

# The Impact of Ice Phase Cloud Parameterizations on Tropical Cyclone Prediction

Yi Jin

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Acknowledgement: Steve Lowder, A. Reinecke, J. Schmidt



# Outline

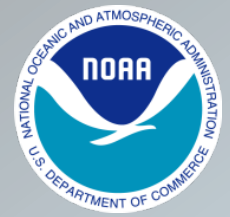


- Introduction
- COAMPS-TC system overview
- Experiment setup
- Impact of microphysics on the synoptic environment
- Evaluation of TC tests
- Summary and future research

**Results in press at MWR (early release)**



# Introduction - Background



- **Observational studies:**
  - **Descriptions of mature TC inner core structure and environment** (e.g., Riehl and Malkus 1961; Grey and Shea 1973; Zipser 2003)
  - **Limited direct observations of microphysical properties in TCs** (e.g., Houze et al. 1992; Heymsfield et al. 2006)
- **Modeling studies:**
  - **Idealized and/or axisymmetric simulations** (e.g., Lord et al. 1984; Emanuel 1986, 1999; Hendricks et al. 2004; Fovell et al. 2009)
  - **Three-dimensional modeling with full physics** (e.g., Kasahara et al. 1961; Braun 2002; Liu et al. 1997)
- **High-resolution simulations (1-3 km) and evaluation:**
  - **Success in simulations with explicit microphysics** (e.g., Rogers et al. 2007; Li and Pu 2008; Chen et al. 2011)
  - **Limited to cases studies – TC intensity prediction remains a challenge for Numerical Weather Prediction (NWP) models** (e.g., Rogers et al. 2010; MacFaquhar et al. 2006)



# COAMPS-TC System Overview



- **COAMPS-TC:** Coupled Ocean/Atmosphere Mesoscale Prediction System for Tropical Cyclones
- **Analysis:** Vortex relocation, synthetic observations, 3D-Var (NAVDAS)  
**Atmosphere:** Nonhydrostatic, moving nests, CBLAST fluxes, dissipative heating, shallow convection, spray parameterization option
- **Ocean:** 3D-Var (NCODA), NCOM, SWAN, Wave Watch III options
- **Ensemble:** Coupled Ensemble Transform, Ensemble Kalman Filter
- **Configuration:** NOGAPS/GFS BCs, uncoupled or coupled
- **Objective:** Investigate the impact of ice phase cloud parameterizations on TC prediction through systematic forecast evaluation for both synoptic environment and TC cases



# COAMPS-TC Microphysics



## • **Old Microphysics:**

- Single-moment, bulk, 5 species (cloud water and ice, rain, snow, and graupel) (Derived from Rutledge and Hobbs 1983-84; Lin et al. 1983)
- Optional two moment drizzle parameterization (Khairoutdinov and Kogan 2000)

## • **Thompson V4.3 (updated July 2011):**

- Two-moment for cloud ice and rain only
- Findings from field campaigns incorporated
- Extensively examined for winter storms (Liu et al. 2011; Colle 2012)
- First application to TC cases through COAMPS-TC

## • **New Microphysics (by Schmidt):**

- Thermodynamic constants dependent on temperature & pressure
- Updated vapor deposition rate
- Ice Nuclei formulation (Demott et al. 1994)



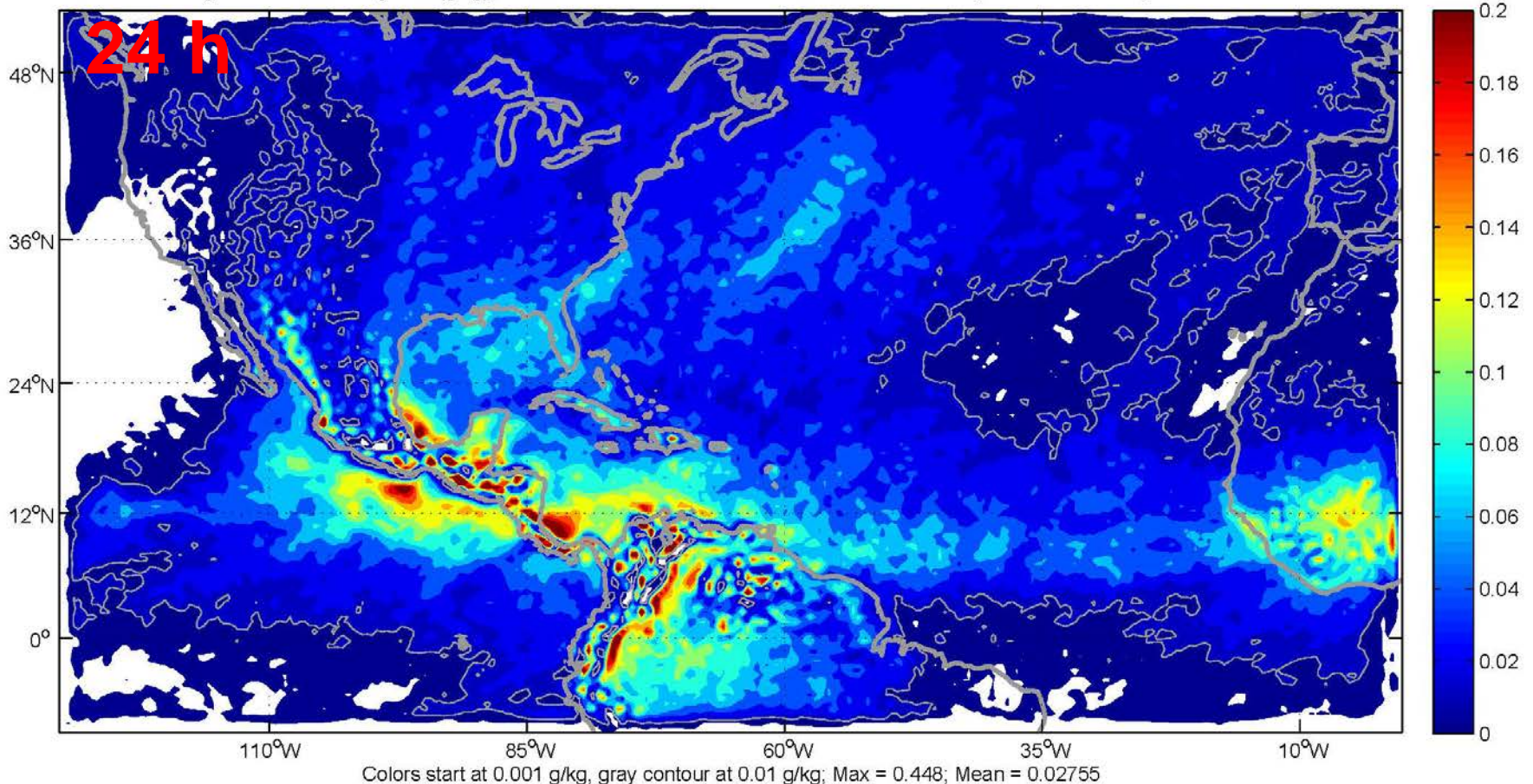
# Experiment Setup

- **Other physics:**
  - Surface fluxes: drag coefficient reduction at high winds; dissipative heating
  - PBL: new implicit TKE dissipation; New mixing length
  - Fu-Liou radiation (both long and short wave)
  - Shallow convection: Tiedtke type shallow convection
  - Kain-Fritsch (KF) cumulus scheme for  $dx > 10$  km
- **Model setup:**
  - 120-h forecasts cycled every 12 h for two months (Aug-Sept 2010) (45-km)
  - Calculate average forecasts and difference between forecasts and analysis as function of forecast time
  - 40 vertical levels with model top at 31 km
  - 3 nests: 45-, 15-, and 5-km grid spacing for TC cases
  - Cycled every 6 h

# Synoptic tests – Control run

250-hPa cloud ice ( $\text{g kg}^{-1}$ ) at 24 h  
(averaged over the 2-month period)

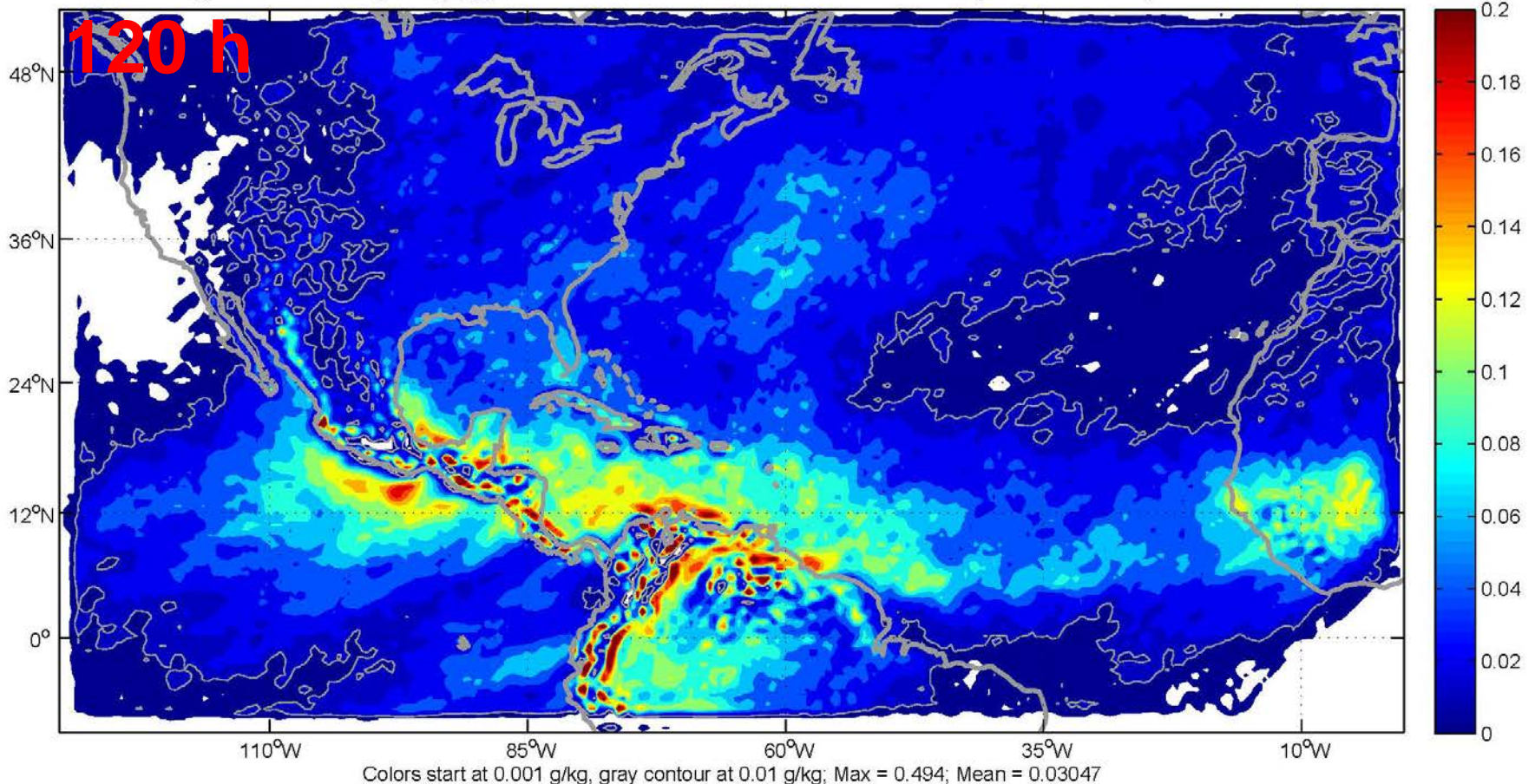
Average 250mb Ice mixing ratio ( $\text{g/kg}$ ), 99 forecasts from DTG = 2010081100 to 2010092900, Lead time = 24 h, COAMPS-TC 4zc



# Synoptic tests – Control run

250-hPa cloud ice ( $\text{g kg}^{-1}$ ) at 120 h  
(averaged over the 2-month period)

Average 250mb Ice mixing ratio ( $\text{g/kg}$ ), 99 forecasts from DTG = 2010080700 to 2010092500, Lead time = 120 h, COAMPS-TC 4zc





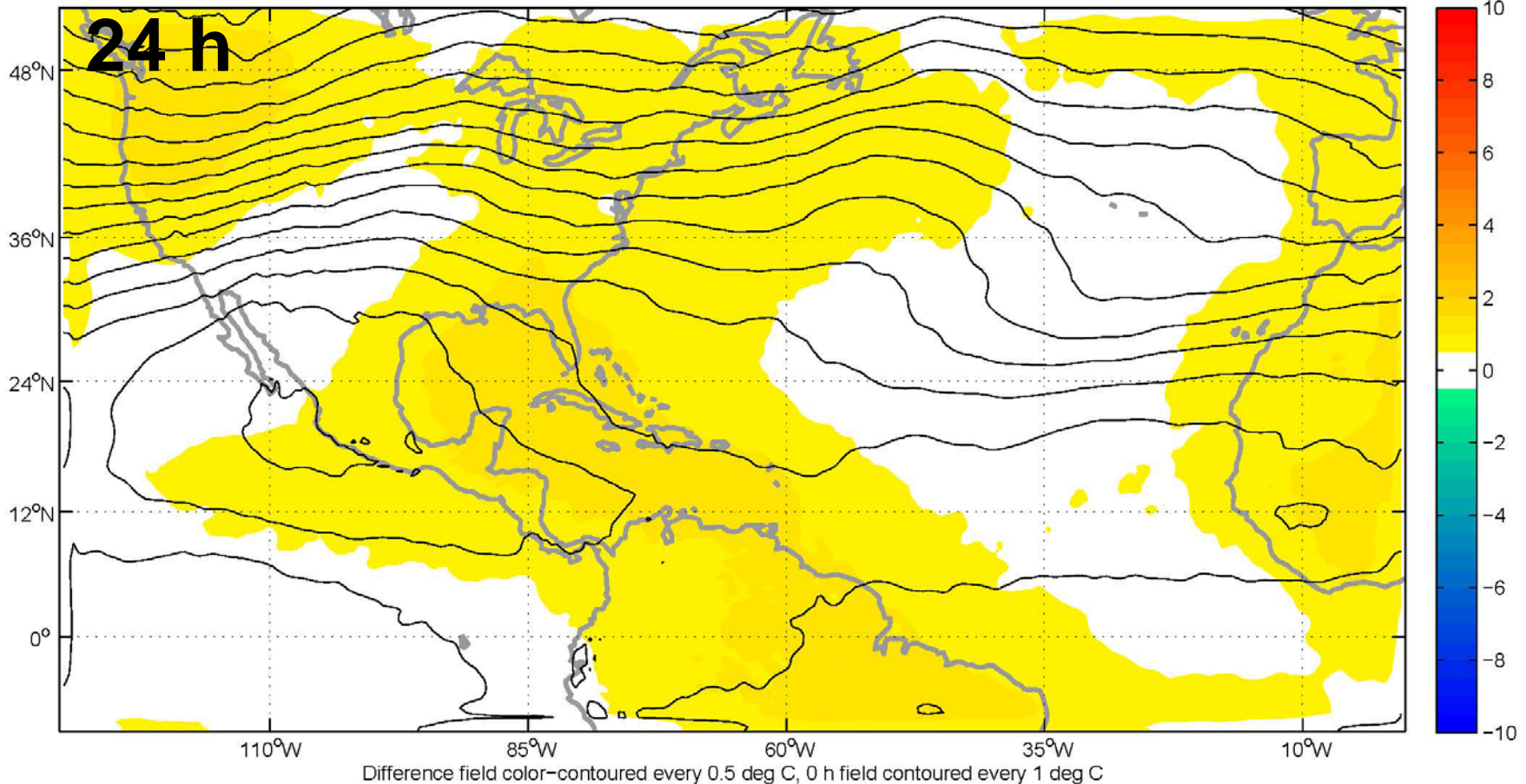


# Synoptic tests – Control run



300 hPa temperature ( $^{\circ}\text{C}$ ) change from the initial time  
(averaged over the 2-month period)

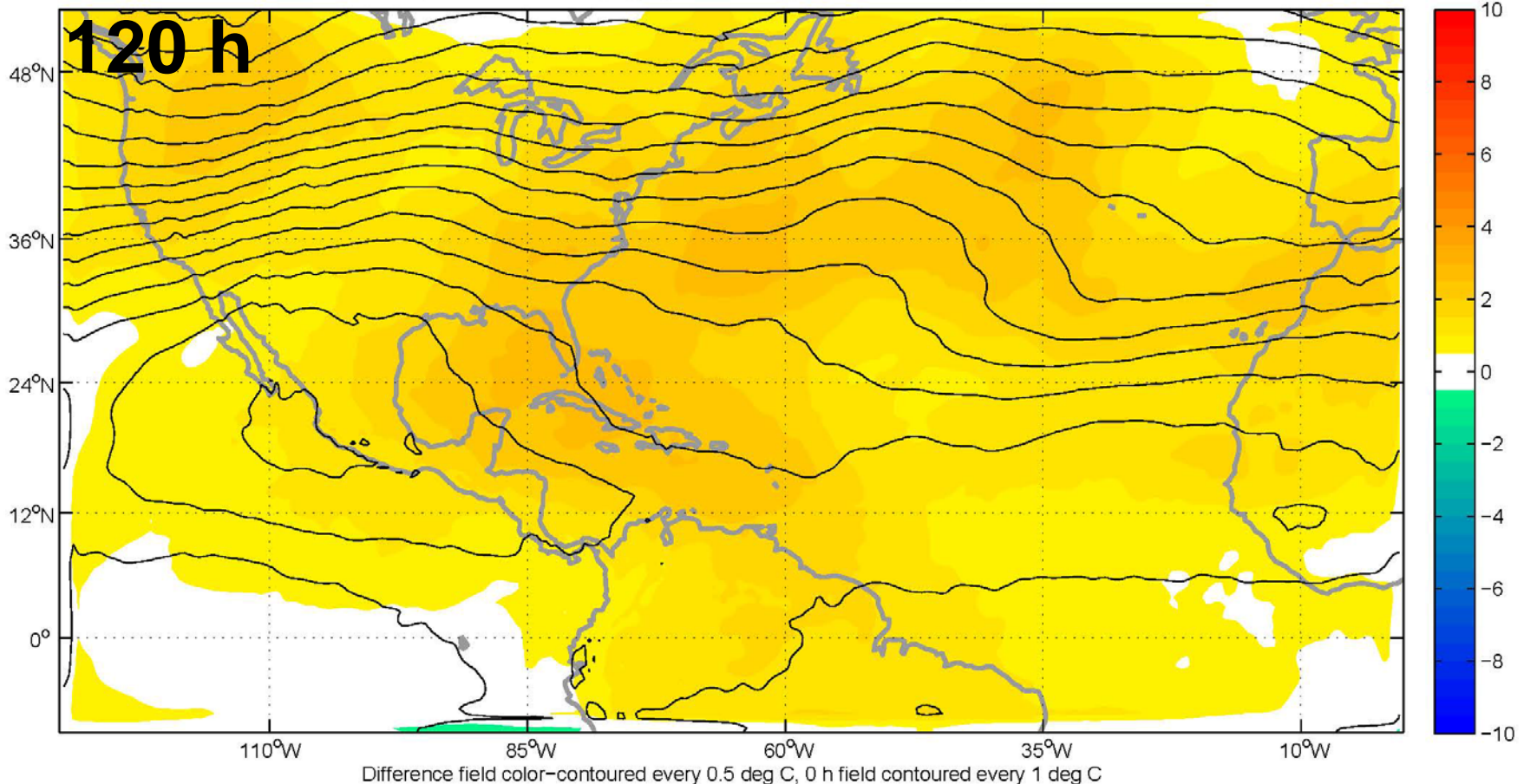
300mb Temperature difference (deg C), 24 h average minus 0 h average, COAMPS-TC 4zc



# Synoptic tests – Control run

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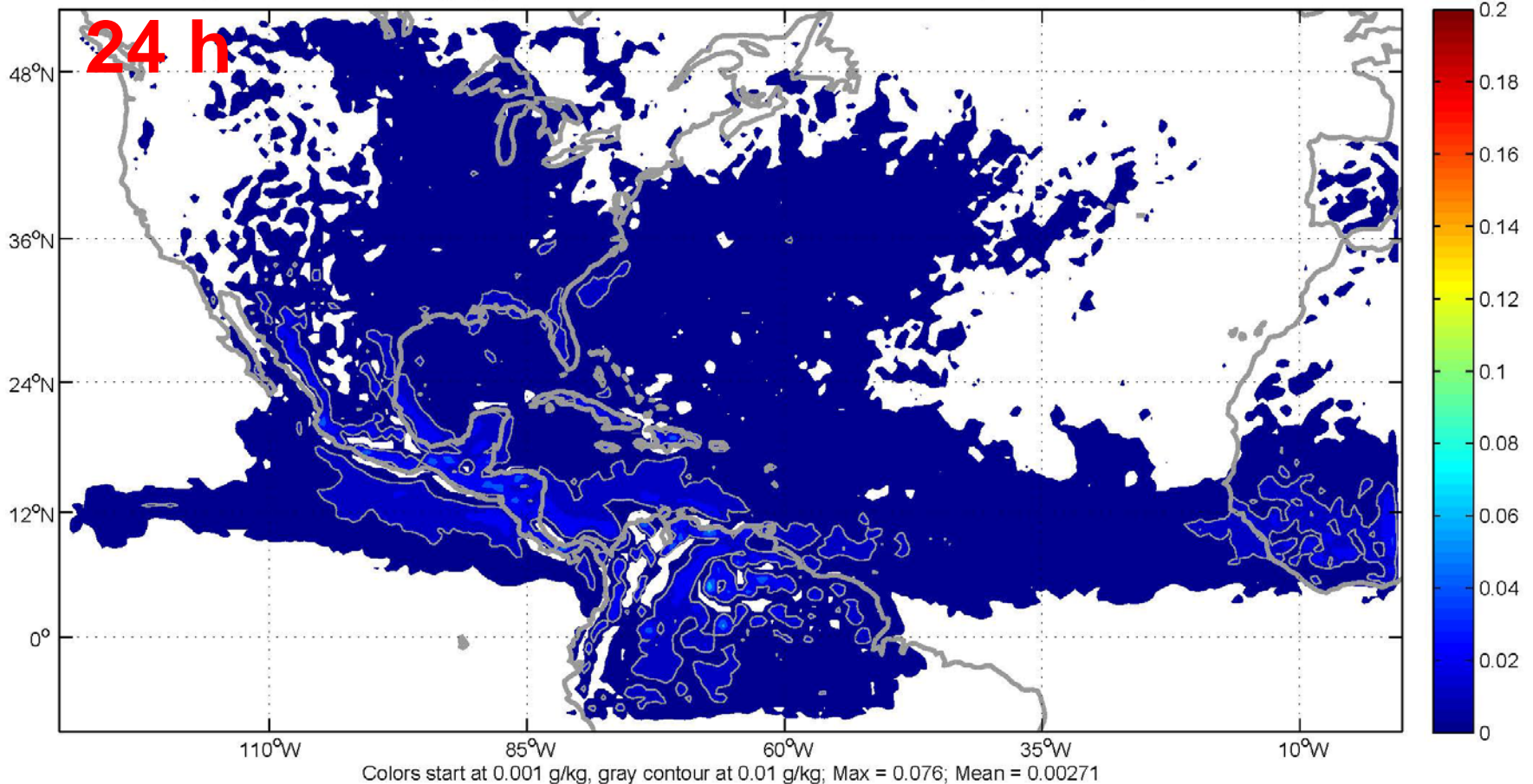
300mb Temperature difference (deg C), 120 h average minus 0 h average, COAMPS-TC 4zc



# Synoptic tests – Thompson run

250-hPa cloud ice ( $\text{g kg}^{-1}$ ) at 24 h  
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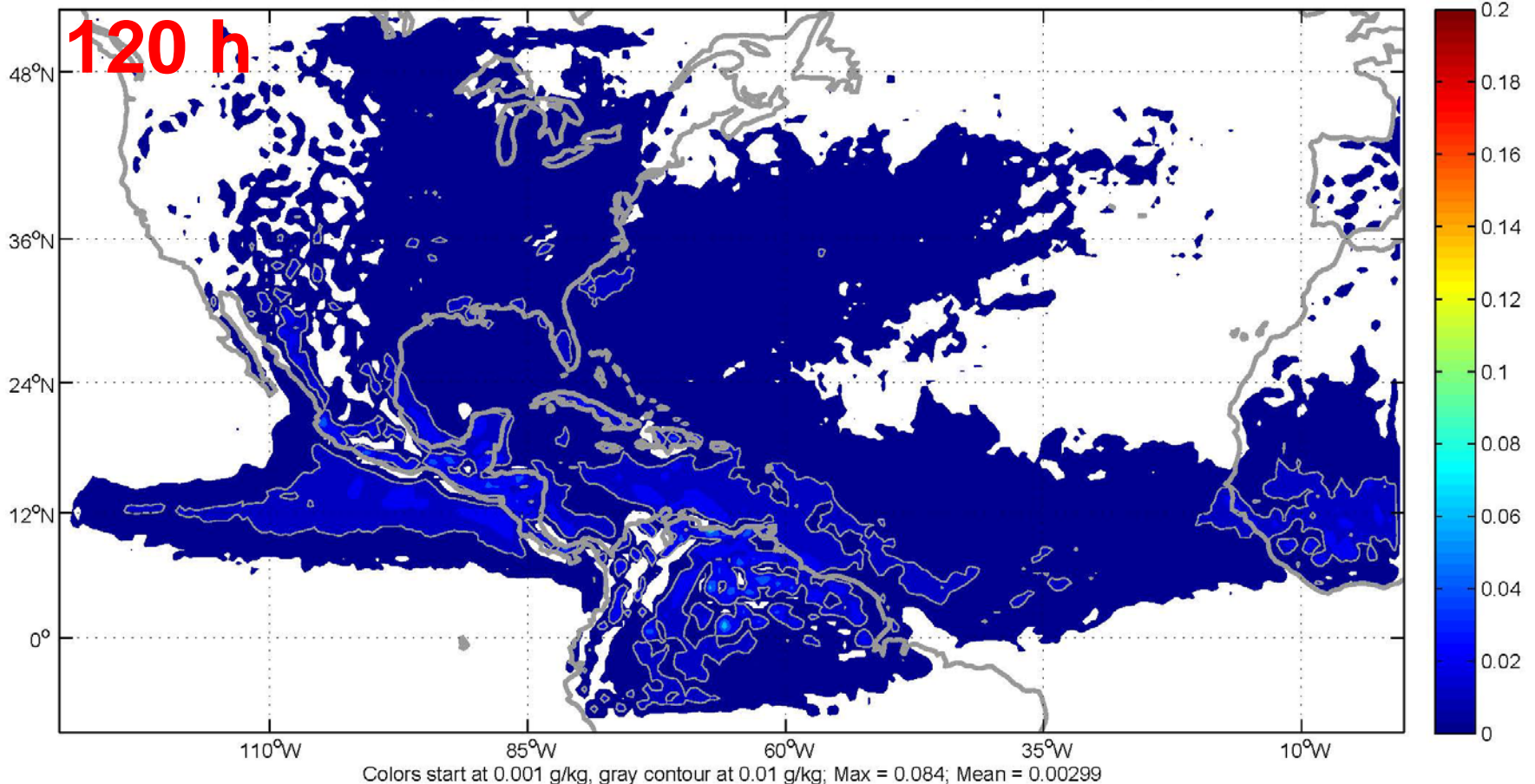




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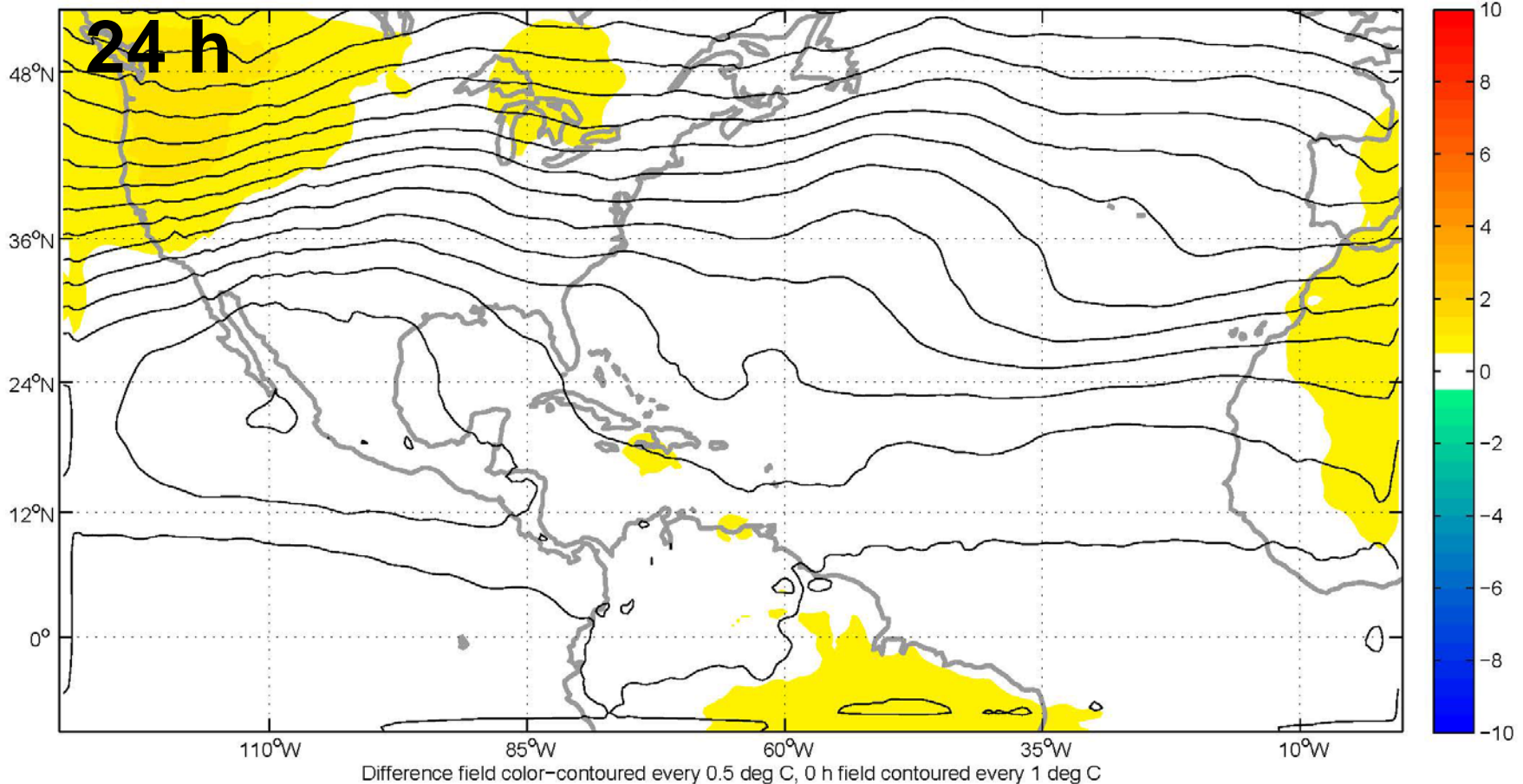




# Synoptic tests – Thompson run

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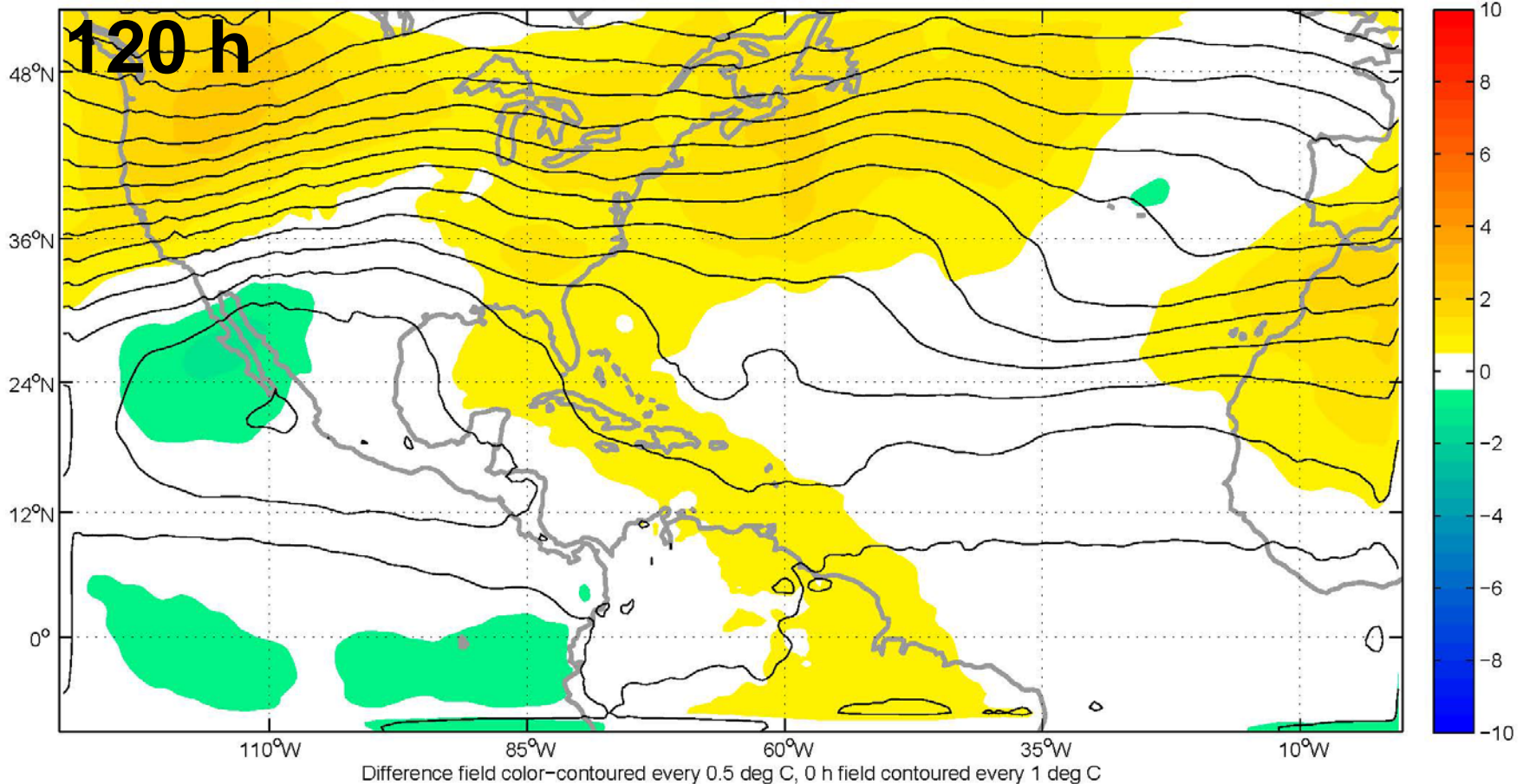
300mb Temperature difference (deg C), 24 h average minus 0 h average, COAMPS-TC 4zt



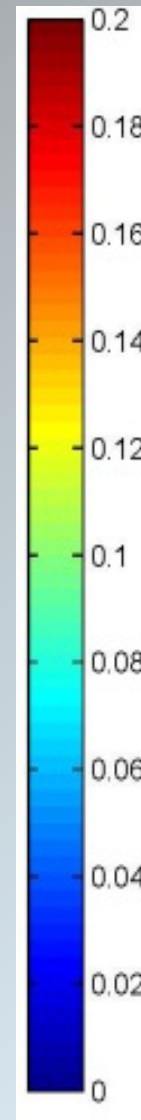
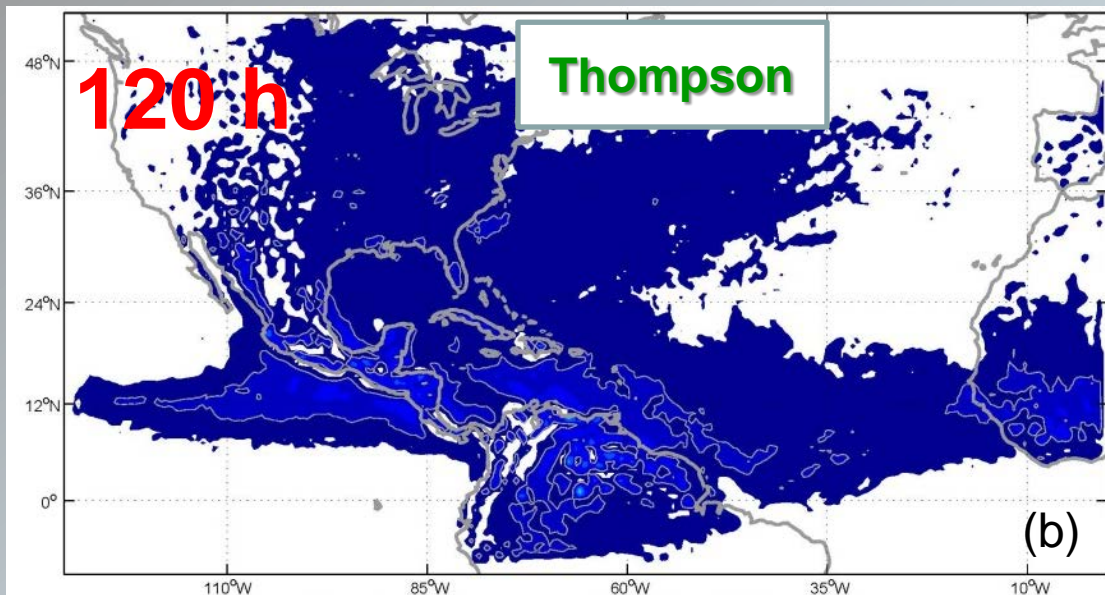
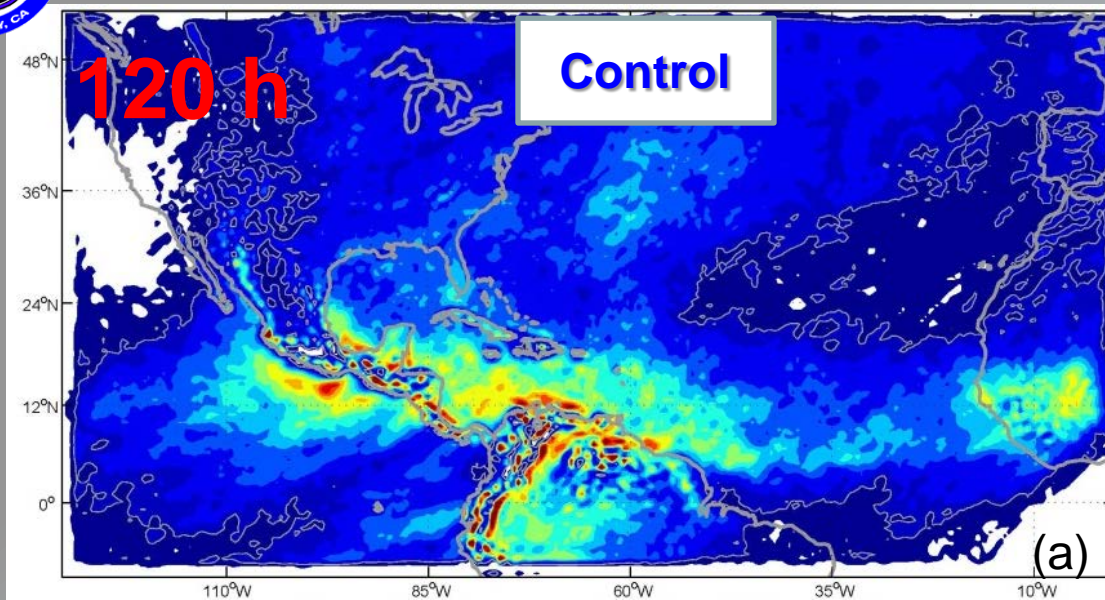
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300mb Temperature difference (deg C), 120 h average minus 0 h average, COAMPS-TC 4zt



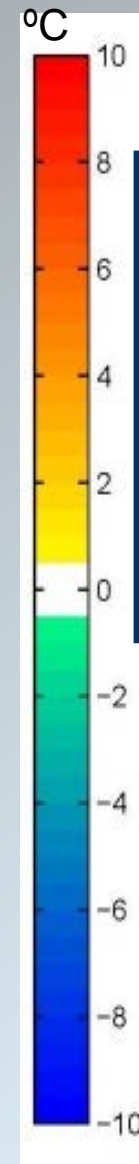
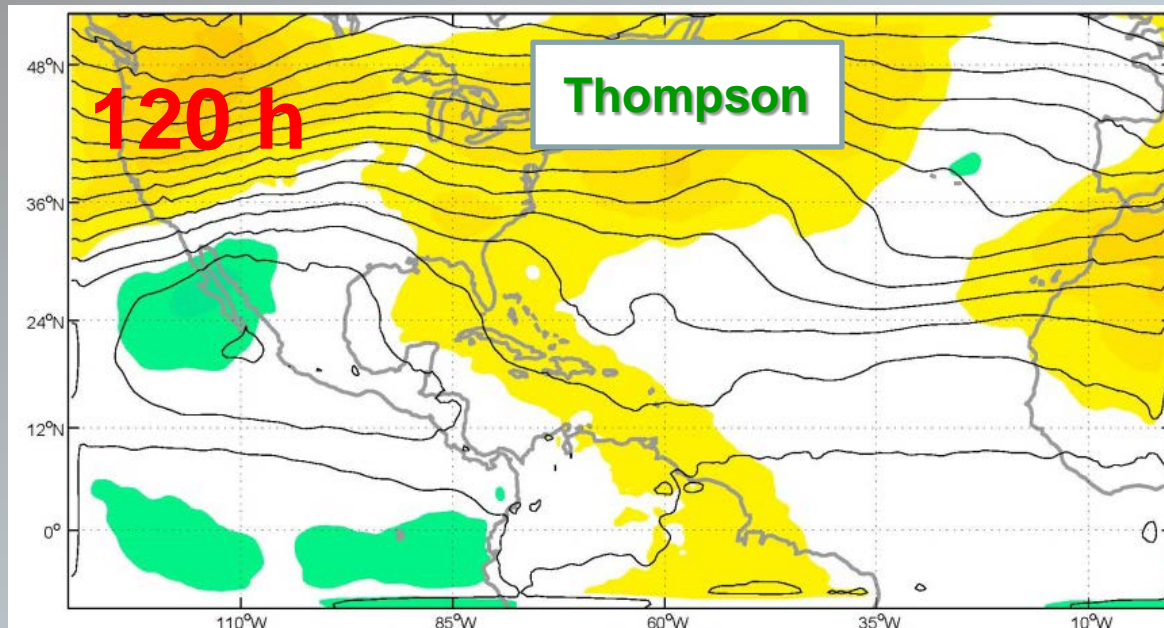
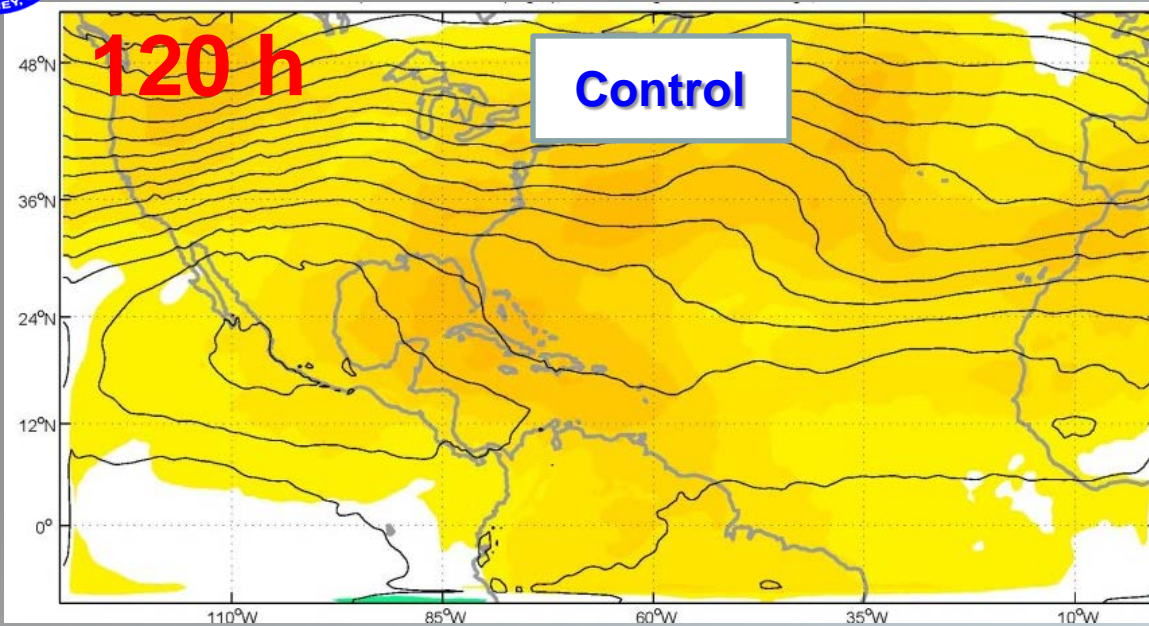
# Control vs. Thompson – Cloud Ice



- Cloud ice increases with time in the control simulations and covers most of the domain (domain mean  $0.03 \text{ g kg}^{-1}$ ; max  $0.5 \text{ g kg}^{-1}$ ).
- Cloud ice is reduced in the Thompson simulations (by an order of magnitude).



# Control vs. Thompson – Temperature



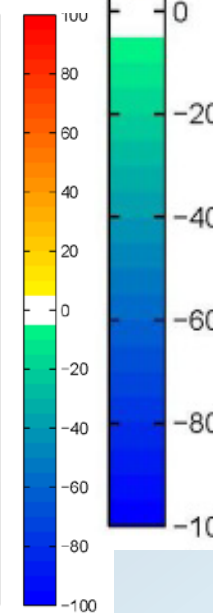
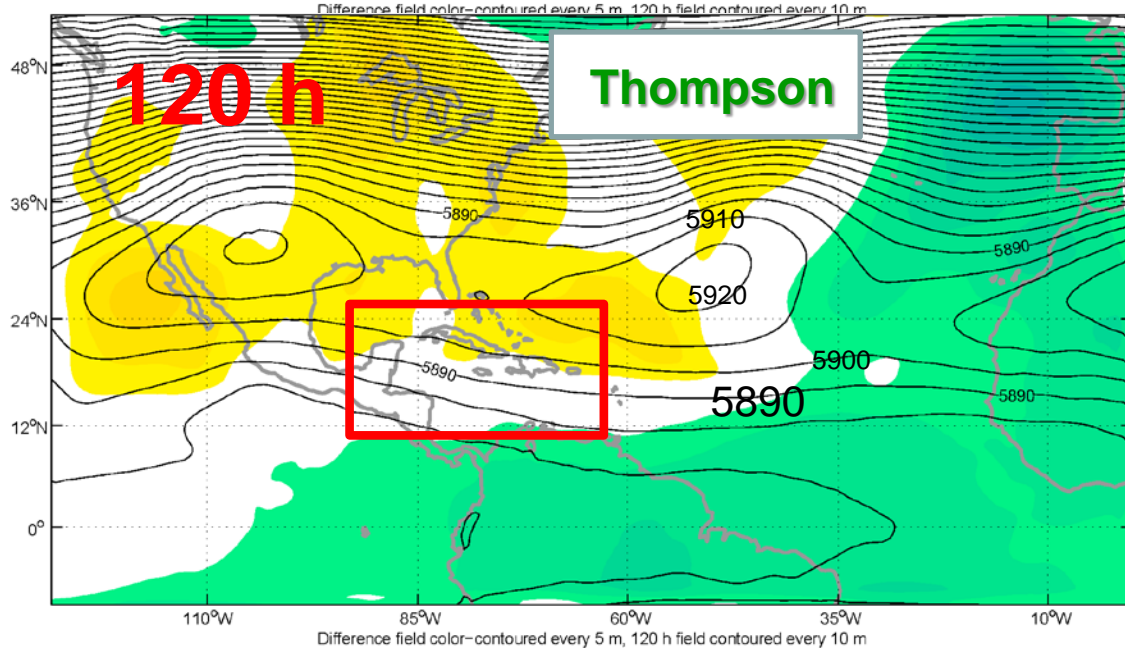
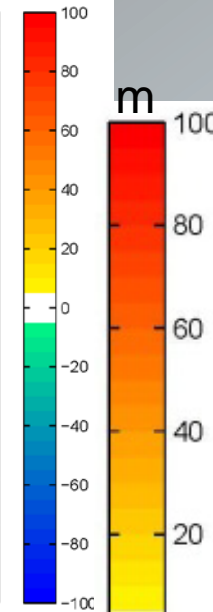
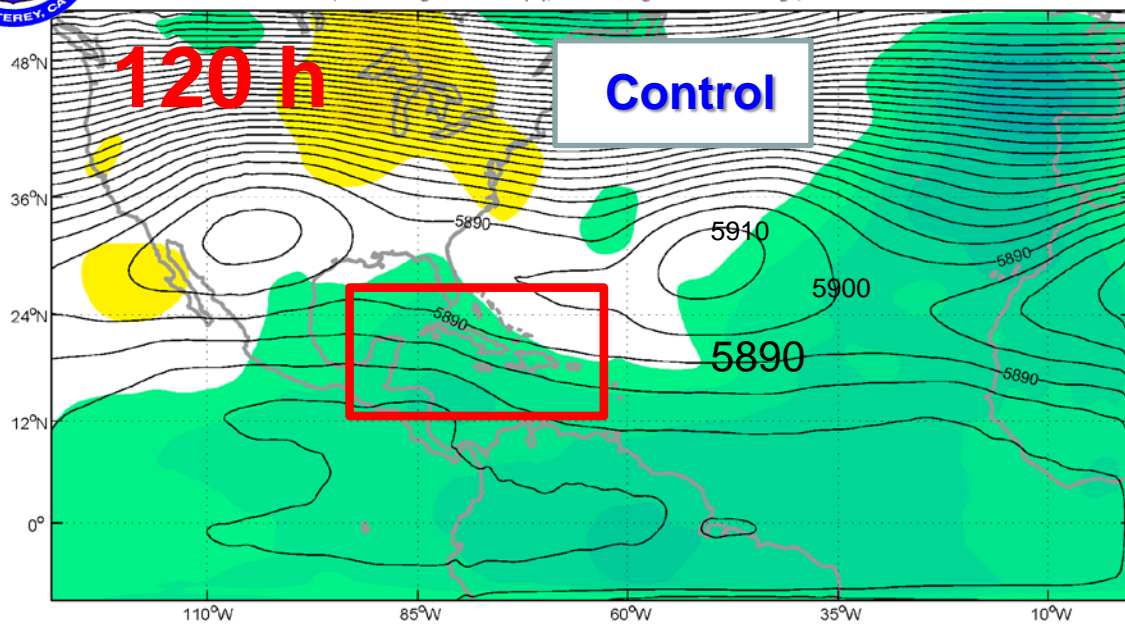
**The Thompson scheme effectively removes upper level warm bias seen in the control simulations.**





# Control vs. Thompson – 500hPa

500mb Geopotential height difference (m), 120 h average minus 0 h average, COAMPS-TC 4zc



- The southern edge of the subtropical high retreats northward in the control simulations but remains stationary in the Thompson simulations.
- TC tracks are influenced by the southward extension of the subtropical high via large-scale steering flow (e.g., Chan et al. 2001; Wu et al. 2007).



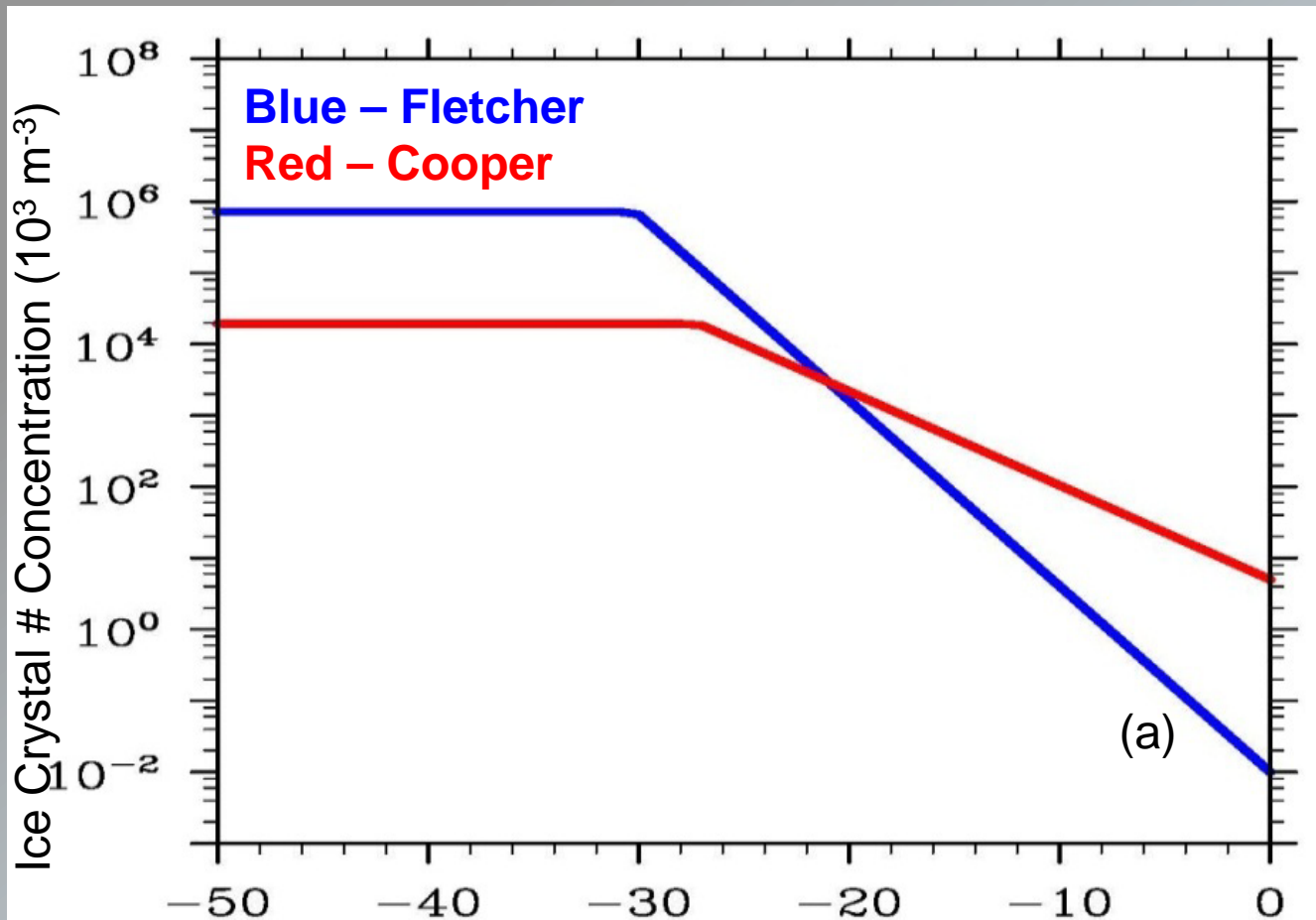
# Ice Nucleation and Formulations



- **Upper-level stratiform cloud ice**
  - Formation mainly through ice nucleation
  - Dependent on the presence of ice nuclei (IN)
  - Aerosols acting as IN in various modes (e.g., deposition, condensation freezing, immersion)
- **Large uncertainties in representing ice nucleation:**
  - Various nucleated ice crystal number formulations employed in microphysical schemes (~ a dozen)
  - Fletcher formulation (1962): derived from observed ice crystal counts at different locations; used in the Control scheme
$$N_{i,Fletcher} = 10^{-2} \exp\left[0.6(T_0 - T)\right] \quad (T_0=273.15K)$$
  - Cooper (1986): based on in-situ measurements of ice crystals in continental clouds; used in the Thompson scheme
$$N_{i,Cooper} = 5.0 \exp\left[0.304(T_0 - T)\right]$$



# Ice Nucleation Parameterization



- The Fletcher formulation has more ice crystals at cold temperatures than Cooper (by an order of magnitude).
- The ice crystal formulation used by the control simulations follows Fletcher's at cold temperatures. The Thompson scheme adopts the Cooper scheme.



# Cloud – Radiation Interaction

- **Sensitivity tests**

- Synoptic simulations with 12-h update cycles
- With changes in microphysics and/or radiation

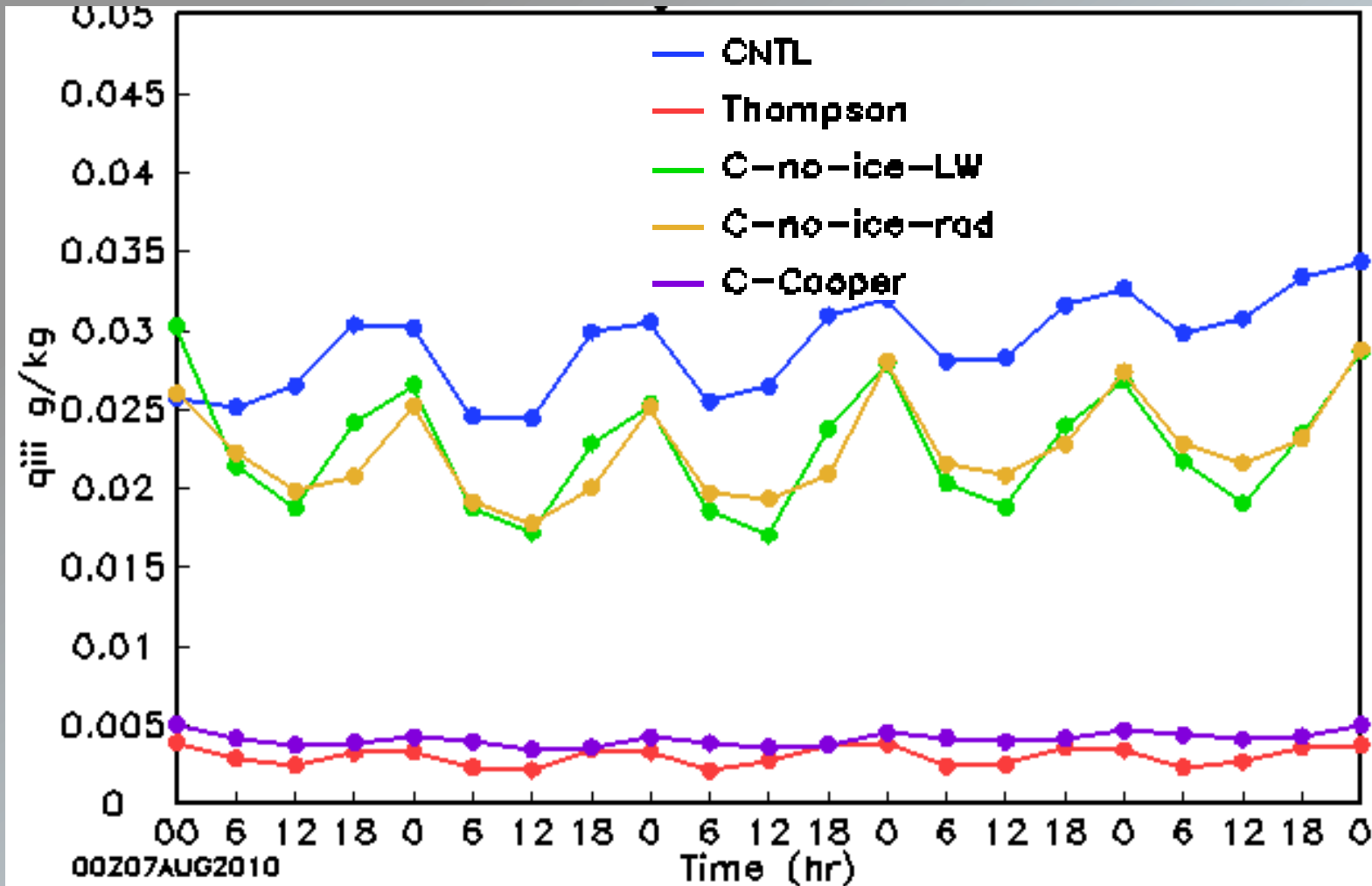
Experiment Name	Period (YYYYMMDDHH)	Main changes
<b>Control</b>	<b>2010080600- 2010093012</b>	<b>Control Microphysics</b>
<b>Thompson</b>	<b>2010080600- 2010093012</b>	<b>Thompson</b>
<b>Cooper</b>	<b>2010080600- 2010080700</b>	<b>Control micro with Cooper IN formulation</b>
<b>No_ice_lw</b>	<b>The same as above</b>	<b>Control micro with no interaction between ice and long-wave radiation</b>
<b>No_ice_rad</b>	<b>The same as above</b>	<b>Control micro with no ice-radiation interaction</b>
<b>Satv_ice</b>	<b>The same as above</b>	<b>Control micro with Thompson ice saturation criteria</b>



# Cloud – Radiation Interaction (I)



- Domain-averaged cloud ice at 250 hPa

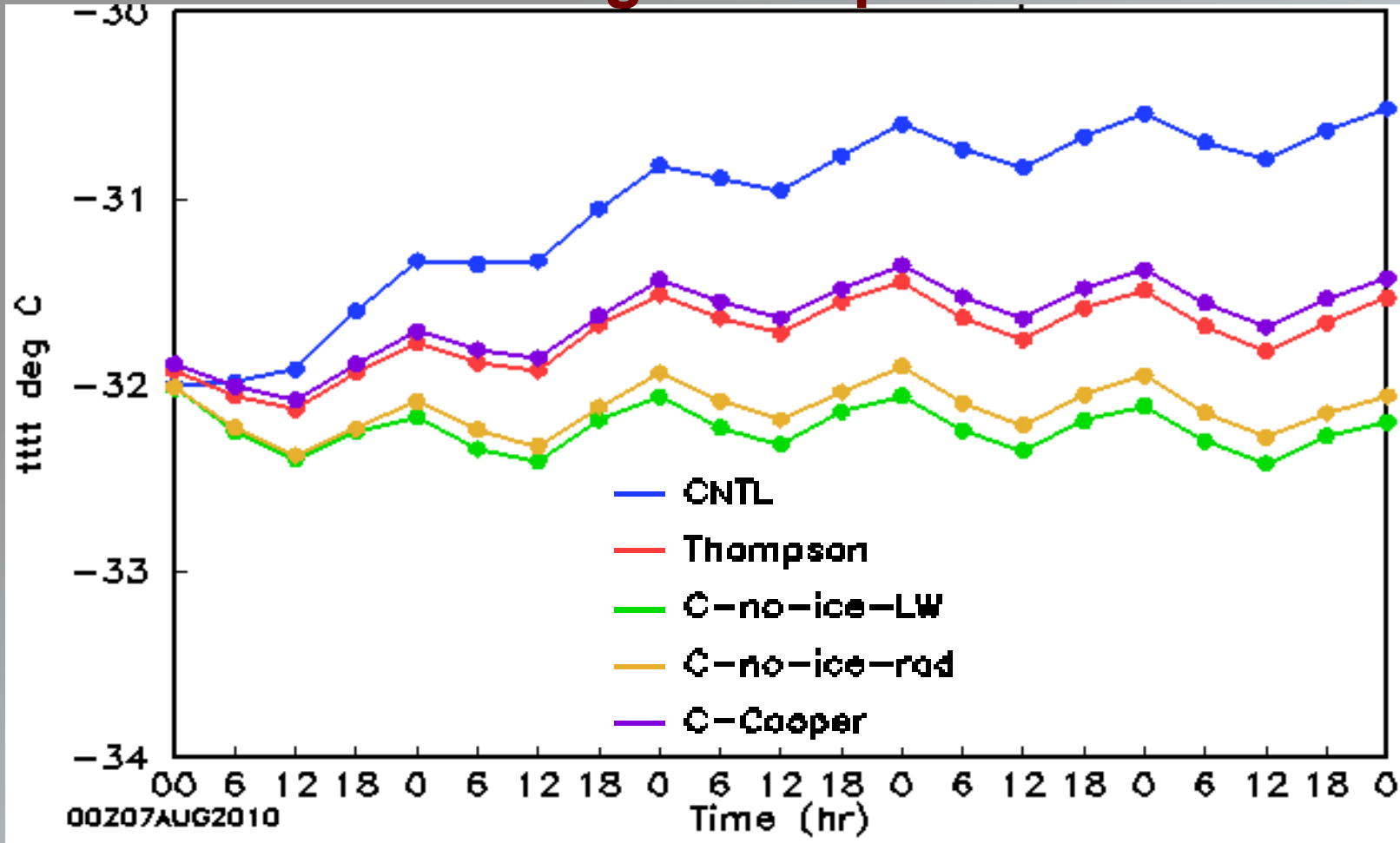




# Cloud – Radiation Interaction (II)



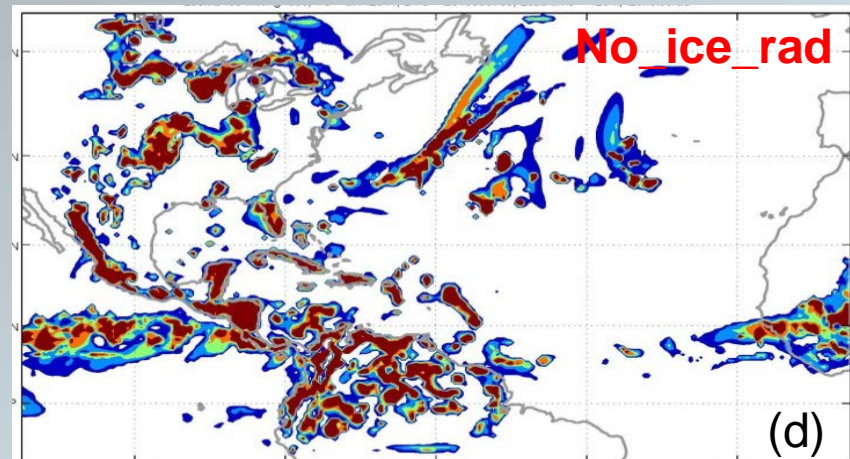
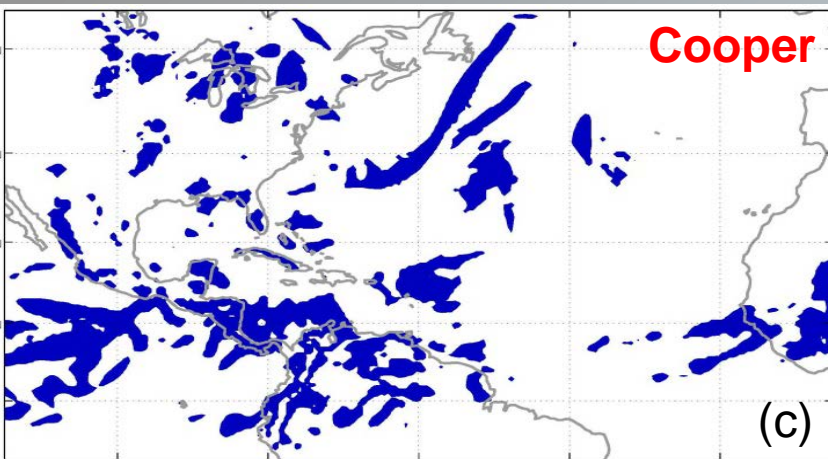
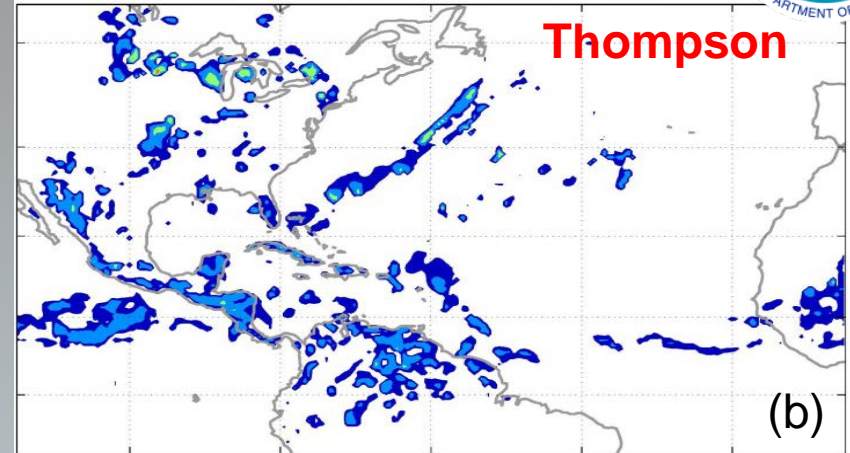
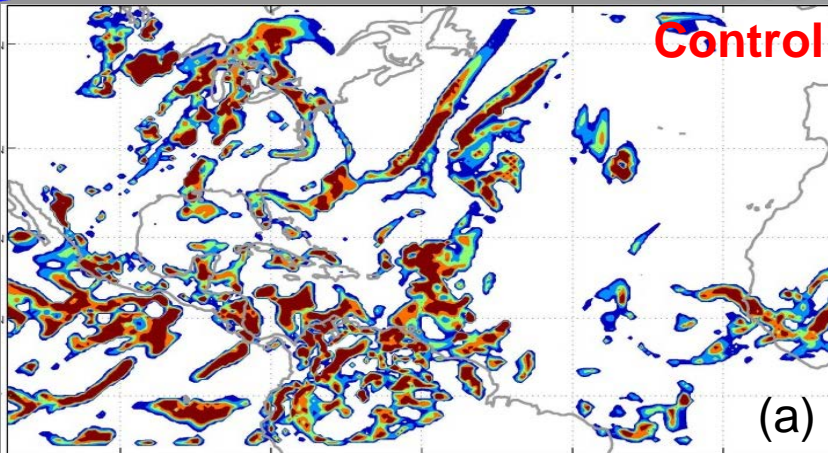
- Domain-averaged temperature at 300 hPa



The tests without radiation-cloud ice interaction and without long-wave-radiation and cloud ice interaction demonstrate the important contribution of cloud-radiation interaction to the upper-level warming.

# Cloud Ice at 250 hPa D1

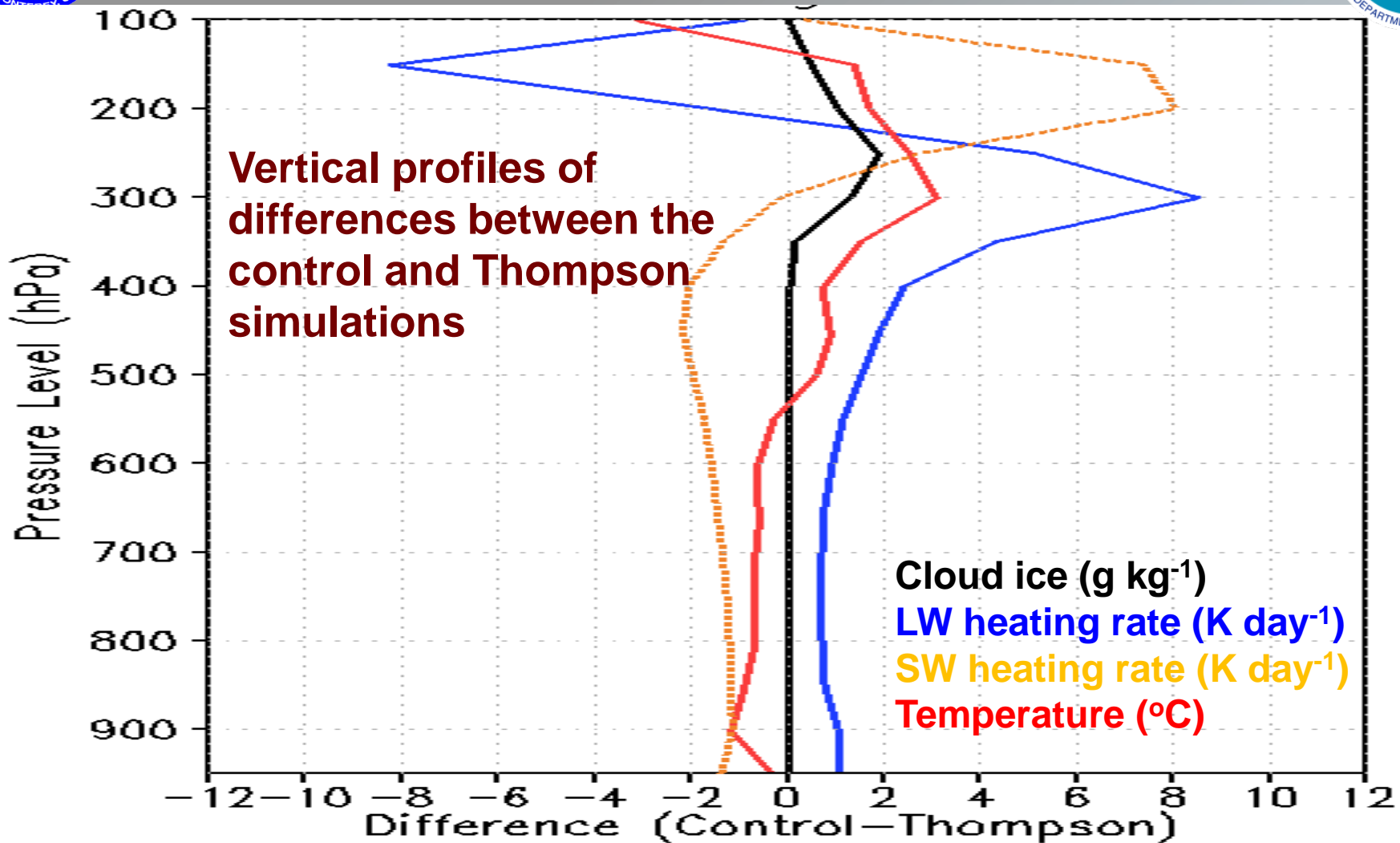
120 h fcst Initialized 2010080700



- The horizontal distribution of cloud ice from the Cooper experiment is generally one order of magnitude less than that in the control, but is similar to the amount simulated using the Thompson scheme.
- The cloud ice from the simulation without the ice-radiation interaction is similar to that from the control.



# Cloud – Radiation Interaction (III)



- The cloud-base warming is due to the localized large convergence of the upward LW radiative heating associated with the large difference between the temperature at the cloud base and at the surface.

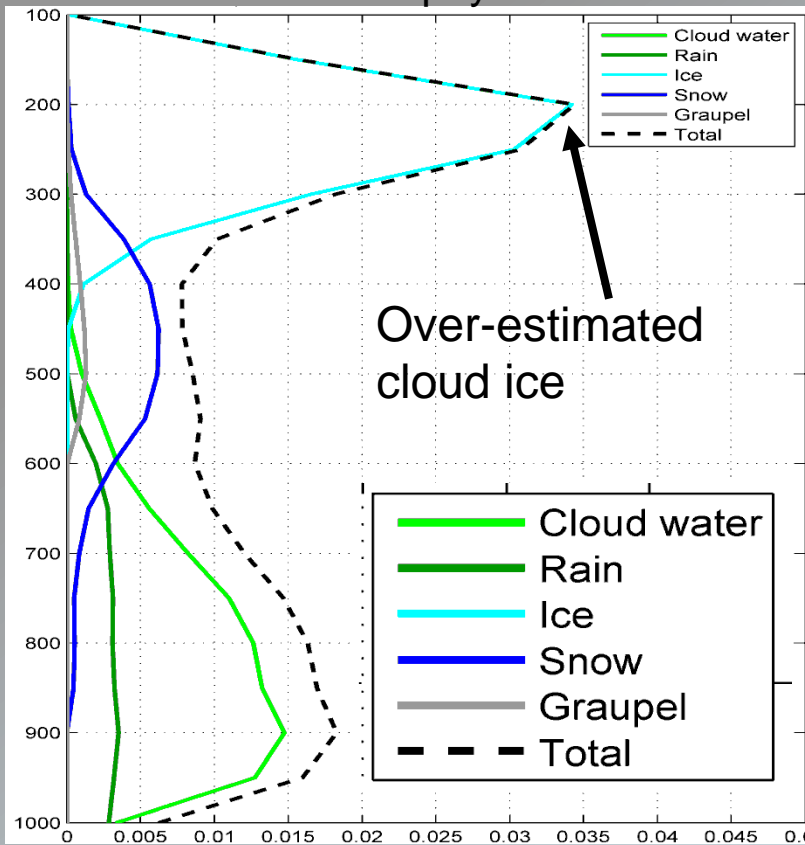




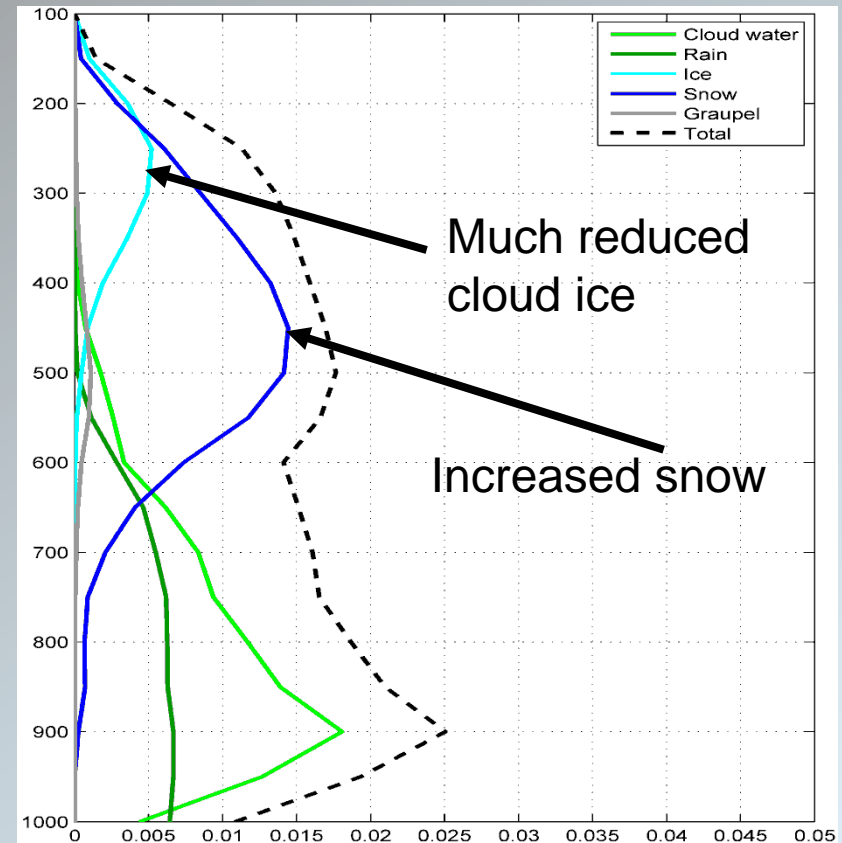
# Hydrometeors – Hurricane Igor (2010)

## • Domain averaged hydrometeors for nest 3

### Control microphysics



### Thompson microphysics



Pressure

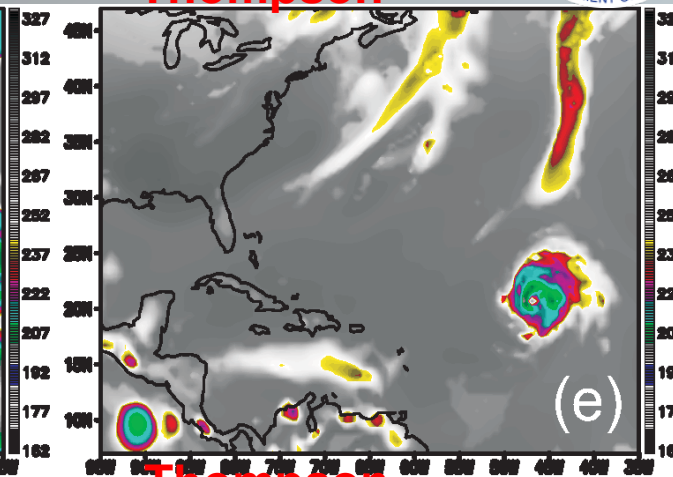
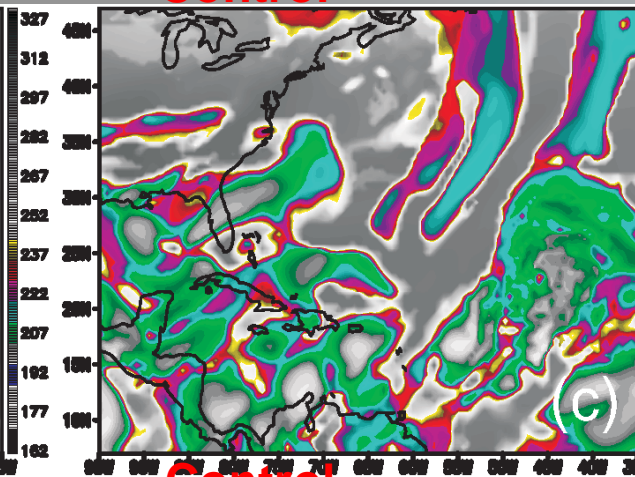
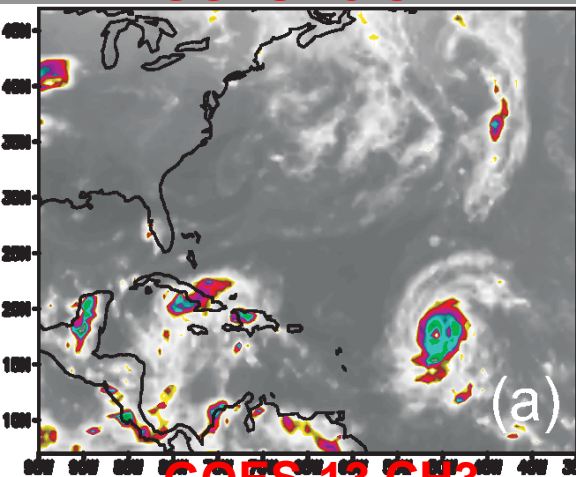
- Significant difference in frozen hydrometeors between the control and Thompson simulations.
- Better observations needed for detailed validation of vertical distribution of clouds.

# Synthetic Satellite Imagery – Igor D1

**GOES-13 CH4**

**Control**

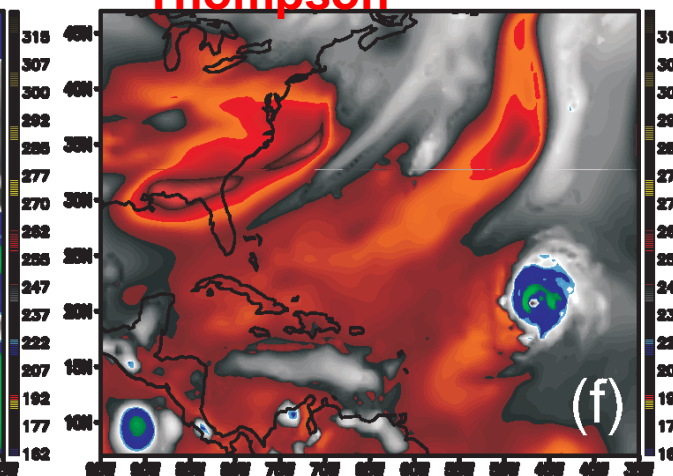
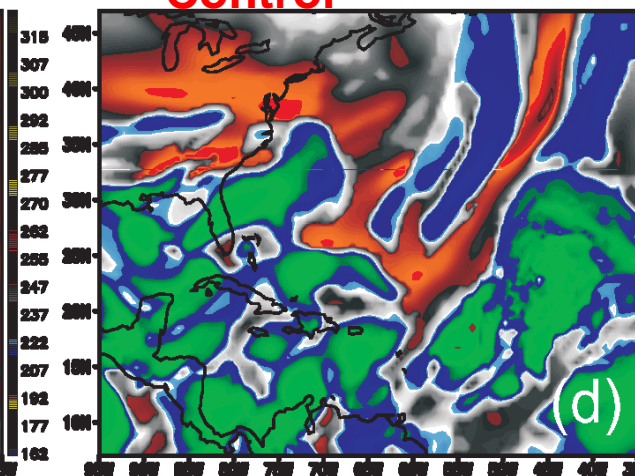
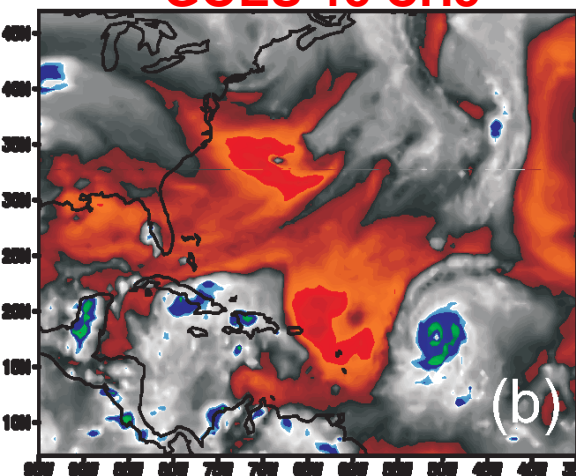
**Thompson**



**GOES-13 CH3**

**Control**

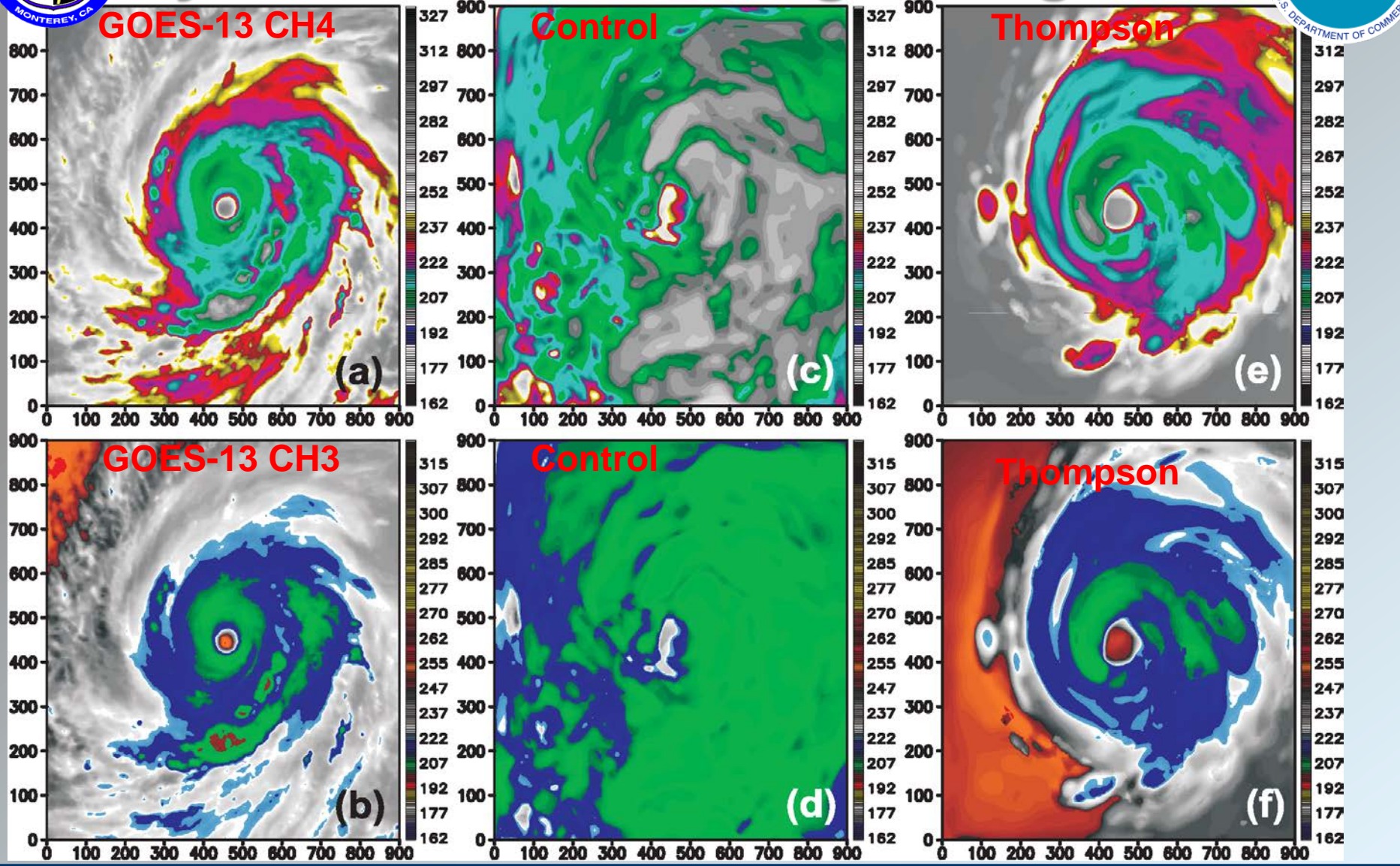
**Thompson**



- The convective region associated with the hurricane becomes indistinguishable under the thick cloud ice in the control simulation.
- The convection over Cuba is not represented in the Thompson simulation, presumably due to the low resolution in the outer domain.



# Synthetic Satellite Imagery – Igor D3



**The Thompson simulation captures the strong convection in the eyewall region, but shows a ~50% wider eye than was observed.**

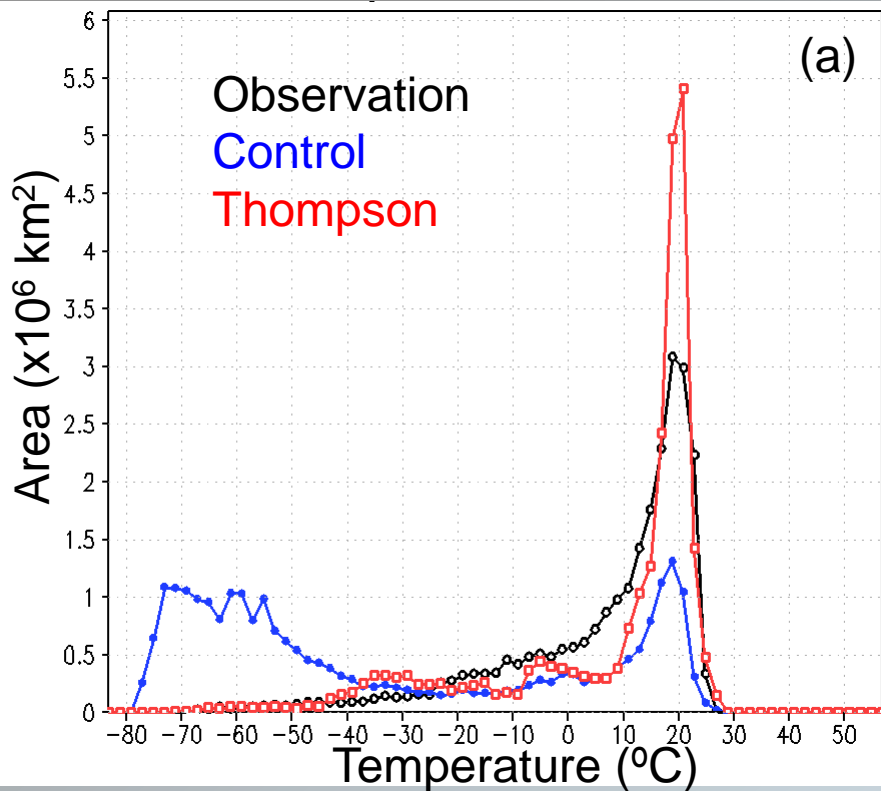


# Synthetic Satellite Imagery – Igor (III)

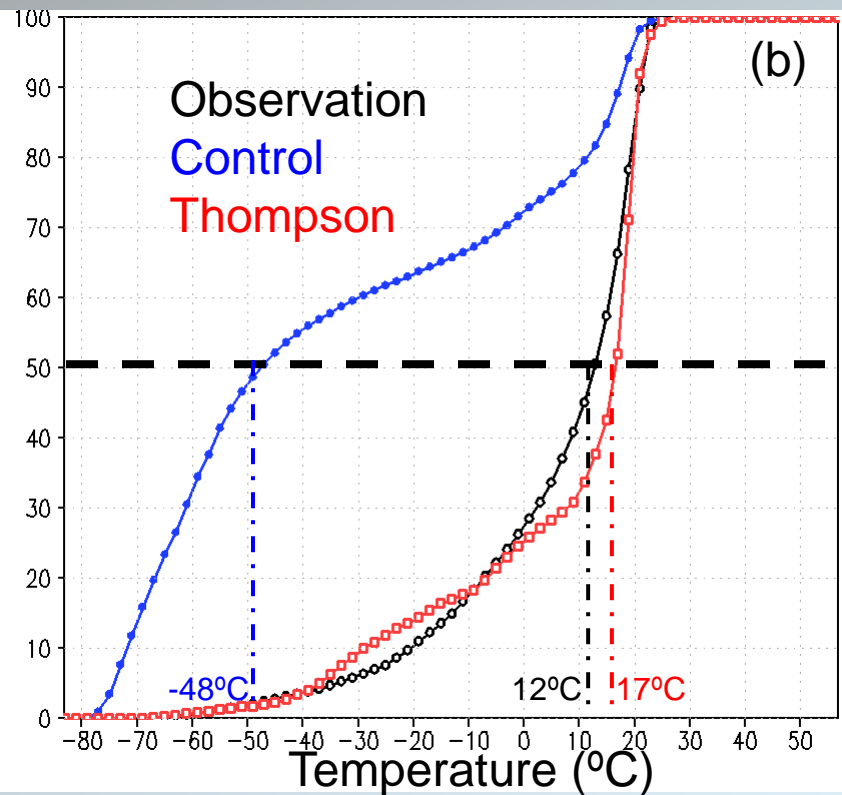


- 45-km domain

### Tb Areal Coverage



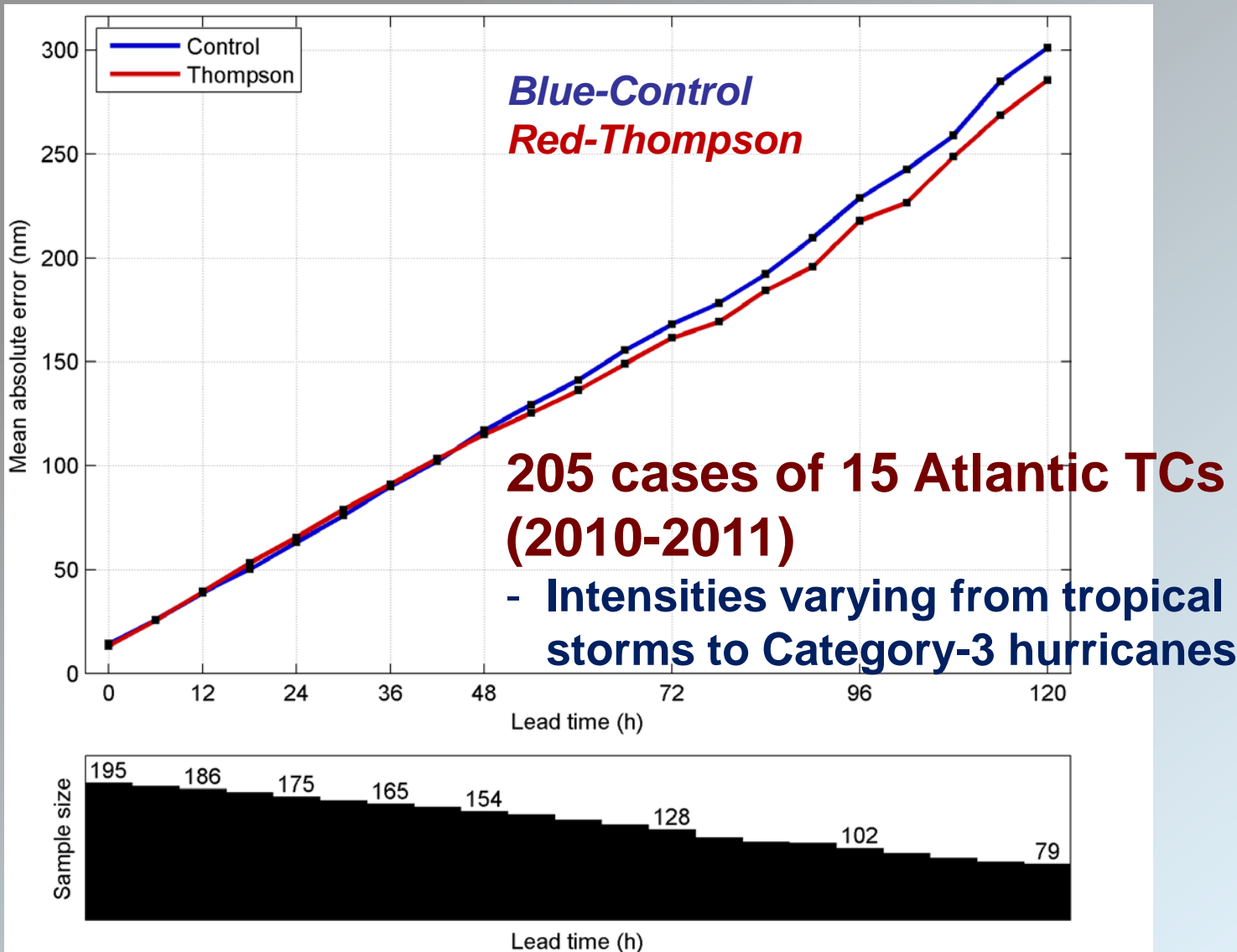
### Cumulative Distribution Function



The quantitative evaluation of the brightness temperature provides further evidence that the Thompson scheme corrected the upper level cloud ice and temperature over-estimated by the control simulation.

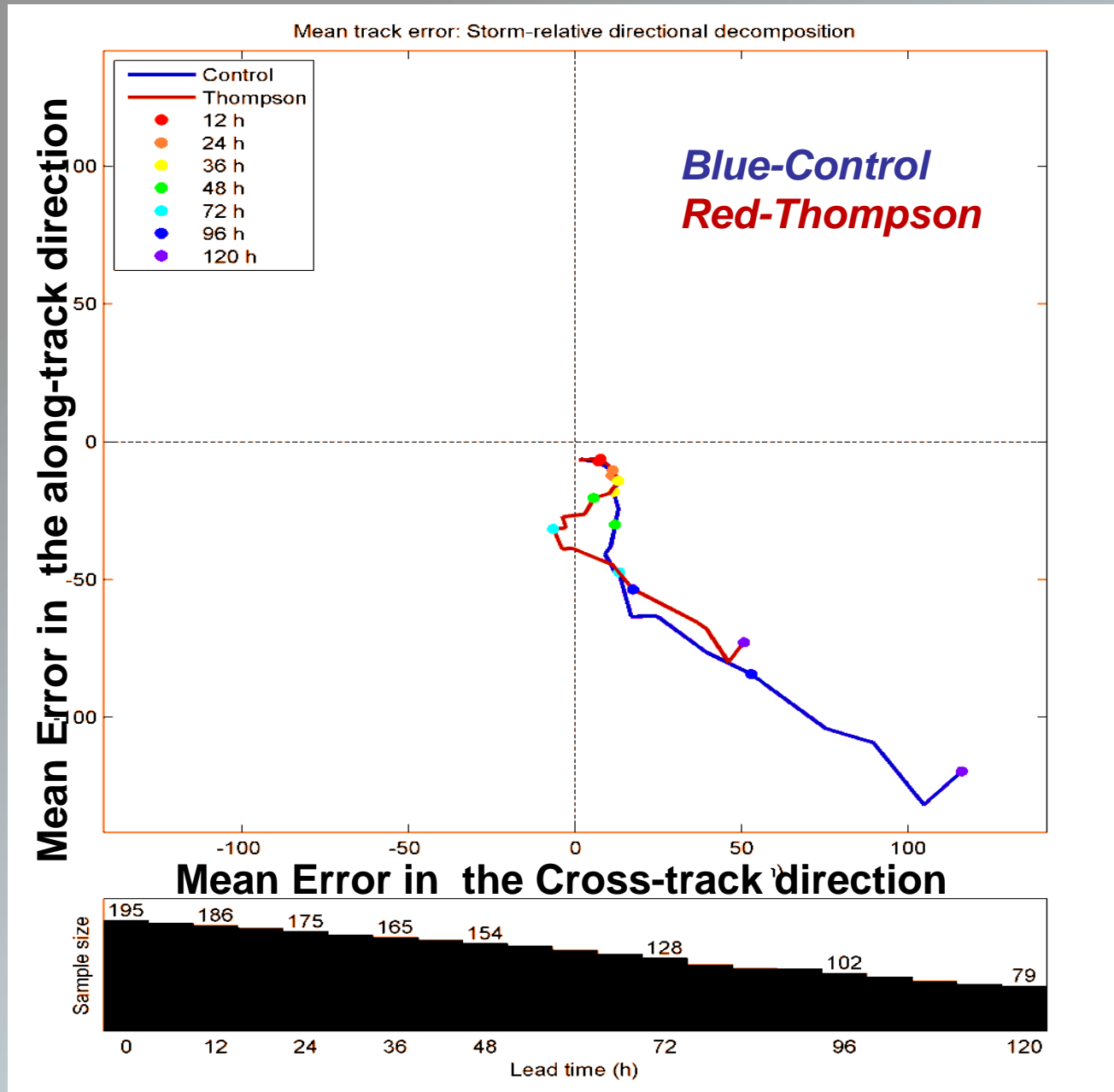


# Track Forecast Errors



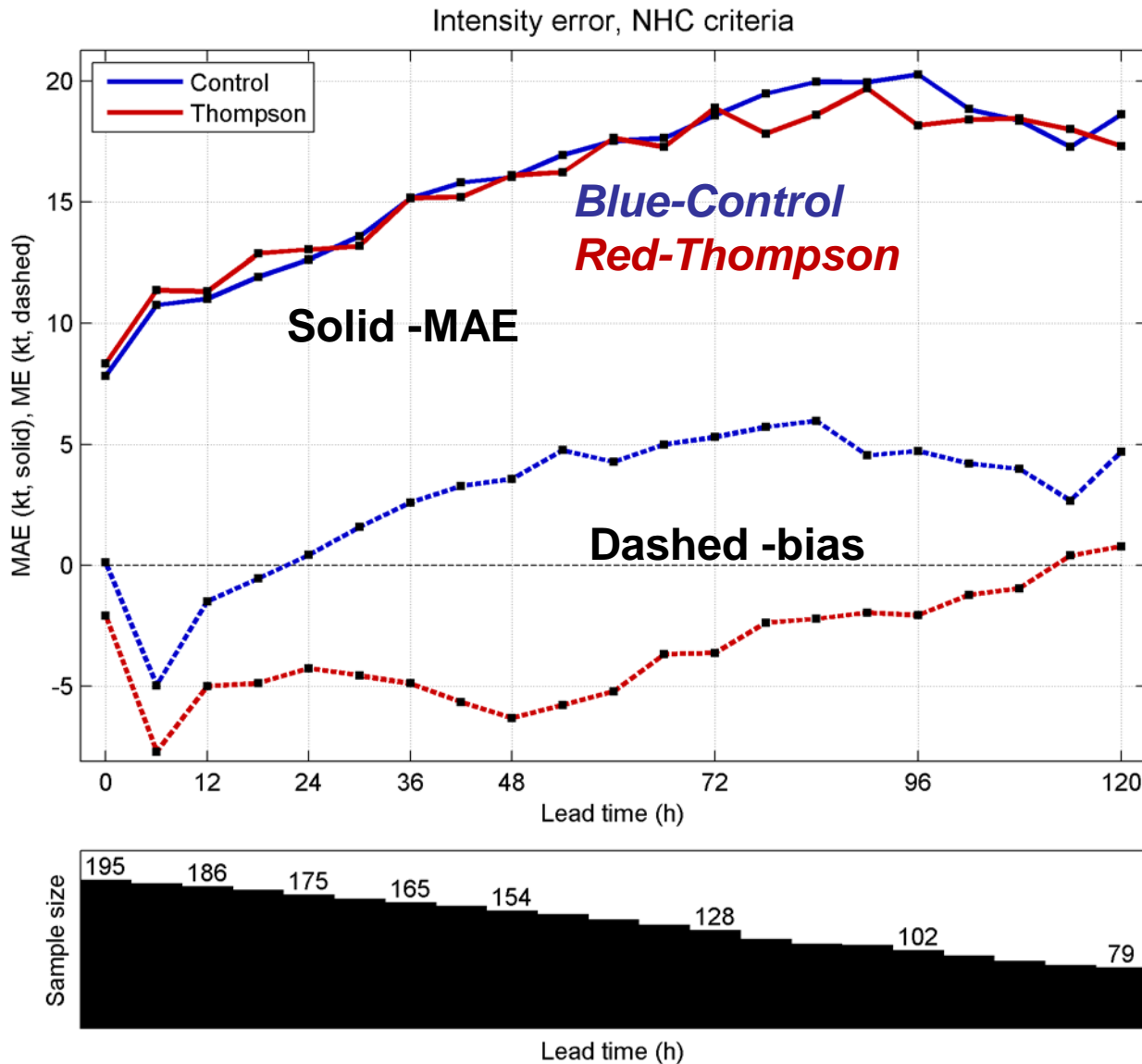


# Track Errors – directional decomposition



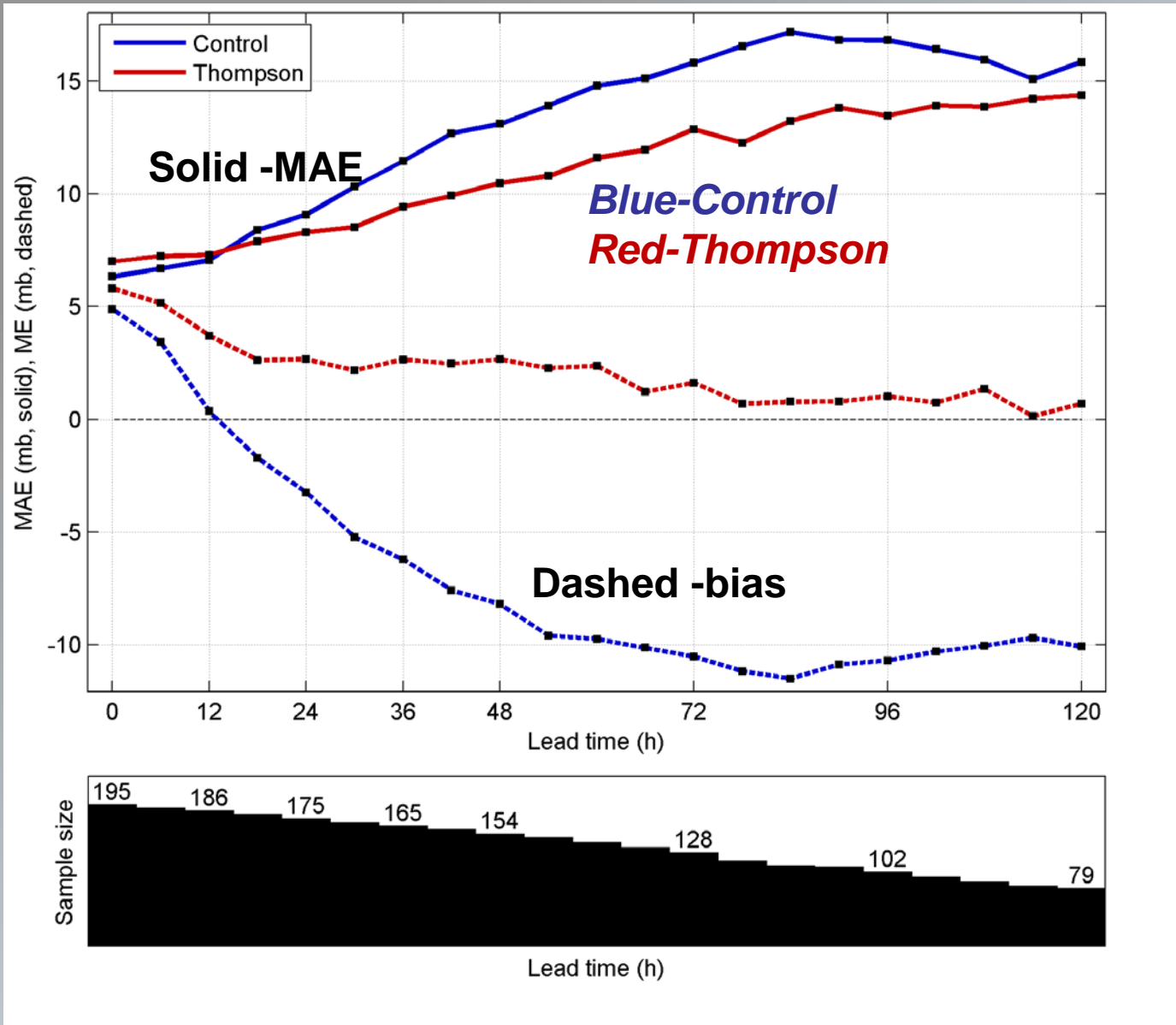


# Intensity (MSW) Forecast Errors





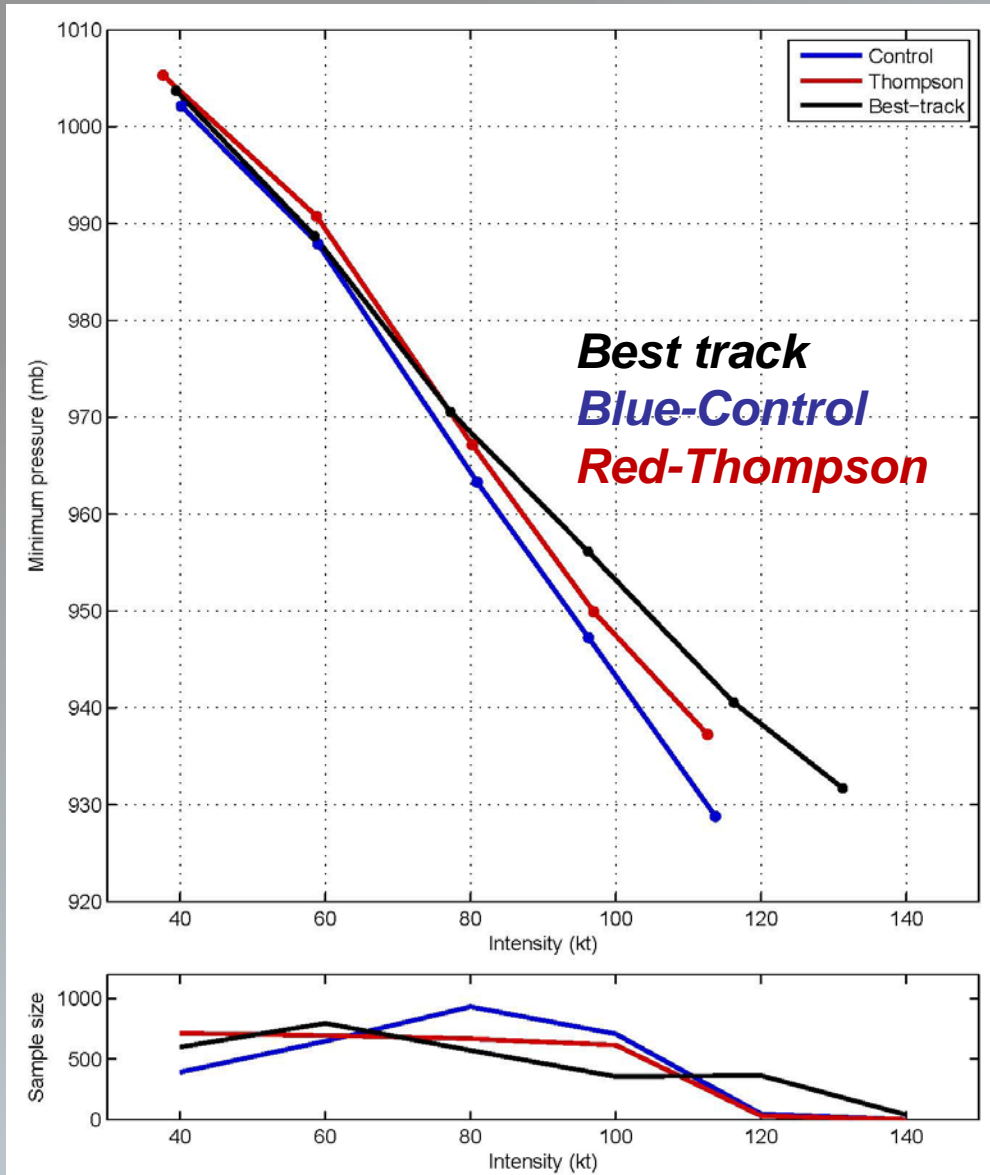
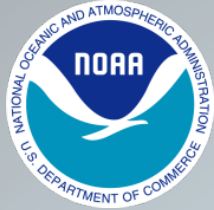
# Intensity (Min SLP) Forecast Errors







# Pressure – Wind Relationship

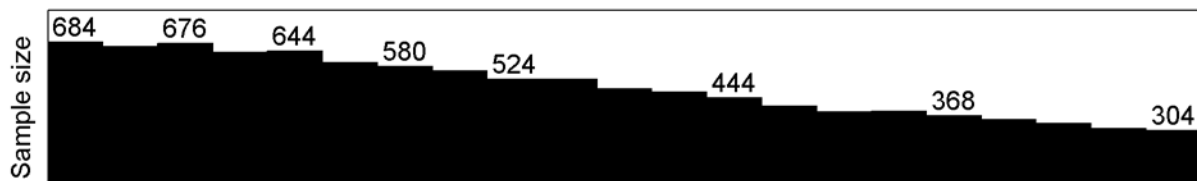
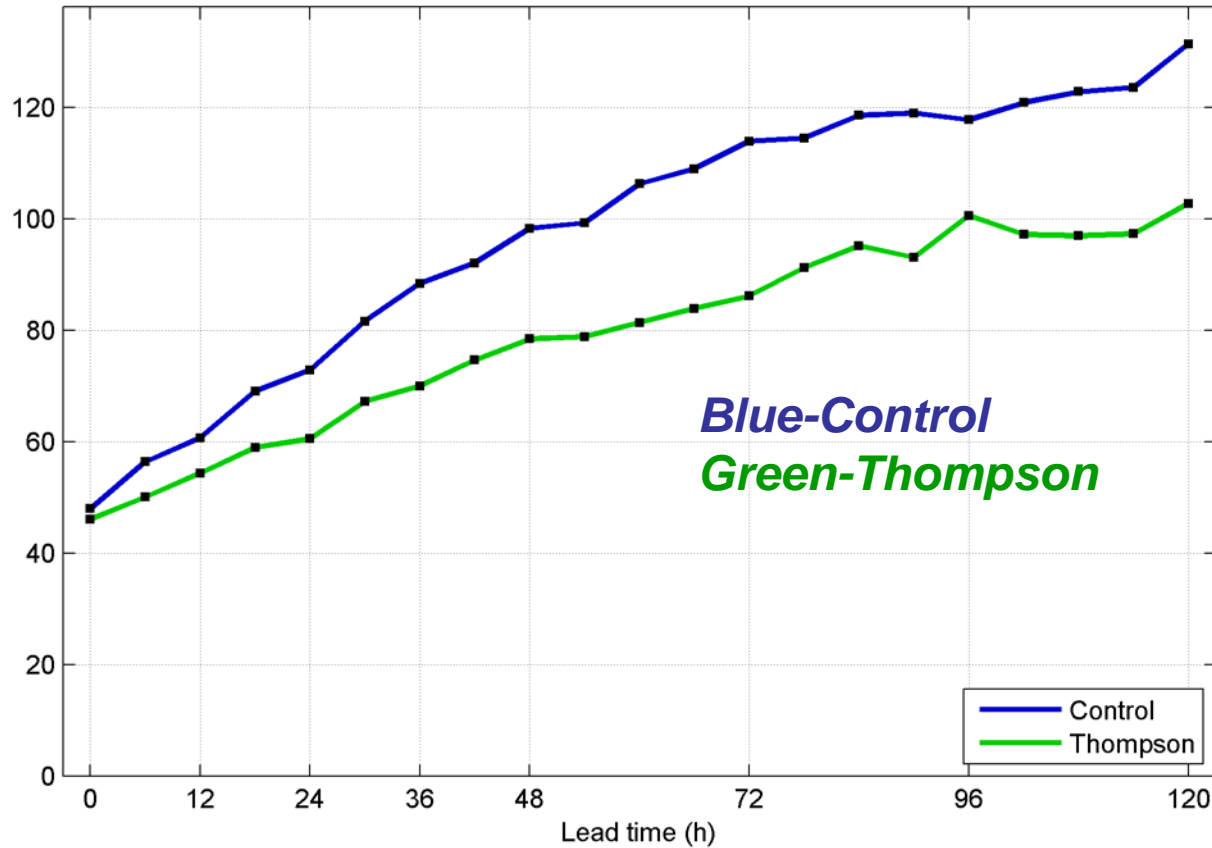


The difference in the pressure-wind relationship between these two experiments indicates different storm sizes.



# Storm Size Comparison

- **R34 – radius of the 34-kt surface wind**



**The R34 values, an important criteria used in the Navy's decision for fleet sortie, are significantly smaller in the Thompson simulations than the control.**



# Summary and Future Direction (I)



- **Noteworthy differences between the old and Thompson microphysical parameterizations from the 2-month synoptic simulations:**
  - Upper-level cloud ice over-estimated by the control simulations due to choice of ice nucleation parameterizations
  - The important role of cloud-radiation interaction in the upper-level warm bias in the control simulations
- **Significant impact on TC cases:**
  - Rightward cross-track and slow along-track biases reduced by the Thompson scheme
  - The occurrence of over-intensified storms in the control is much reduced in the Thompson simulations
  - Better pressure-wind relationship derived from the Thompson simulations than the control, indicating better storm size (e.g. R34) prediction by the Thompson scheme



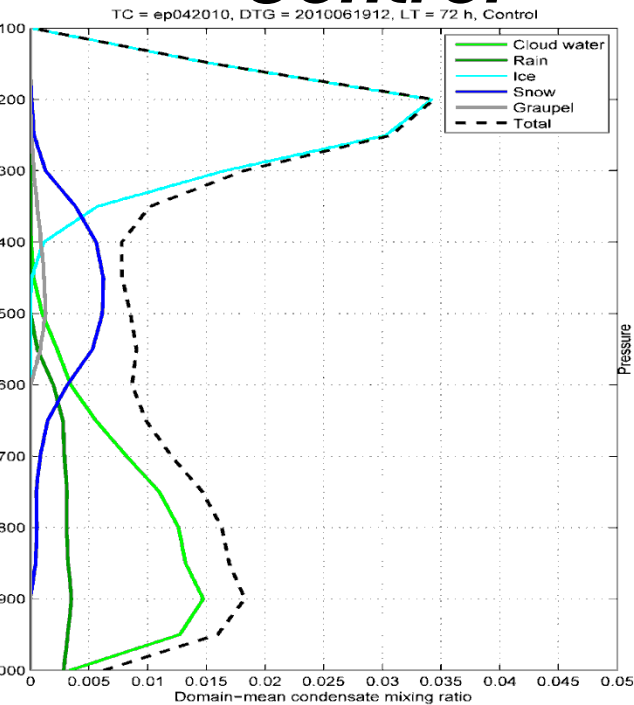
# Summary and Future Direction (II)



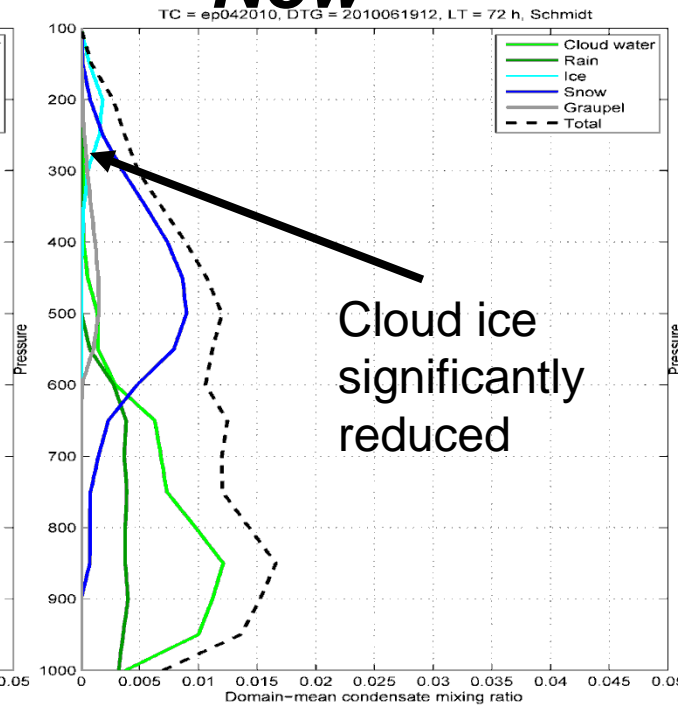
- **Application of synthetic satellite imagery both qualitatively and quantitatively:**
  - Diagnostic tool used to pinpoint the issue of excessive cloud ice in the control
- **A recently added single-moment scheme (by Schmidt) used in COAMPS-TC real-time forecasts since 2012:**
  - Cloud ice substantially reduced
  - Upper-level warm bias corrected
- **Future research:**
  - Sensitivity of TC structure to microphysical parameterizations
  - Further evaluation of cloud – radiation interaction
  - Boundary layer processes

- Domain averaged hydrometeors for nest 3

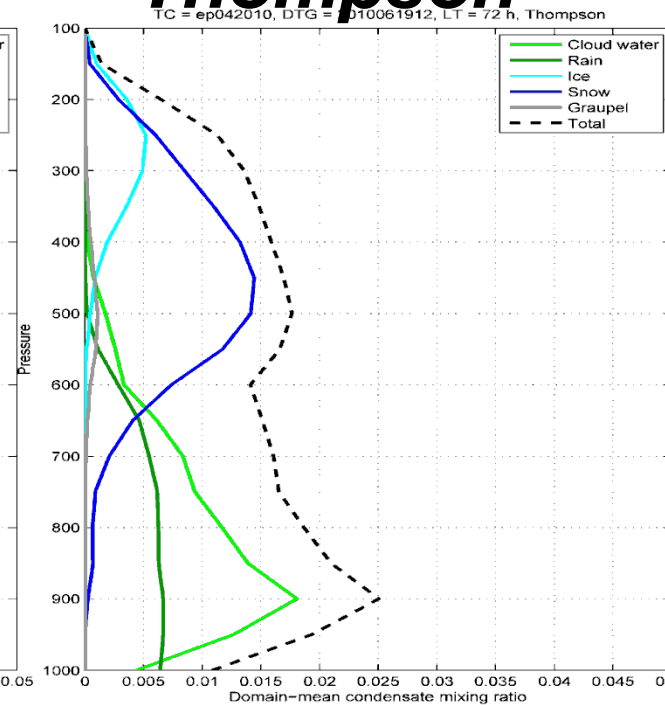
## Control

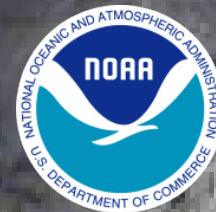


## New



## Thompson





*Thank You*

# Extra Slides

# Major Differences in Cloud Ice Treatment

Schemes	Ice nucleation	Ice crystal number concentration	Ice deposition growth	Threshold for autoconversion from ice to snow	Ice particle terminal velocity
<b>Modified R-H</b>	Fletcher (1962)	Diagnostic (See text)	Linear function of ice supersaturation (Eq. A18 of RH83)	Ice particle mass (a value corresponding to a particle with 500 $\mu\text{m}$ diameter)	Mass weighted following Cotton and Anthes (1989)
<b>Thompson</b>	Cooper (1983)	Prognostic (see text)	Cubic polynomial function of ice supersaturation (Eq. C1 of T2008)	Ice particle diameter (200 $\mu\text{m}$ , T2008)	mass weighted (T2008)  (see text)