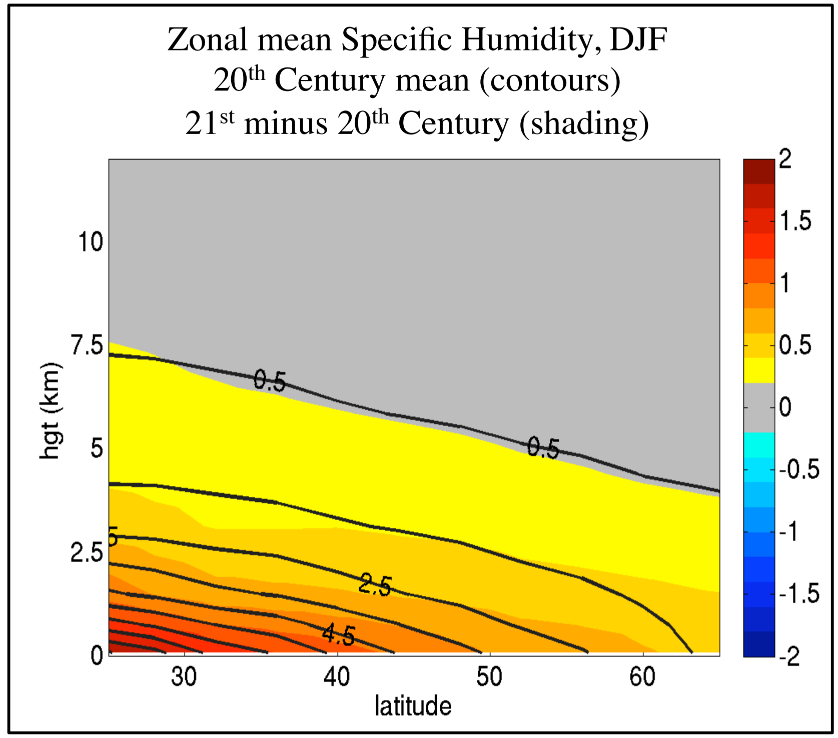
How will components of the atmosphere that influence storms change with global warming?

(1) dT_{SURF}/dy decreases :: less low-level baroclinicity.

(2) Low-level atmospheric water vapor increases.

Do climate models capture these changes? YES





Output taken from the IPCC CMIP3 Archive

(Climate Model Intercomparison Project, Phase 3)

*Changes in atmospheric stability might also affect storms

What will happen to midlatitude storms in a warmer world?

Midlatitude Storm Results from the CMIP3 GCM Projections

(GCM: Global Circulation Model)

(1) Total number of NH storms decreases **– Lambert and Fyfe (2006)**

(2) Frequency of most violent midlatitude wind storms increases.

-Gastineau and Soden (2009)

(3) Amplitude of 99.9%tile of heavy precipitation events per latitude increases in midlatitudes.

-O'Gorman and Schneider (2009)

What will happen to midlatitude storms in a warmer world?

Results from higher resolution GCM forecasts

Bengtsson et al., 2009
No increase in occurrence of strongest storms
(850 hPa relative vorticity)

- Used GCM with ~60km resolution, ECCHAM
- CMIP3 models resolutions range: 80-200km

Catto et al. 2011, Champion et al. 2012:

Same results as Bengtsson.
(using ~60km resolution Hadley Center model)

What will happen to midlatitude storms in a warmer world?

Results from higher resolution GCM forecasts

Bengtsson et al., 2009
No increase in occurrence of strongest storms
(850 hPa relative vorticity)

- Used GCM with ~60km resolution, ECCHAM
- CMIP3 models resolutions range: 80-200km

Their logic:

decreased dT_{SURF}/dy

balances

strength increase associated with **increase moisture**.

Catto et al. 2011, Champion et al. 2012:

Same results as Bengtsson.
(using ~60km resolution Hadley Center model)

Given the CMIP3 results & idealized models & weather case-studies

Perhaps moisture forcing of storm strength deserves further study?

What will happen to midlatitude storms in a warmer world?

Can we approach the original question, in a simpler manner?

Idealized life cycle experiments!

- Changing moisture in initial conditions leads to:
  - **weak** change in storm (Pavan et al. 1999)
  - **strong** change in storm (Boutle et al. 2011)

Our question:

What is the response of idealized midlatitude storms to changes in moisture?

Experiment and Methods

Method: integrations of a baroclinic wave in a channel.

Model: WRF: Weather Research and Forecasting Model

-**Domain: 80° of latitude centered at 45° N**
50° of longitude, periodic in zonal direction

- f-plane

-Horizontal grid spacing: 50 km.

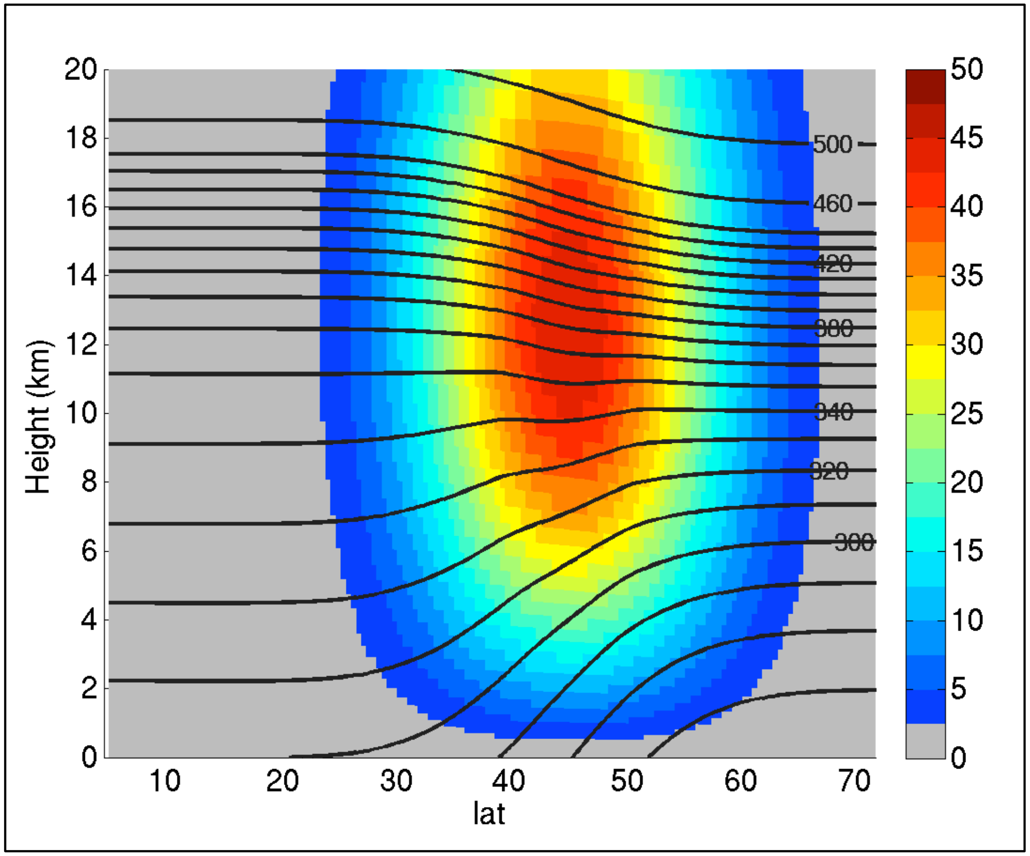
Parameterizations:

-convection
-turbulent mixing within the planetary boundary layer
-bulk microphysics
*No radiation in the integrations

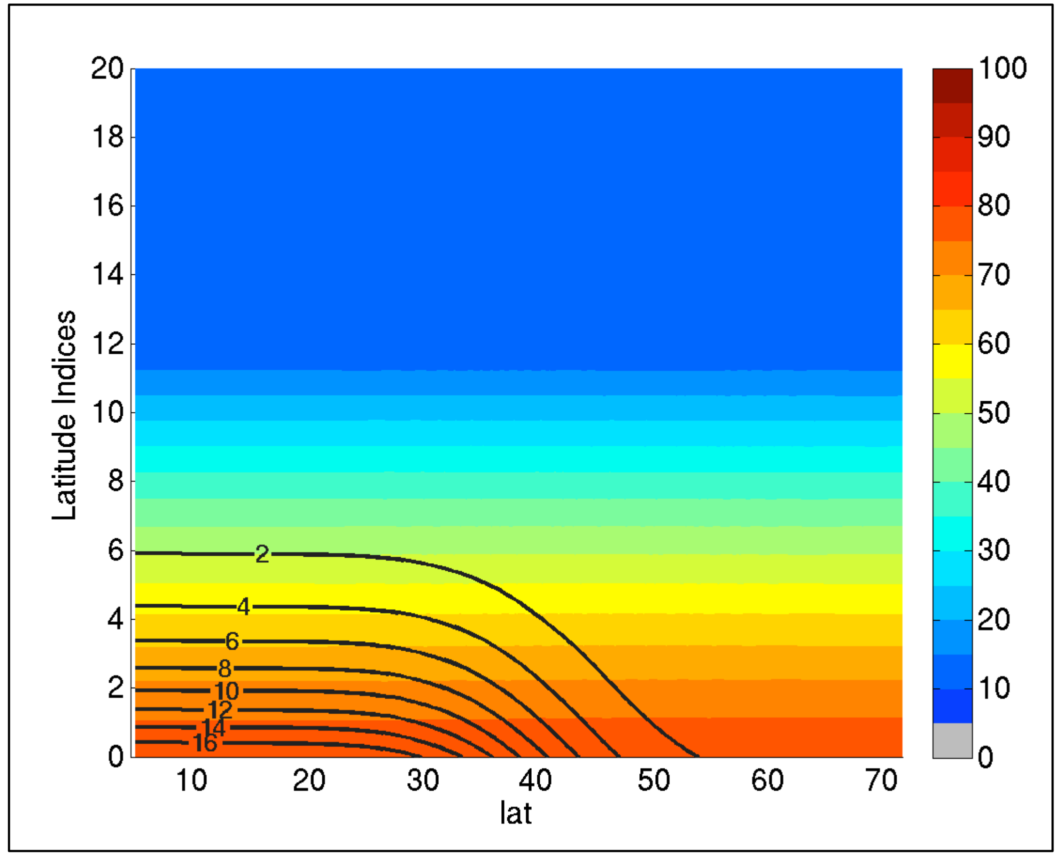
Surface Boundary: SST = T_{SURF}-.5 C
i.e., there is a moisture source at the surface.

Initial Conditions

Zonal Wind (shading)
and
Potential Temperature (contours)



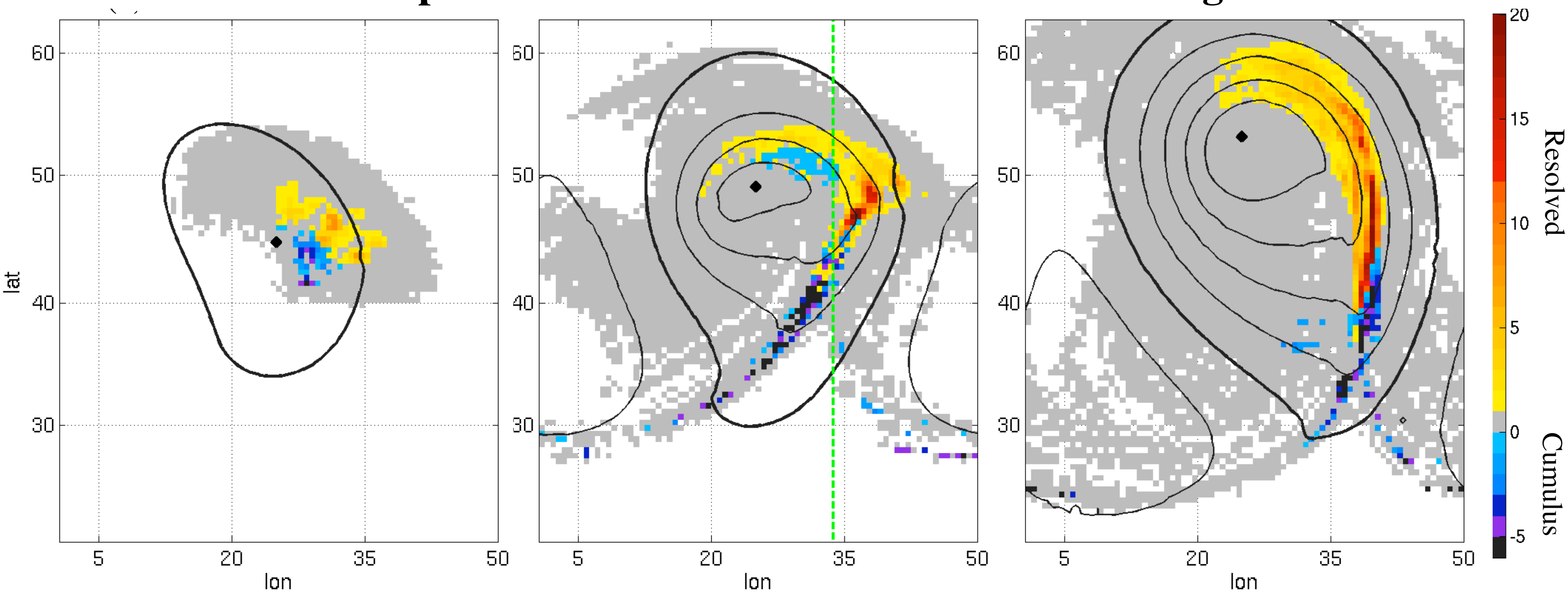
Relative Humidity (shading)
and
Specific Humidity (contours)



T at 45° = 280K

Analytic, balanced initial conditions for T,U
from **Polvani and Esler 2007**

Snapshots of Storm Evolution for Control Integration



(a) EKE ¼ max, Day 6.5 (b) EKE ½ max, Day 8 (c) EKE max, Day 9.5

Time

SLP contours (Thickest: 1000hPa. contour interval:10 hPa)
Precipitation Rates (mm/day), yellow-red: resolved, blue-purple: cumulus

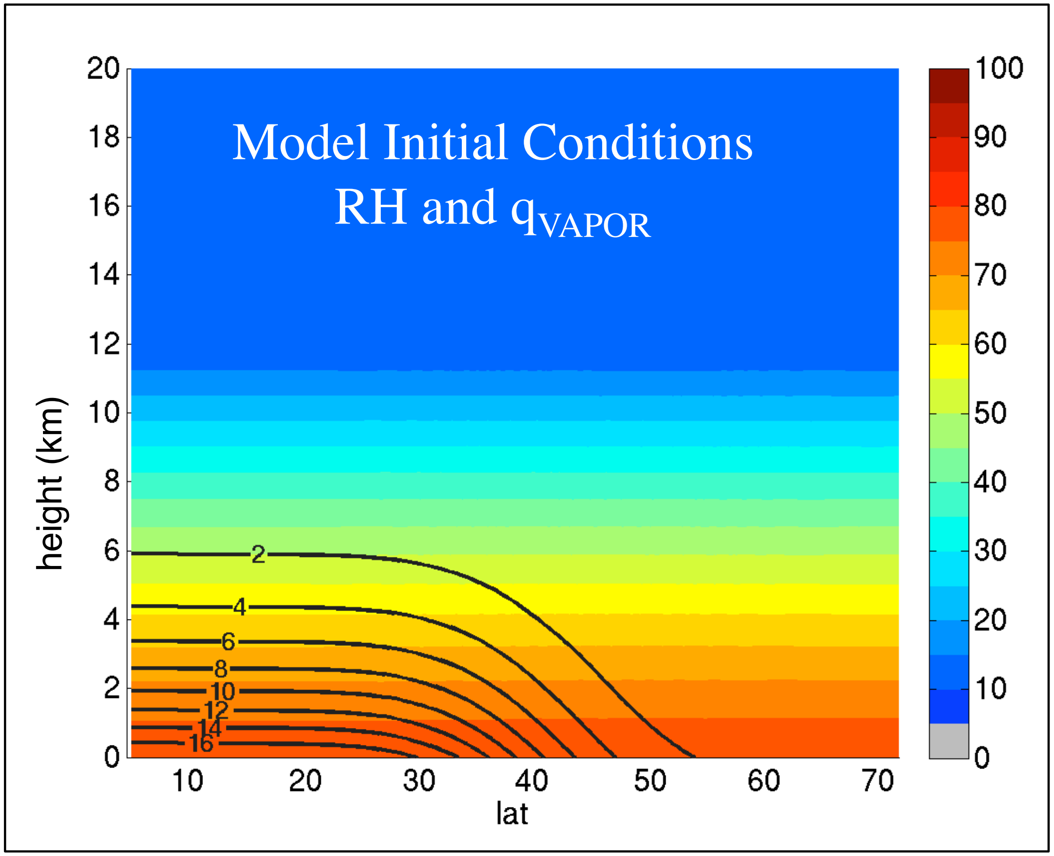
Experiment #1: DRY-TO-OBSERVED Initial conditions of Relative Humidity (RH)

Replicating Boutle et al. (2011)

$$RH = RH_0 * \begin{cases} (1-0.85 * Z/Z_T)^{1.25} & for\ Z \leq Z_T \\ 0.12 & for\ Z > Z_T \end{cases}$$

-Six integrations with 6 different values of RH0: 0, 0.2, 0.4, 0.6, 0.8, 0.95

$RH_0 = 0.8$ creates conditions closest to observations



Surface Boundary: SST = T_{SURF}-.5 C
i.e., there is a moisture source at the surface.

Results: RH_0 Set of Experiments

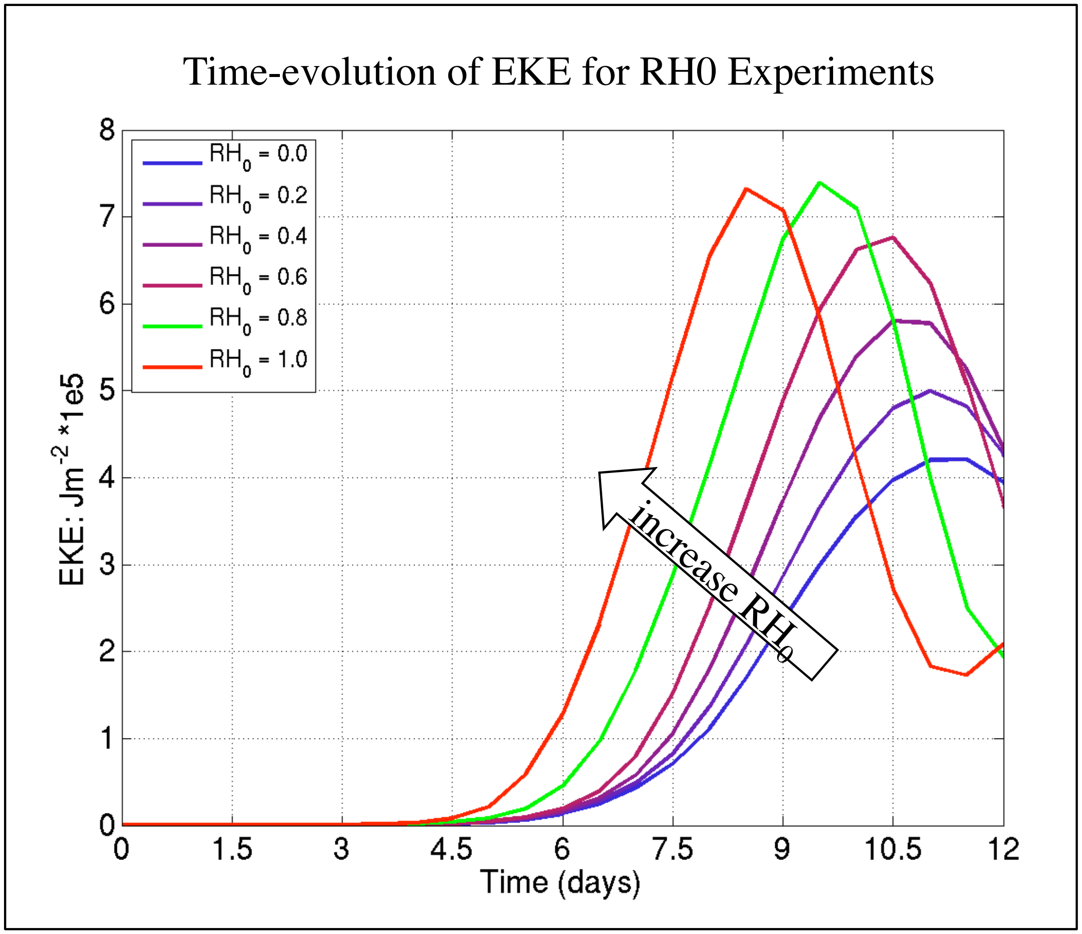
Eddy Kinetic Energy:: EKE

$$EKE = \int_{VOL} \rho * 1/2\left((u^*)^2 + (v^*)^2\right)$$

$$u^* = u - [u]$$

$$[\cdot] \equiv \textit{zonal mean}$$

- The storm eddy kinetic energy increases monotonically with RH_0.
- Storm growth rate increases.
- EKE increase for $RH_0 = 0.0$ vs. 0.8 : ~ 100%.
- The increase for $RH_0 = 0.8$ to 1 is the smallest.



Results: RH_0 Set of Experiments

Alternate Storm Strength Metrics

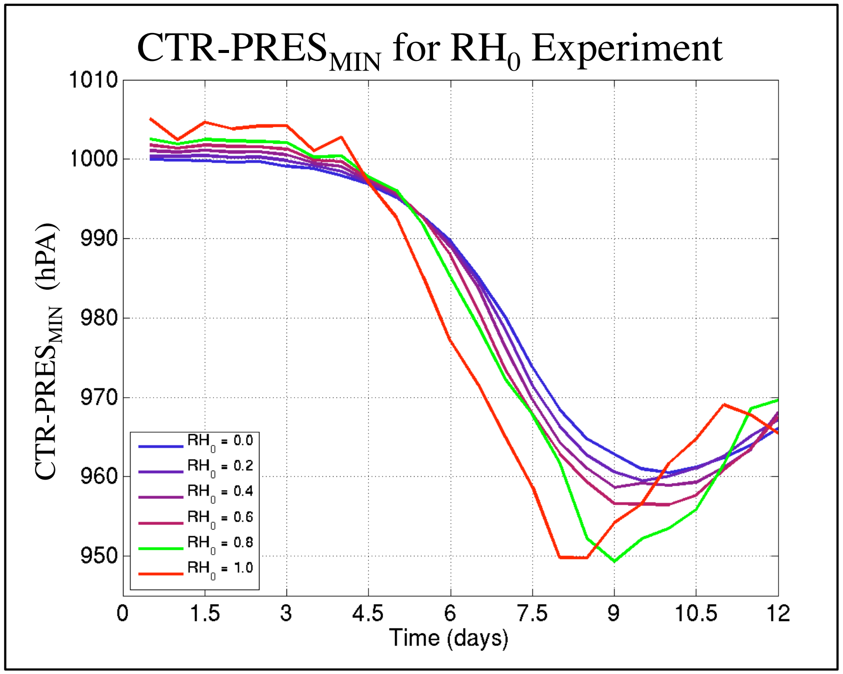
Storm Central Pressure Minimum ::
$CTR\text{-}PRES_{MIN}$

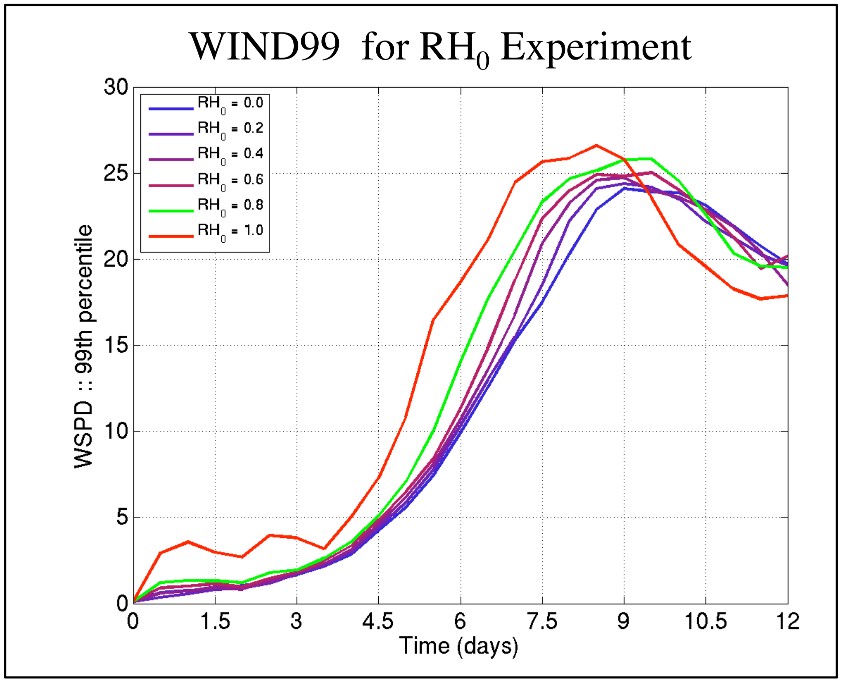
-objectively identify minimum SLP at each time step

Strongest winds:: WIND99

-strongest 99th percentile for surface wind speed.

$CTR\text{-}PRES_{MIN}$ and WIND99 response:
larger initial RH creates a stronger storm





Results: RH_0 Set of Experiments

Storm Precipitation Extremes

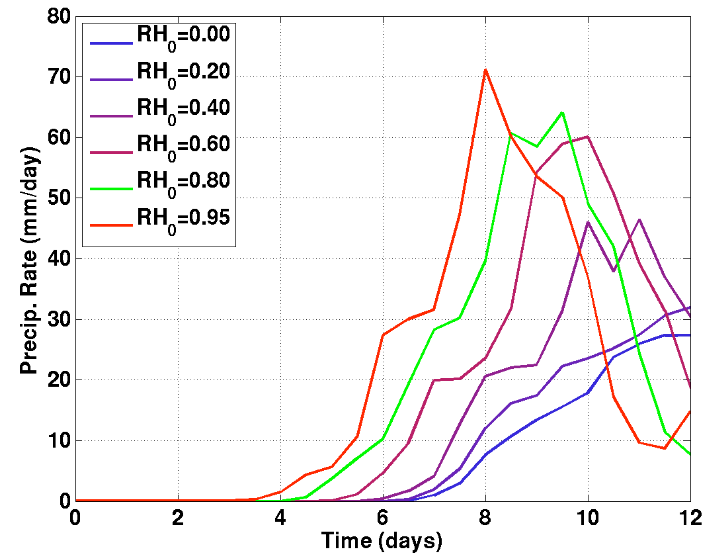
(a) Strongest 99th percentile precipitation rate for precipitation created at the resolved scale (mm/hour).

(b) Strongest 99th percentile precipitation rate precipitation rate for precipitation created by the cumulus* scheme (mm/hour).

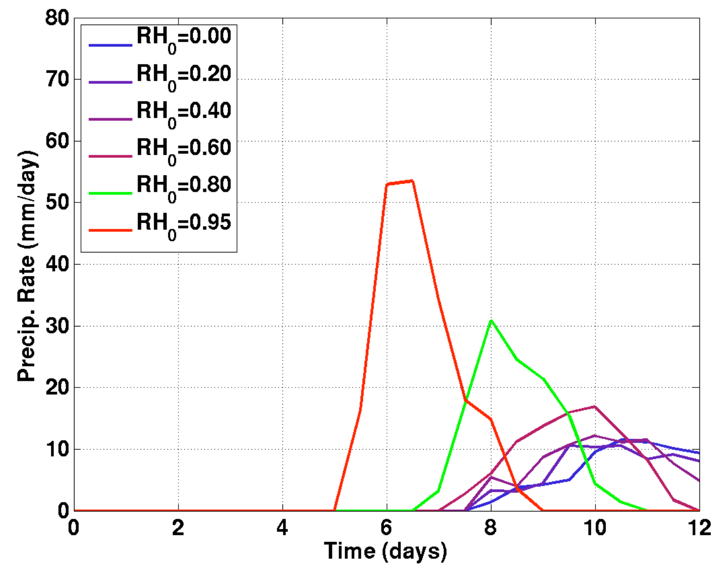
Extreme Rain rates respond to changes in RH_0 in the same manner as EKE.

**What is cumulus precipitation?: rain formed by the vertical mixing parameterized by the cumulus scheme.*

(a) Resolved Rain Rate, ΔRH_0



(b) Cumulus Rain Rate, ΔRH_0

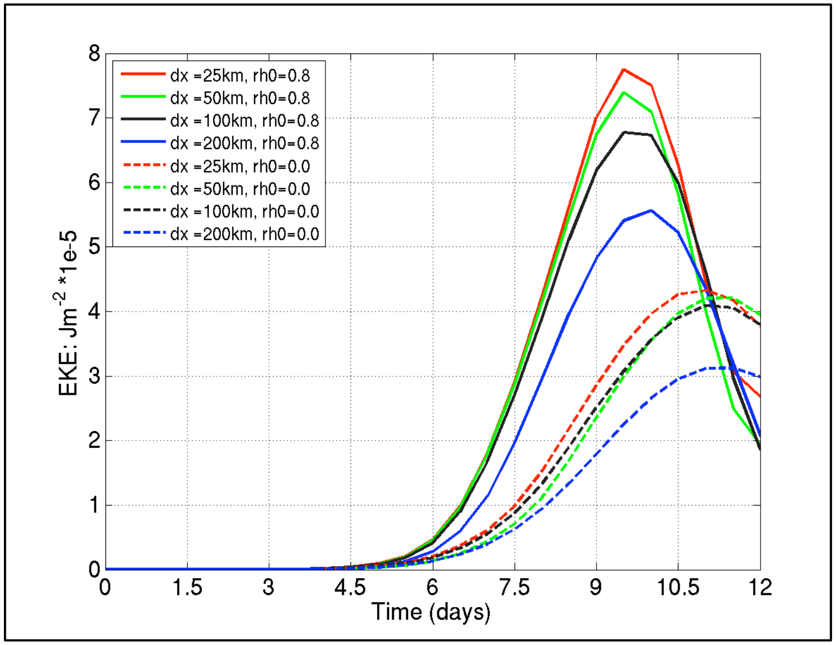


Results: RH_0 Set of Experiments, vs. grid-spacing

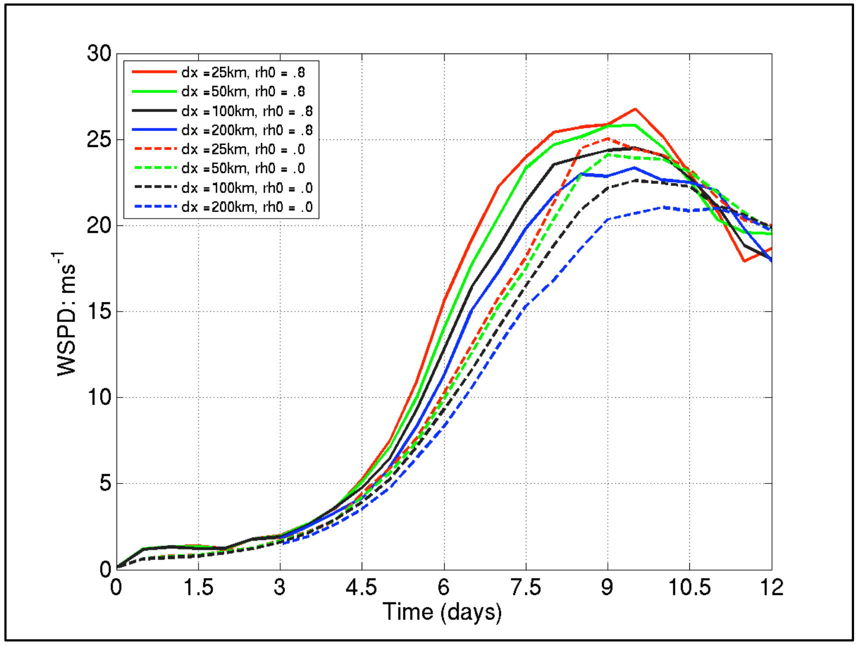
Increase in strength with RH0 is robust across various horizontal grid-spacing.

Results for RH0 experiments using:
25 km (red), 50 km (green), 100 km (black) and 200 km (blue).
Solid lines show $RH_0 = 0.8$
Dashed lines show $RH_0 = 0$.

Eddy Kinetic Energy



WIND99

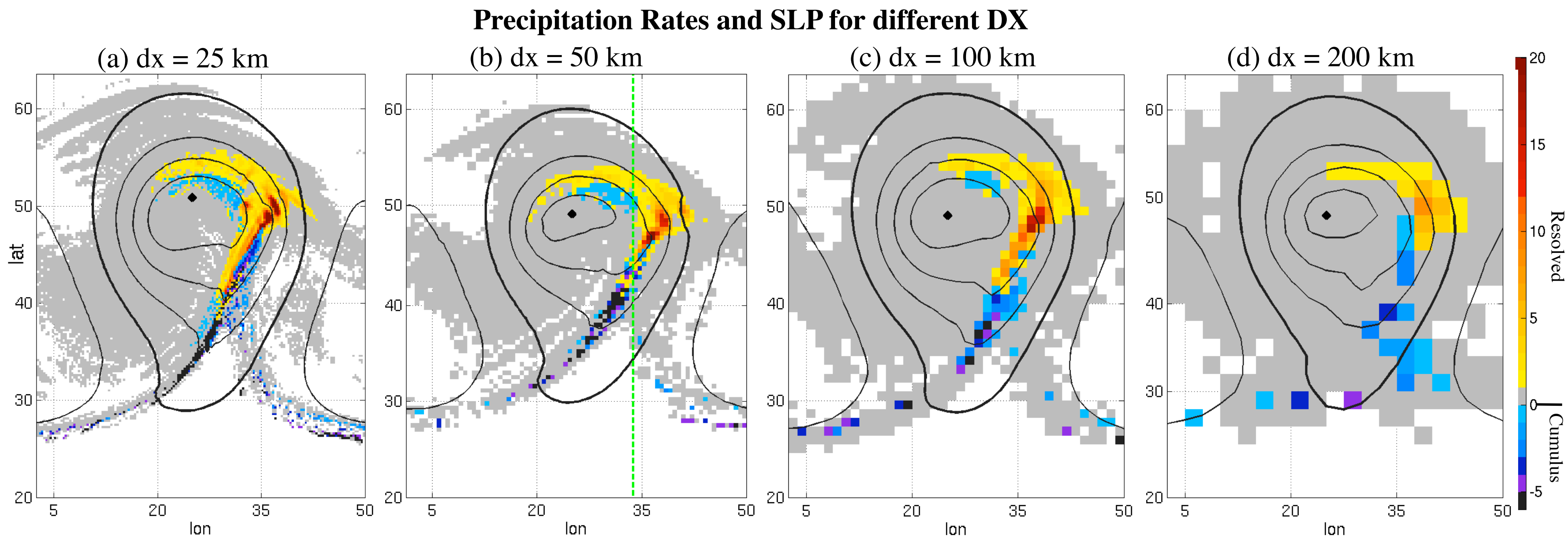


KEY: Increase in storm strength with DX is primarily caused by a decrease in the numerical diffusion.

Results: RH_0 Set of Experiments, vs. grid-spacing

Increase in strength with RH0 is robust across various horizontal grid-spacing.

SLP contours (Thickest: 1000hPa. contour interval:10 hPa)
Precipitation Rates (mm/day), yellow-red: resolved, blue-purple: cumulus



SLP patterns and precipitation rates also show a convergence with respect to grid-spacing.

**The storm response to RH_0 is also robust to changes in the cumulus and microphysics parameterizations schemes.

Changing Moisture Content: Method #2

Are the RH_0 experiments the best method for understanding moisture changes with global warming?

- With global warming, changes in RH are expected to be small, e.g. Sherwood et al. 2010.
- Changing temperature would increase moisture, but where should we warm?

Changing Moisture Content: Method #2

Are the RH_0 experiments the best method for understanding moisture changes with global warming?

- With global warming, changes in RH are expected to be small, e.g. Sherwood et al. 2010.
- Changing temperature would increase moisture, but where should we warm?

Method 2 for changing moisture, add a coefficient into Clausius-Clapeyron Equation
inspired by Frierson et al. 2008

$$q_{SAT} = C_{SVP} * 6.11 * e^{\left(\frac{L_v}{R_v} * \left(\frac{1}{273} - \frac{1}{T}\right)\right)}$$

C_{SVP} :: coefficient of saturation vapor pressure
$C_{SVP} = 1$ creates observed initial conditions

Experiment #2: DRY-TO-OBSERVED by changing saturation vapor pressure.

We start with an analog to the RH^0 experiment.

Run 6 integrations, with C_{SVP} ranging from 0 → 1 with intervals of 0.2

$$q_{SAT} = C_{SVP} * 6.11 * e^{\left(\frac{L_v}{R_v} * \left(\frac{1}{273} - \frac{1}{T}\right)\right)}$$

Results: ΔC_{SVP} DRY-TO-OBSERVED

Eddy Kinetic Energy ::
EKE

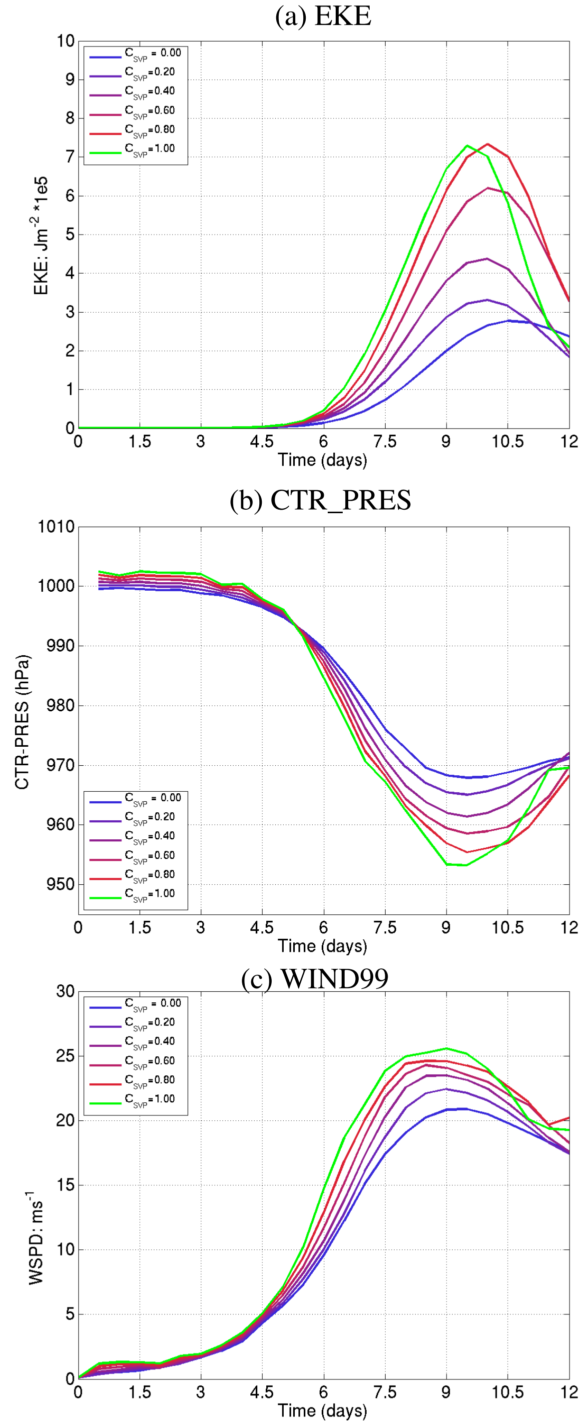
$$EKE = \int_{VOL} \rho * 1/2\left((u^*)^2 + (v^*)^2\right)$$

Storm Central Pressure Minimum ::
$CTR\text{-}PRES_{MIN}$

Strongest winds::
WIND99

-value of the strongest 99th percentile for surface wind speed.

Set 2: ΔC_{SVP} 0-to-1



Results:

Storm strength increases with increasing moisture content: consistent with the RH_0 experiment.

Experiment #3: OBSERVED-TO-2X-OBS by changing saturation vapor pressure.

$$q_{SAT} = C_{SVP} * 6.11 * e^{\left(\frac{L_v}{R_v} * \left(\frac{1}{273} - \frac{1}{T}\right)\right)}$$

C_{SVP} :: coefficient of saturation vapor pressure
C_{SVP} = 1 creates observed initial conditions

Run 6 integrations, with C_{SVP} ranging from 1 → 2 with intervals of 0.2

i.e., synthetically increase moisture content beyond observed values.

Results: Moisture content greater than observed

Eddy Kinetic Energy ::
EKE

$$EKE = \int_{VOL} \rho * 1/2\left((u^*)^2 + (v^*)^2\right)$$

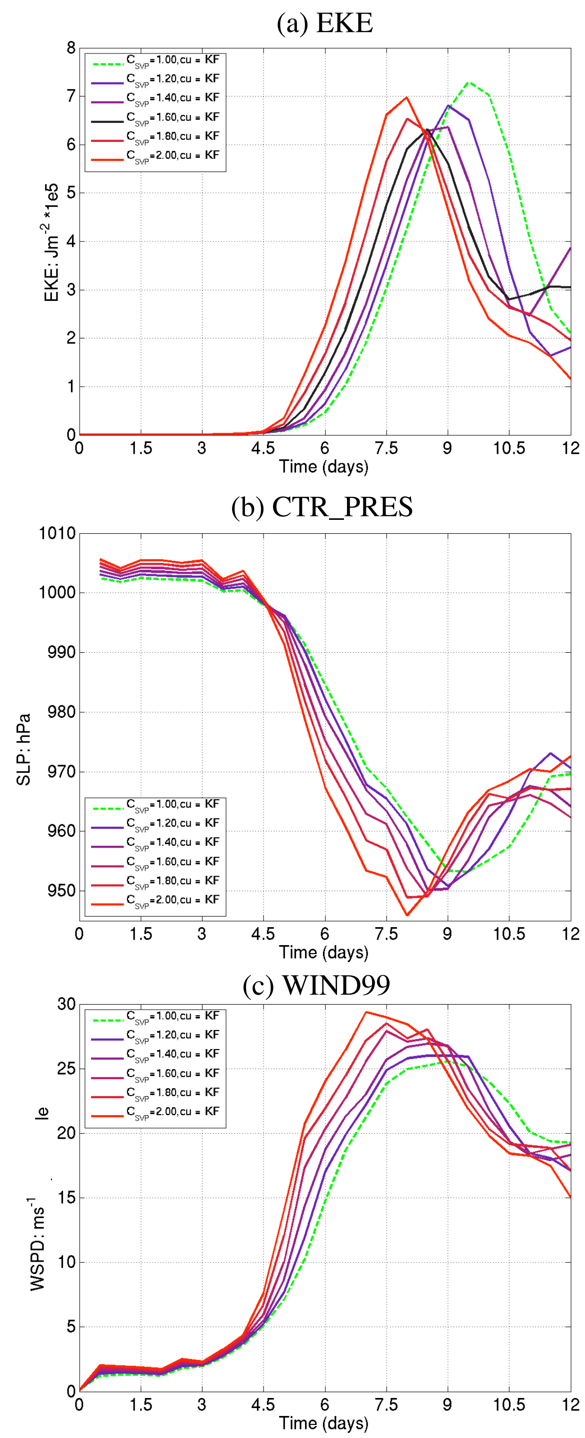
Storm Central Pressure Minimum ::
CTR-PRES$_{MIN}$

-objectively identify minimum in sea level pressure following the storm.

Strongest winds::
WIND99

-value of the strongest 99th percentile for surface wind speed.

Set 3: ΔC_{SVP} 1-to-2



Results:

EKE:
-maximum changes non-monotonically.

Growth rate increases with moisture.

CTR-PRES$_{MIN}$ deepens with increased moisture.

WIND99 increases.

Eddy Kinetic Energy ::
EKE

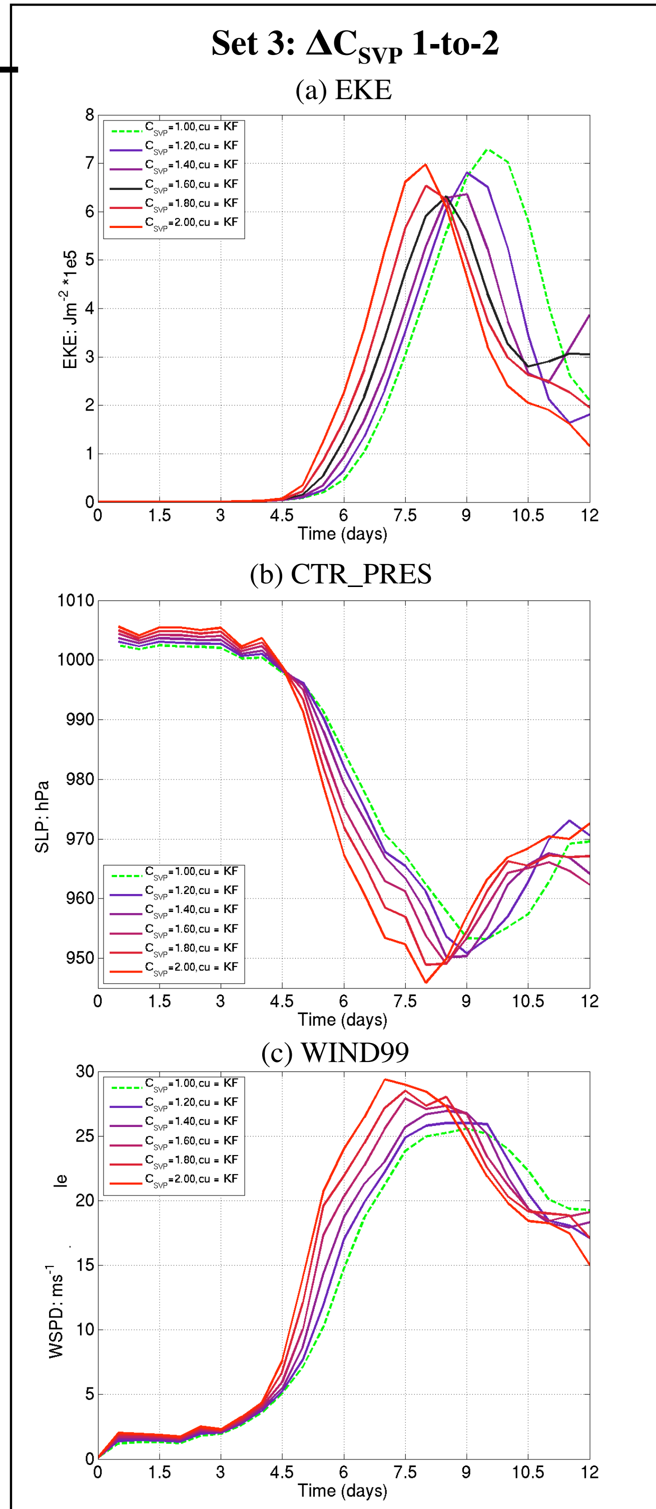
$$EKE = \int_{VOL} \rho * 1/2\left((u^*)^2 + (v^*)^2\right)$$

Storm Central Pressure Minimum ::
$\text{CTR-PRES}_{\text{MIN}}$

-objectively identify minimum in sea level pressure following the storm.

Strongest winds::
WIND99

-value of the strongest 99th percentile for surface wind speed.



Results:

PURPLE CURVE
$C_{SVP} = 1.2$

corresponds to a moisture increase with the magnitude predicted by GCMs for 2100.

For all 3 metrics:

$C_{SVP} = 1.2$ does not create a substantial change.

Storm Precipitation Extremes

(a) PRCP99$_{RES}$ ::Strongest 99th percentile precipitation rate for precipitation created at the resolved scale (mm/hour).

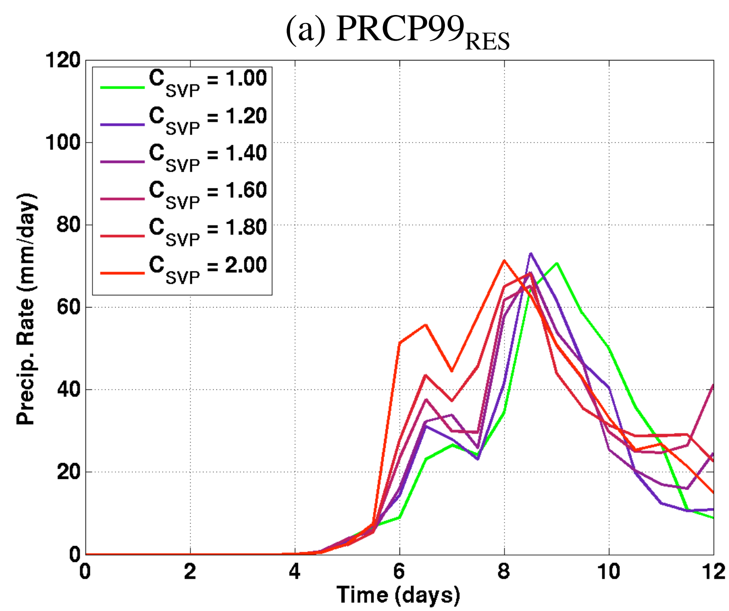
(b) PRCP99$_{CU}$ ::Strongest 99th percentile precipitation rate precipitation rate for precipitation created by the cumulus* scheme (mm/hour).

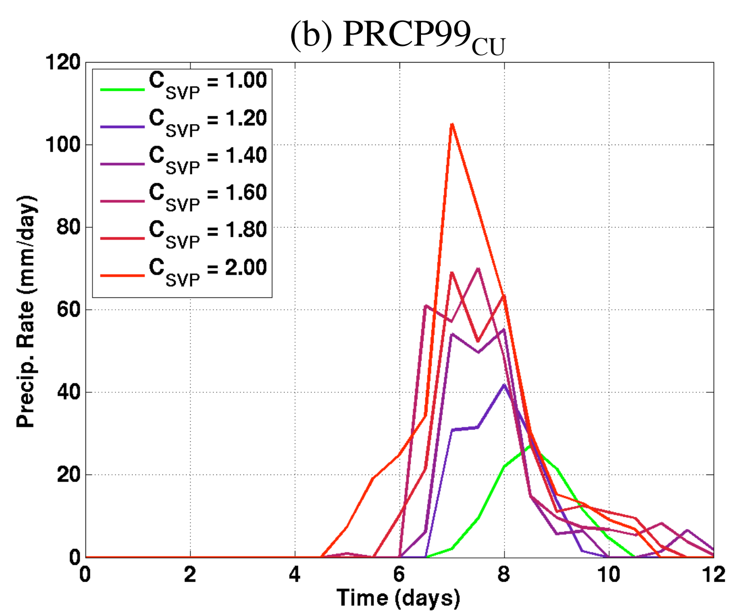
Extreme Rain rates:
- -no change in maxima at resolved scale.
- -increase in maxima for cumulus.

Total amount of rainfall increased monotonically.

C_{SVP} = 1.2 does not create a large change.

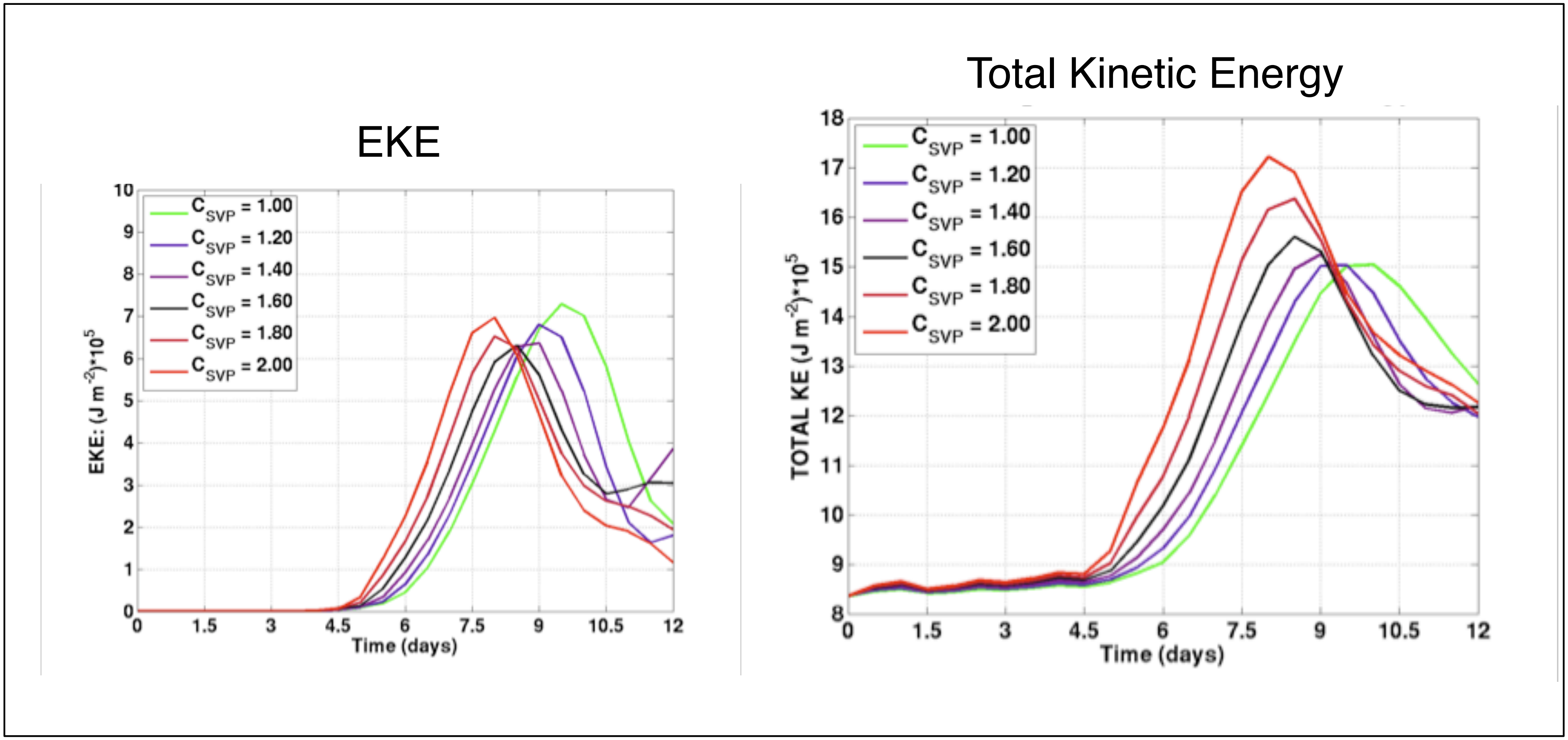
Set 3: ΔC_{SVP} from 1 to 2





Can we explain the EKE behavior for $C_{SVP} > 1$?

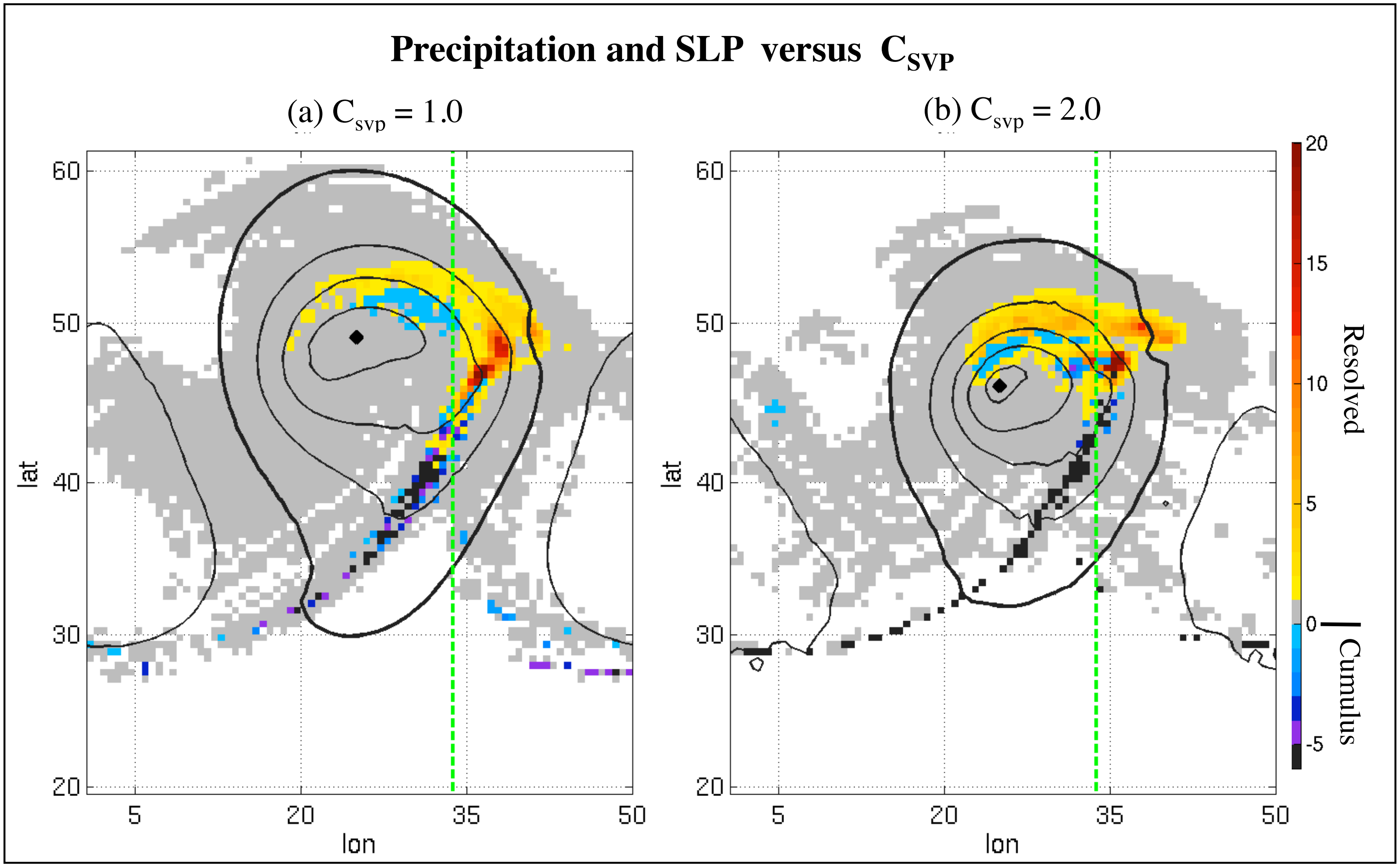
Experiment 3: Increasing CSVP from 1 → 2.



Response of TKE a monotonic increase with moisture;
i.e, the same as SLP_{MIN} and WIND99

Explanation of storm response

Thickest Contour: 1000 hPa. Contour Interval: 10 hPa.
Precipitation: Cumulus precip. is multiplied by (-1)



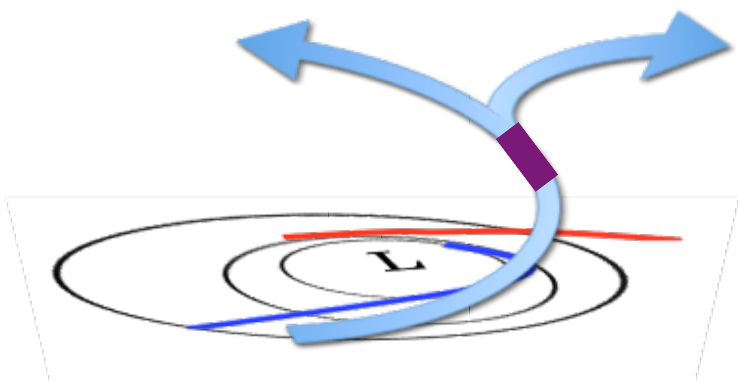
The meridional extent of the storm decreases as moisture increases.

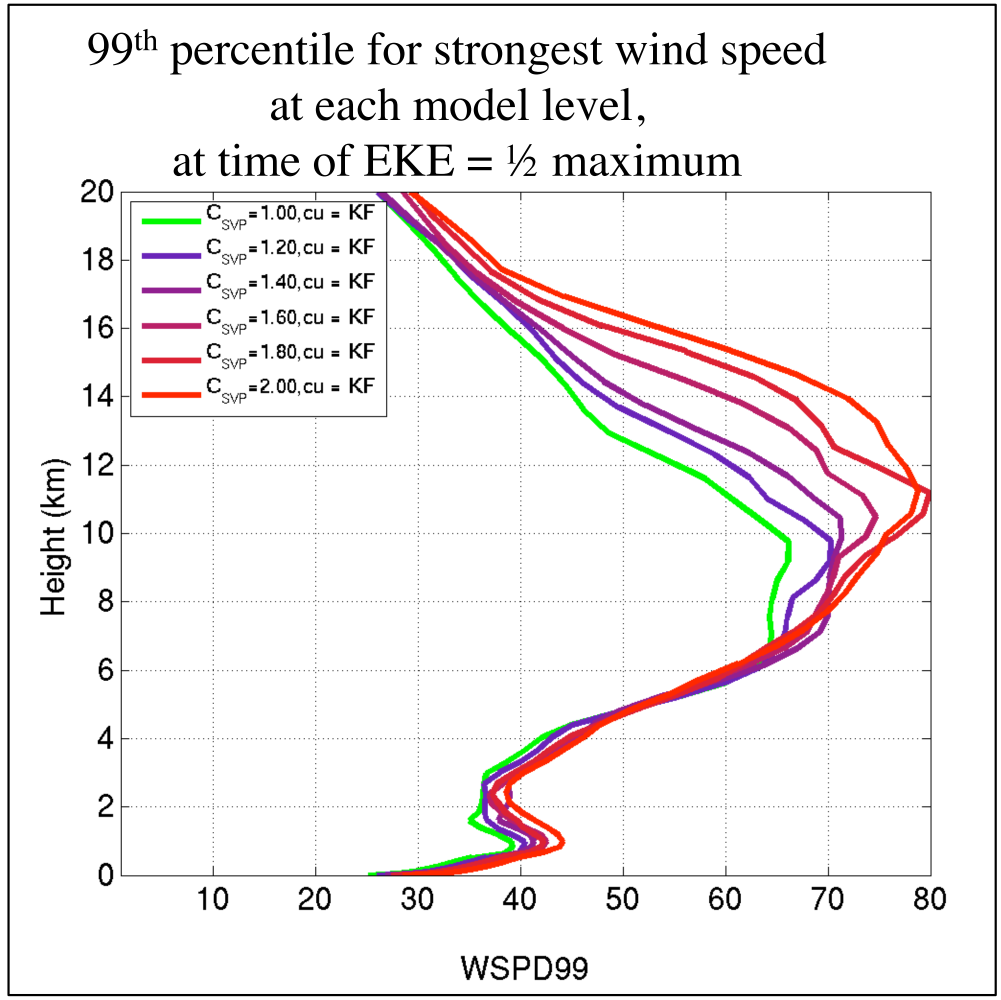
Experiment #3: Explanation for storm response

Mechanism affecting both storms:

Increase in conditional instability
→ increased verticality of
warm conveyor belt.

3-D Schematic of Warm Conveyor Belt





Wind speed versus height also shows the increased verticality of the storms.

Interesting?:

- Horizontal scale decreases with moisture increase, consistent Emanuel et al. 1987.
- Vertical scale increases with moisture increase

Summary & Conclusions

① Increasing moisture from dry to observed:

Strengthens the storm EKE, CTR-PRES$_{MIN}$, WIND99 and precipitation

Cause: positive-PV anomaly generated by latent heat release within warm conveyor belt (WCB).

Storm develops faster.

② For moisture increased above observed values:

Increased vertical motion within the WCB affects storm response: EKE decreases, while strongest surface winds and precipitation increase.

Storm develops faster.

IMPLICATIONS

Moisture increase will not lead to stronger magnitude of extreme storms.
However:

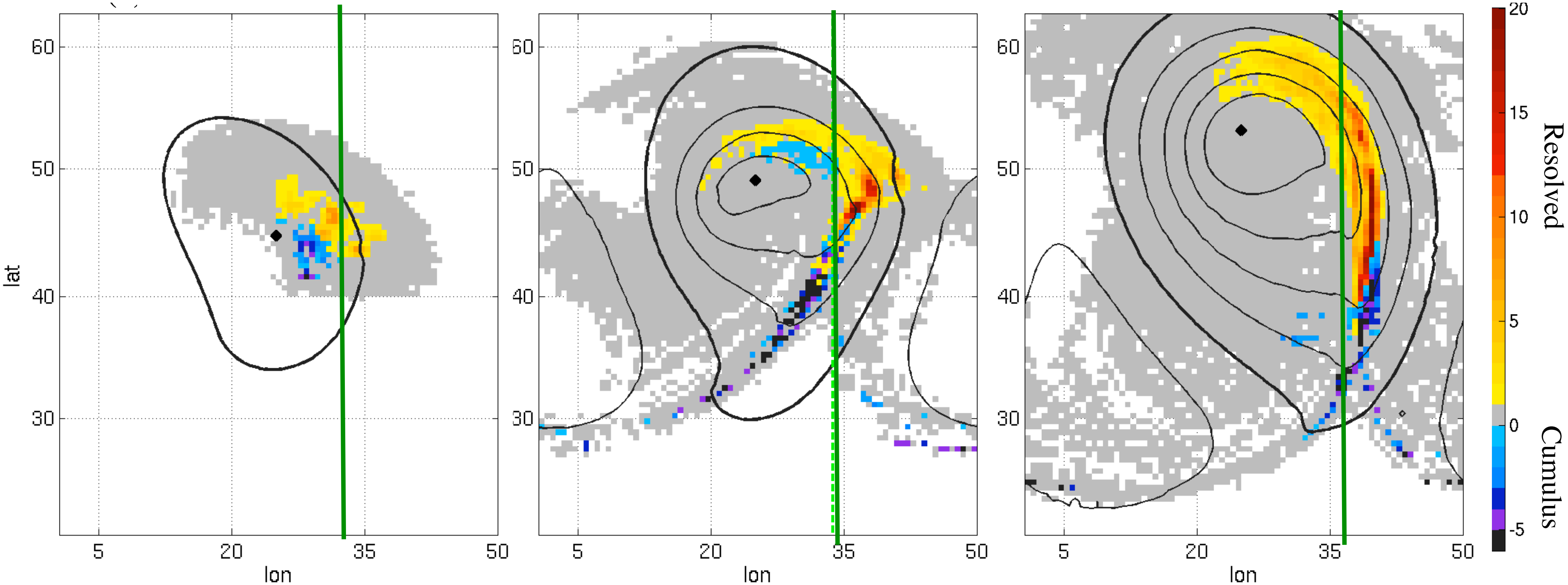
- -storm growth rates could increase
- -the number of moderate storms could increase.

Booth et al. Climate Dynamics (early online release)

Thank you

Can we explain the increase in strength?

Snapshots of Storm Evolution for Control Integration



(a) EKE ¼ max, Day 6.5 (b) EKE ½ max, Day 8 (c) EKE max, Day 9.5

Time

SLP contours (Thickest: 1000hPa. contour interval:10 hPa)
Precipitation Rates (mm/day), yellow-red: resolved, blue-purple: cumulus

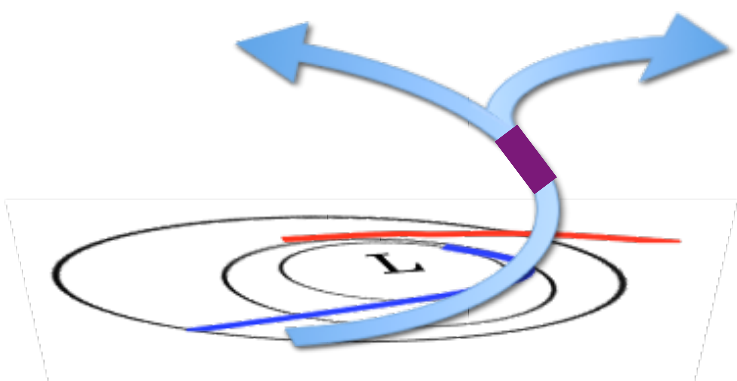
Can we explain the increase in strength?

Cross section of 2PVU at mid-point of storm shows: warm conveyor belt has is more upright and larger for higher RH_0.

(1 PVU = 10^{-6} K kg^{-1} m^2 s^{-1})

At full EKE, height maximum of warm conveyor belt is larger for larger RH_0

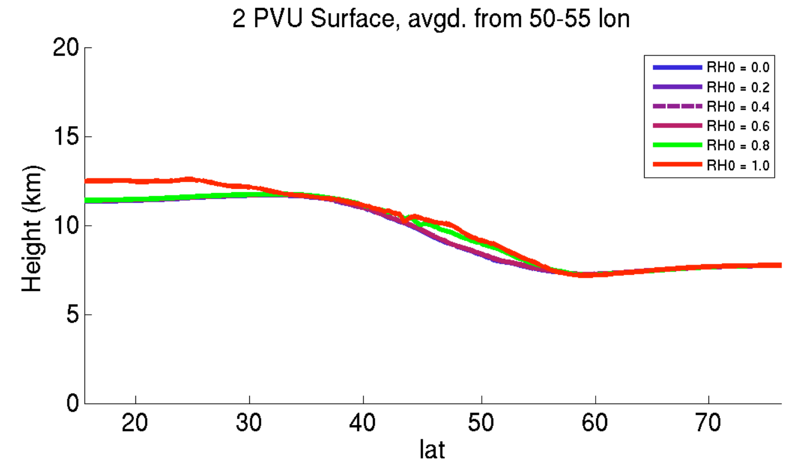
3-D Schematic of Warm Conveyor Belt



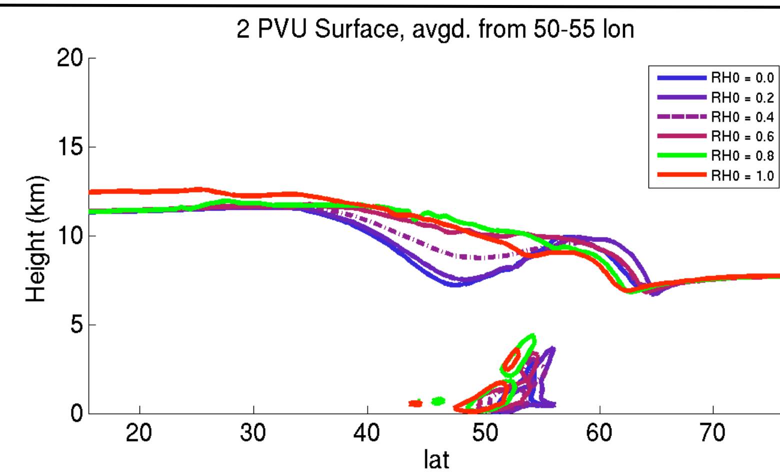
Cross-section of 2PVU Surface at Warm Conveyor Belt

RH_0 Experiments. Colors: blue = dry, green = control, red = moist

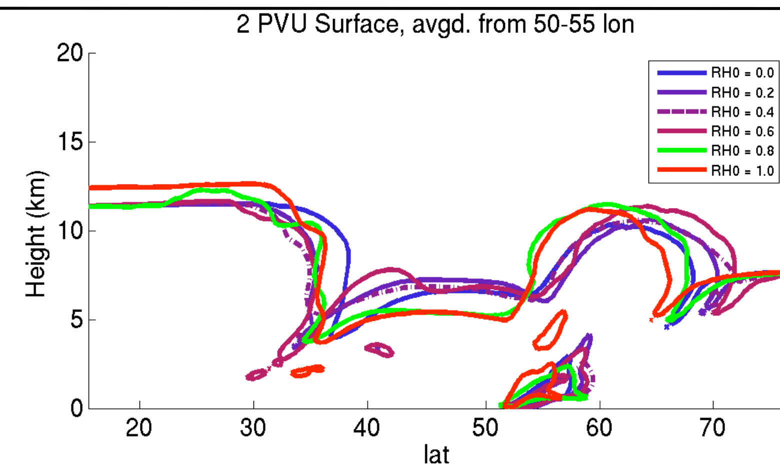
TIME: 1/3 of EKE maxima



TIME: 1/2 of EKE maxima



TIME: EKE maxima

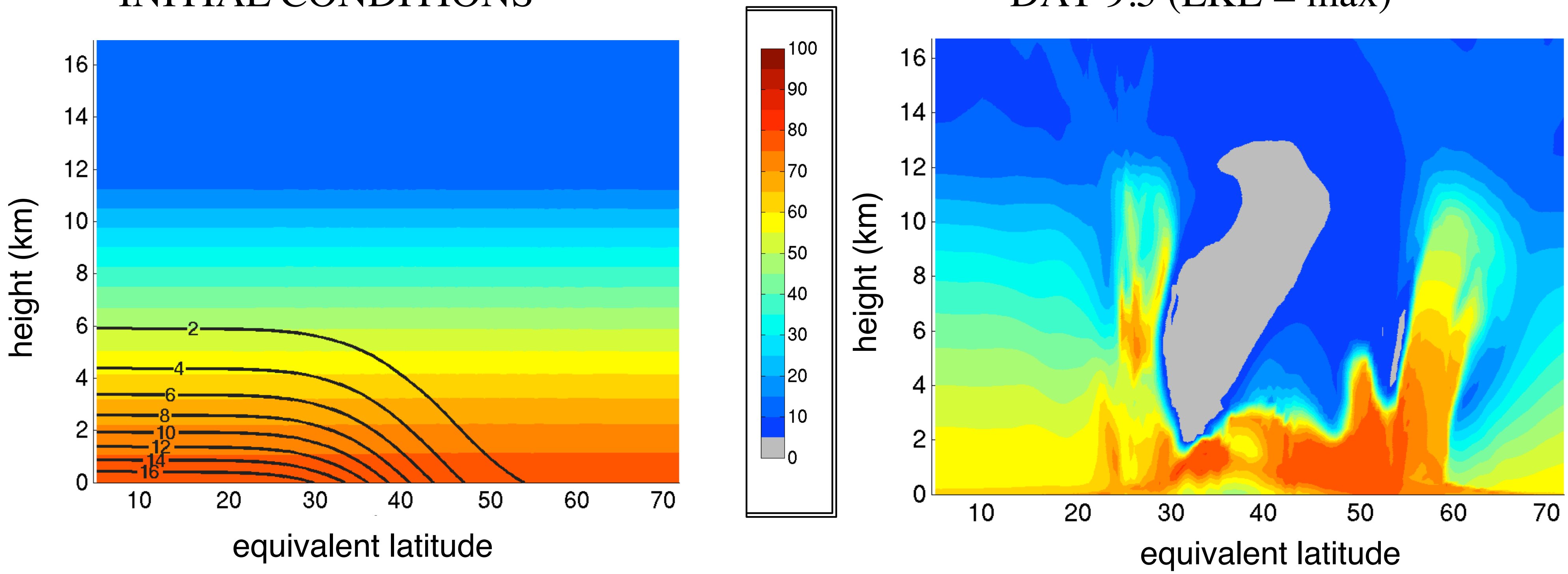


Results: RH_0 experiments, 50 km

Final RH conditions help to show the warm conveyor belt.

<u>Cross Sections of RH at time of EKEmax</u>

INITIAL CONDITIONS — DAY 9.5 (EKE = max)



The influence of moisture on extratropical cyclone circulation

Two ways to think about the impact of latent heat release during stable moist ascent:

the external approach:

latent heat release is regarded as an external forcing mechanism that ... drives or helps to drive the vertical circulation (fits with potential vorticity view).

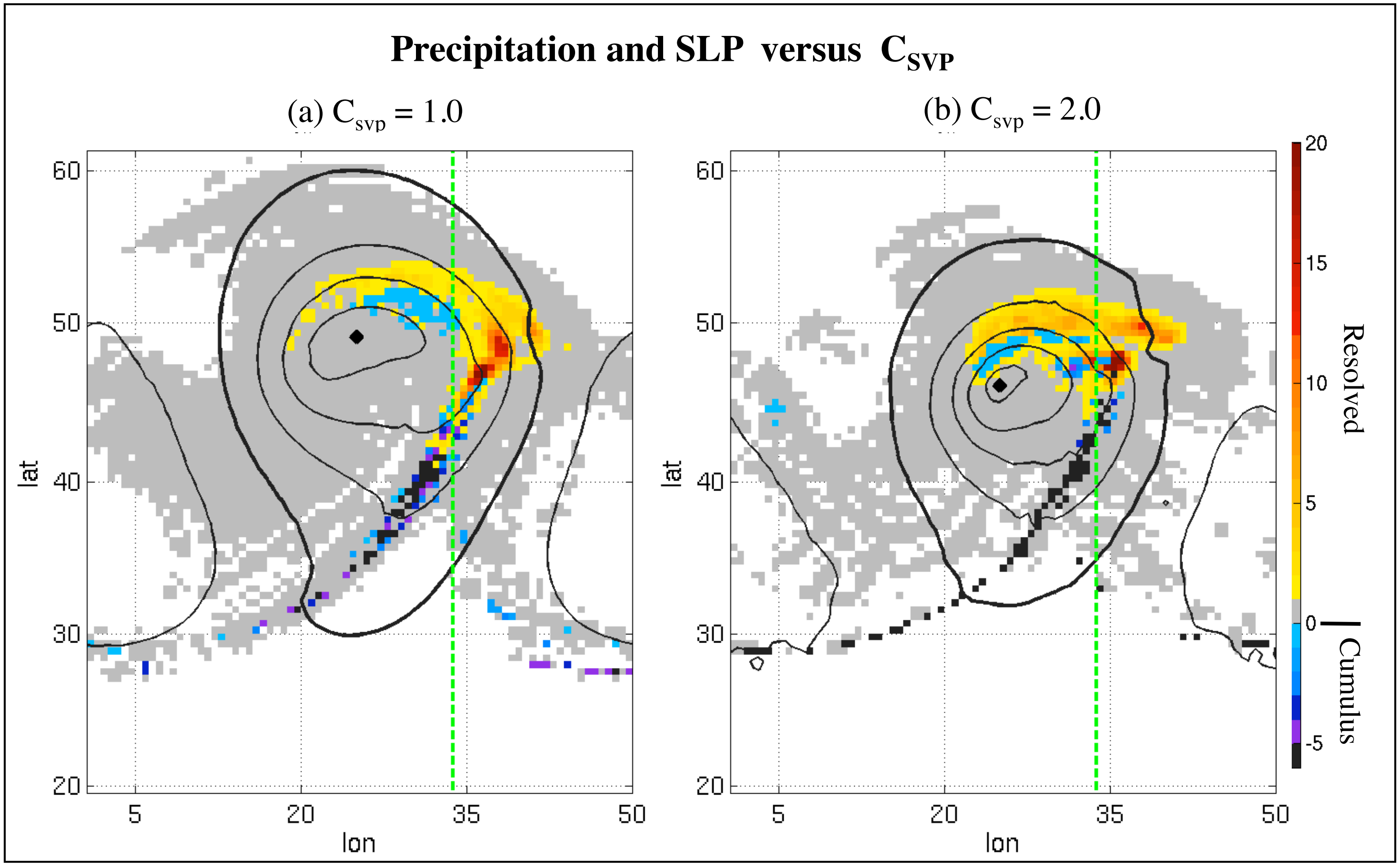
the stratification approach:

the latent heat release ... is manifested as a modification to the stratification in the vertical advection term of the thermodynamic equation:

$$\frac{\partial \theta}{\partial t} + u \nabla_H \theta + \omega \left[\frac{\partial \theta}{\partial p} - \frac{\partial \theta}{\partial p}\bigg|_{\theta_{esat}} \right] = 0$$

Nielson-Gammon and Keyser, MWR,2000

NEXT: zonal mean @ green line + 5° of latitude.



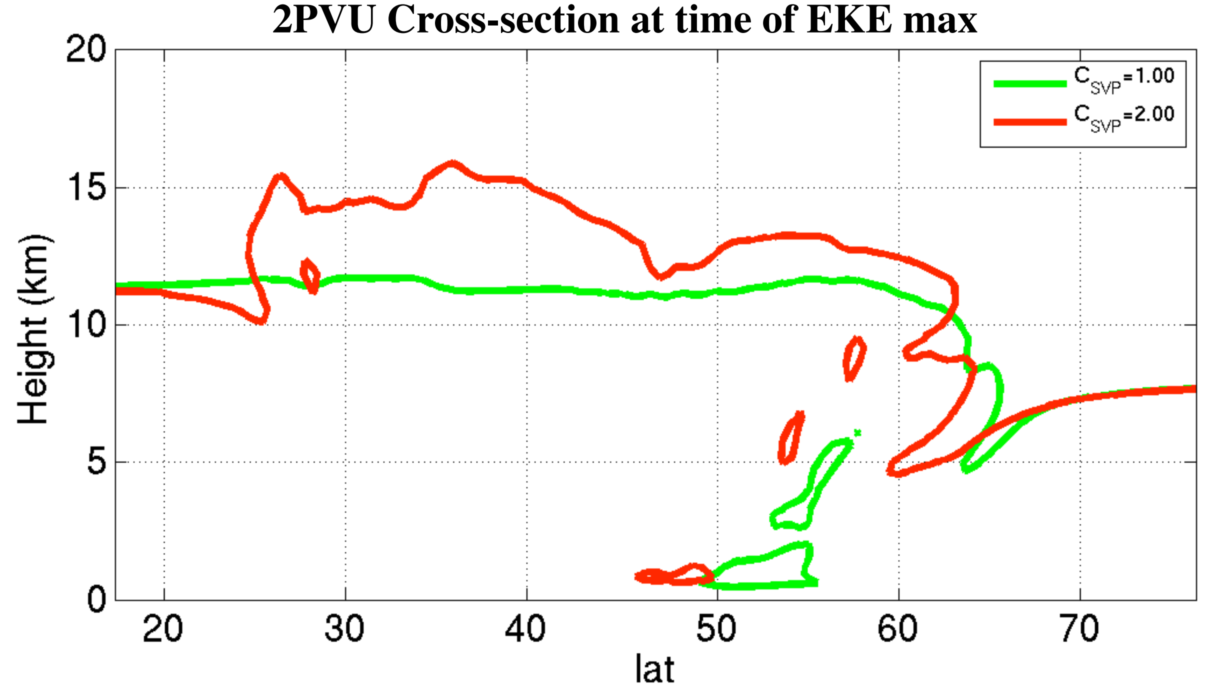
Explanation of storm response

Mechanism affecting storms:

Increase in moisture

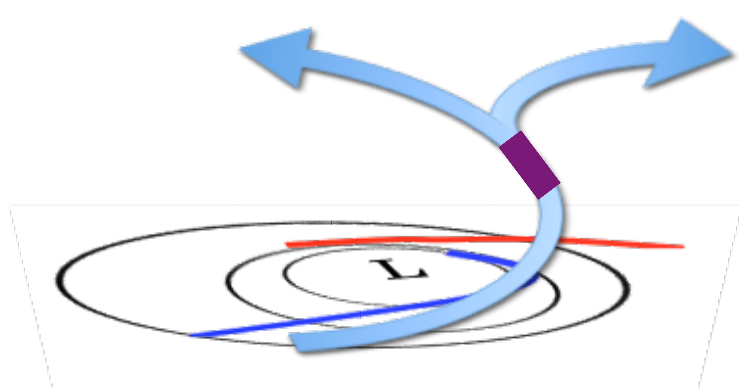
→ more latent release and increase in conditional instability.

→ increased verticality and decrease in meridional extent of warm conveyor belt.



green: $C_{SVP} = 1$, **red**: $C_{SVP} = 2$

3-D Schematic of Warm Conveyor Belt



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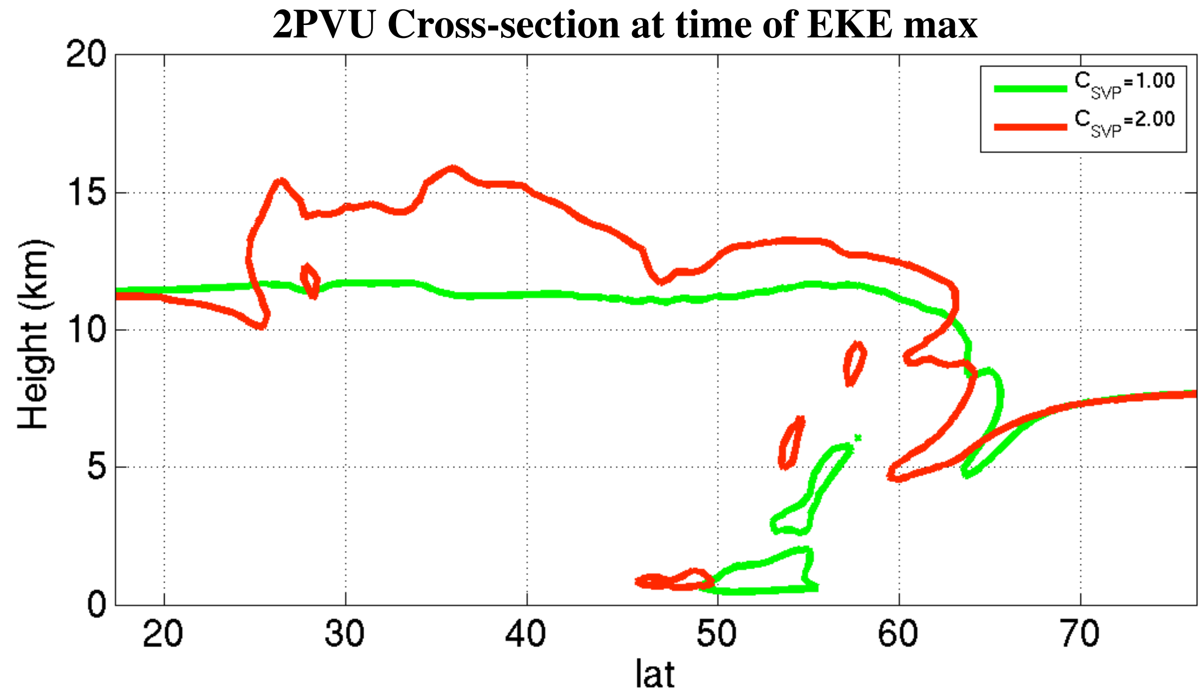

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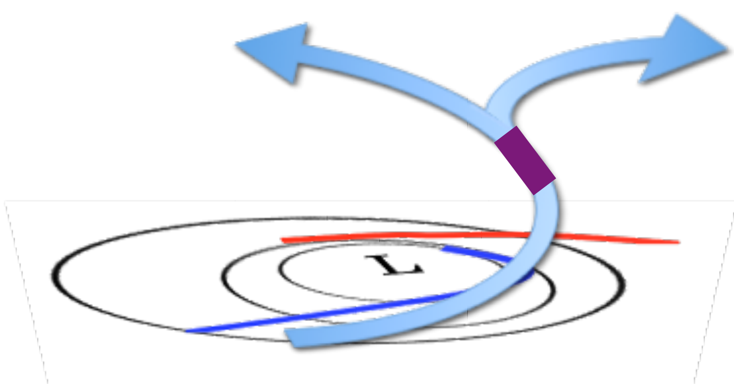
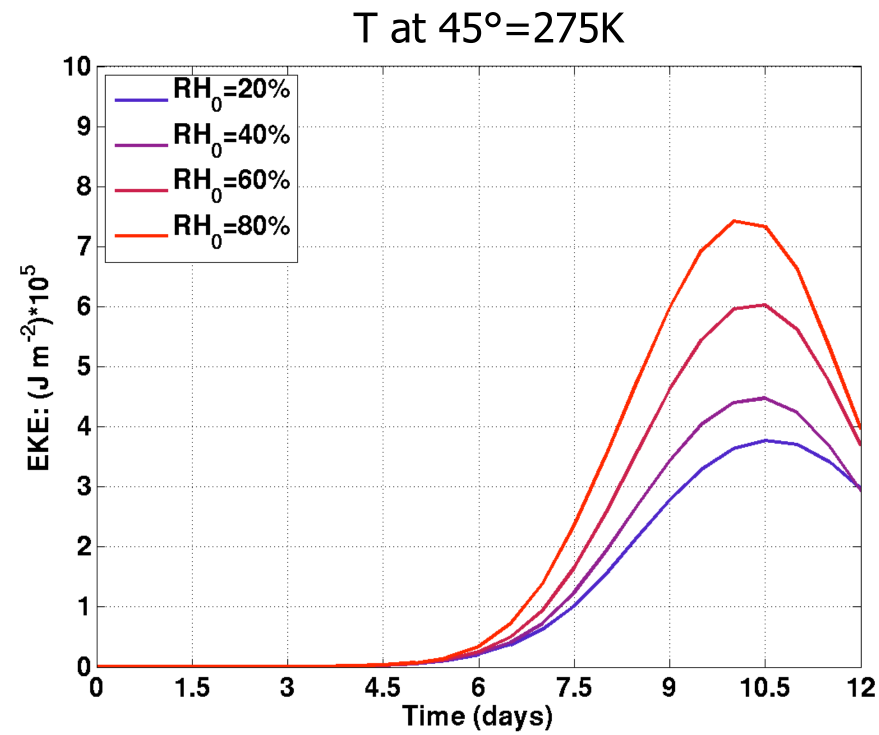
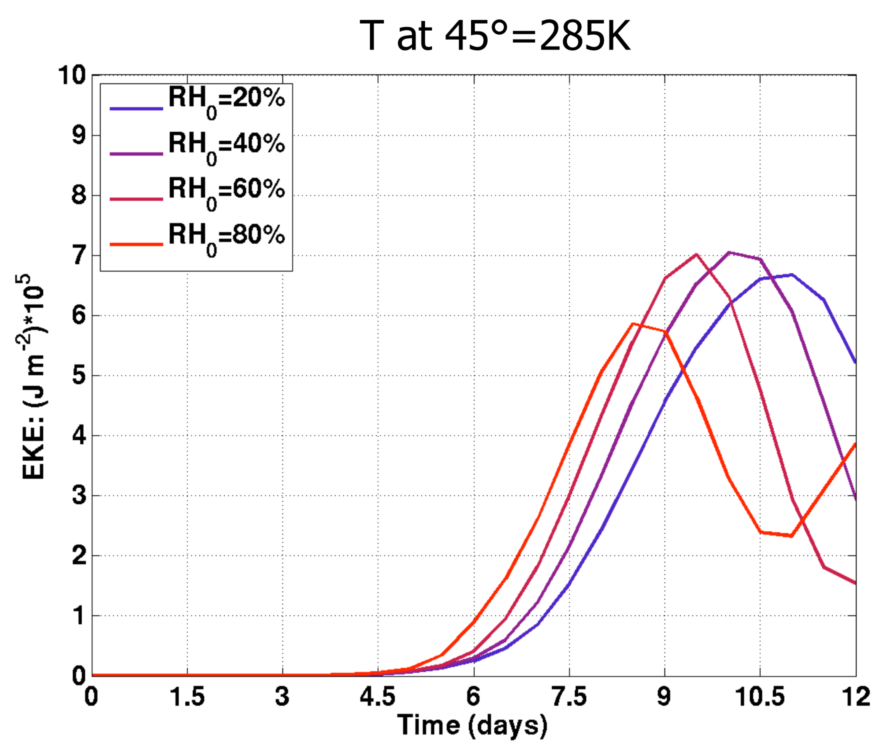
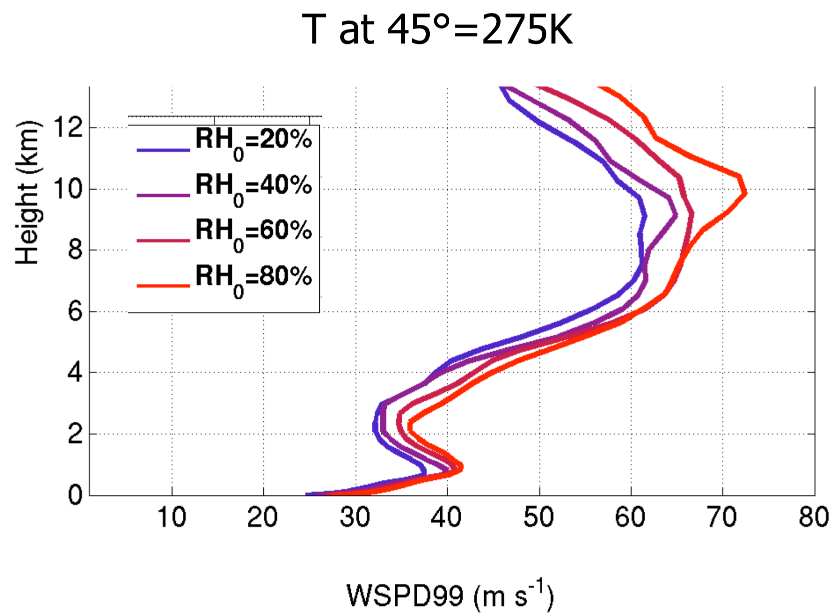
3-D Schematic of Warm Conveyor Belt

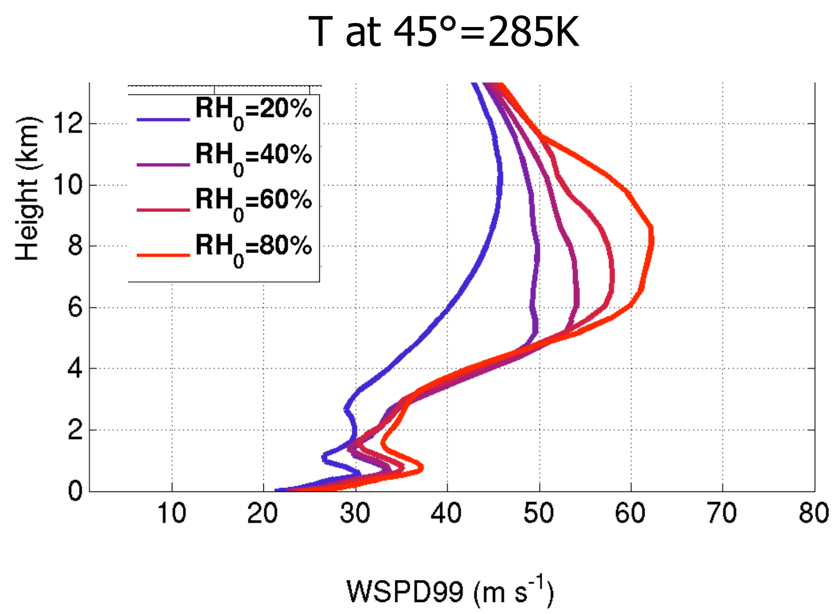


?


T at 45°=275K
EKE: (J m-2)*10^5
Time (days)
RH0=20%
RH0=40%
RH0=60%
RH0=80%
0
1.5
3
4.5
6
7.5
9
10.5
12
0
1
2
3
4
5
6
7
8
9
10


T at 45°=285K
EKE: (J m-2)*10^5
Time (days)
RH0=20%
RH0=40%
RH0=60%
RH0=80%
0
1.5
3
4.5
6
7.5
9
10.5
12
0
1
2
3
4
5
6
7
8
9
10


T at 45°=275K
Height (km)
WSPD99 (m s-1)
RH0=20%
RH0=40%
RH0=60%
RH0=80%
0
2
4
6
8
10
12
10
20
30
40
50
60
70
80


T at 45°=285K
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RH0=60%
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0
2
4
6
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12
10
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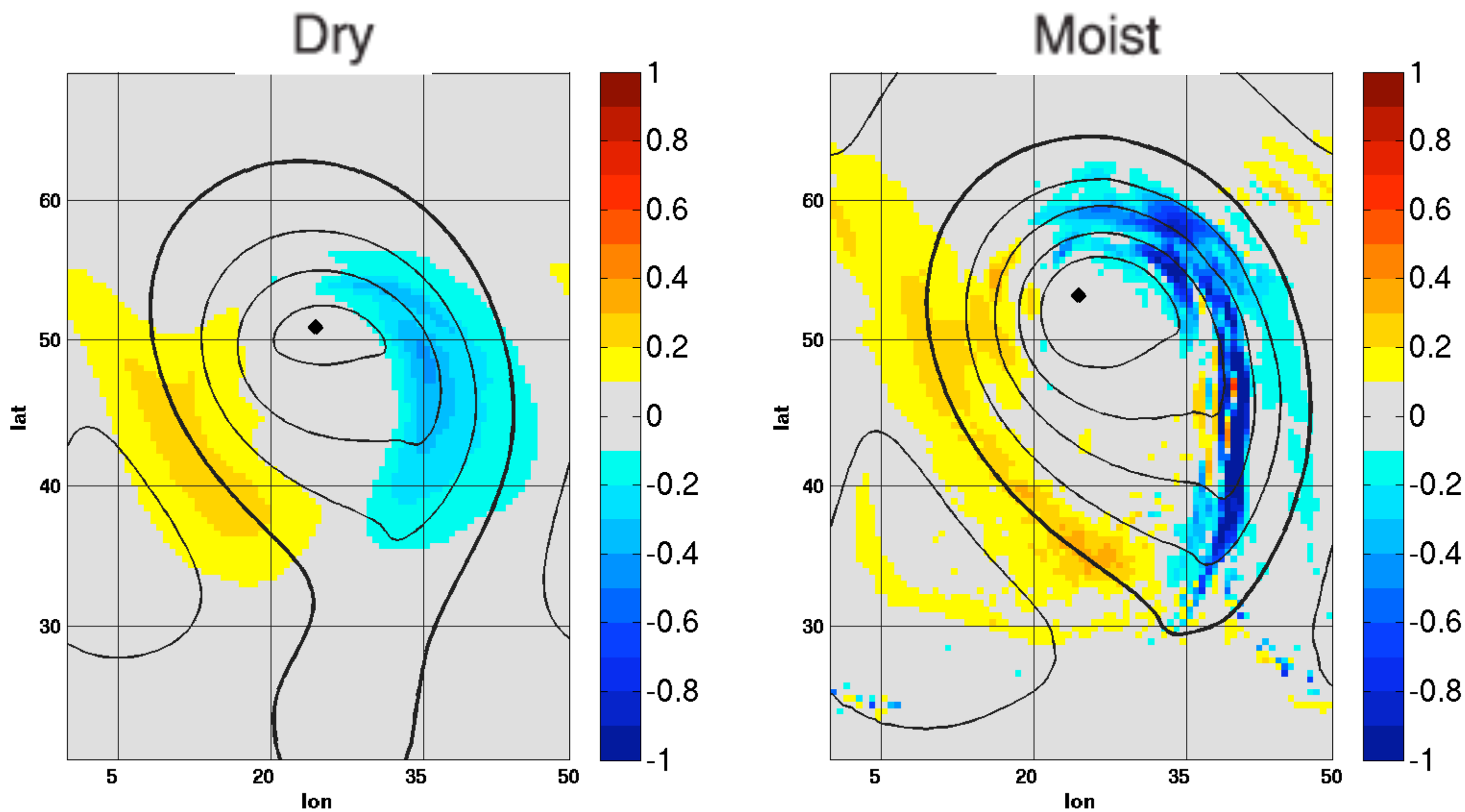
30
40
50
60
70
80

REVISIT: Dry (C_{SVP}=0) vs. Moist (C_{SVP}=1)

700 hPa Vertical Velocity



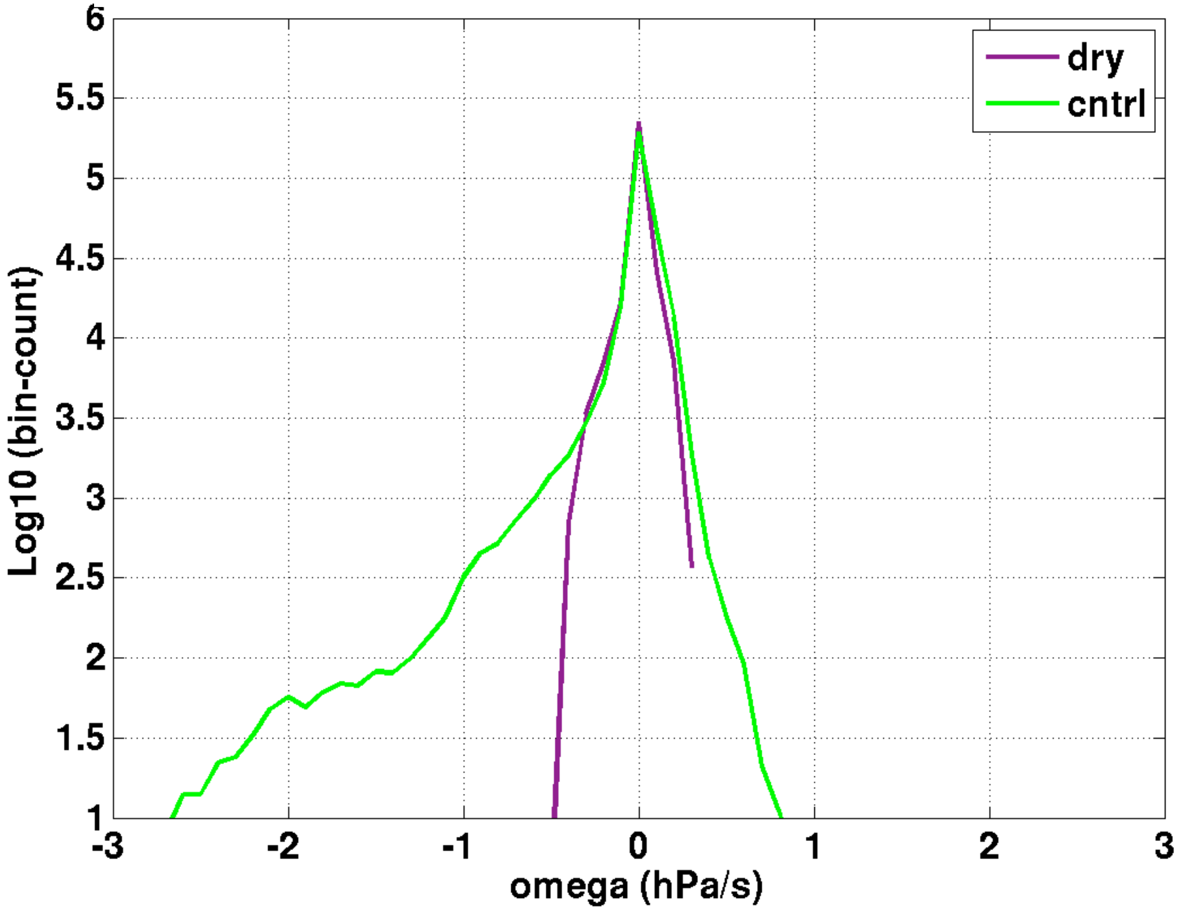
COLORS: ω (Pa/sec)
SHADING: sea level pressure

adding moisture leads to scale collapse at the fronts (~Emanuel et al. 1987)
Scale changes for storm as a whole ? Needs more work.

$$\lambda \equiv \frac{\overline{\omega'\omega^{\uparrow}{}'}}{\overline{\omega'^2}}$$

Relates to asymmetry of impact that moisture has on vertical motion.

Distribution of all vertical velocities
at 1 – 8 km range
from init. until EKE_{MAX}



Moisture increases the asymmetry between upward and downward motions