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The Influence of Boundary Layer Mixing on the Evolution of an Extratropical Cyclone

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University at Albany

WRF Workshop

Boulder, Colorado

14 June 2018

Motivating Question

- How do **<u>boundary layer (PBL) turbulent mixing processes</u>** impact the development and evolution of baroclinic cyclones?

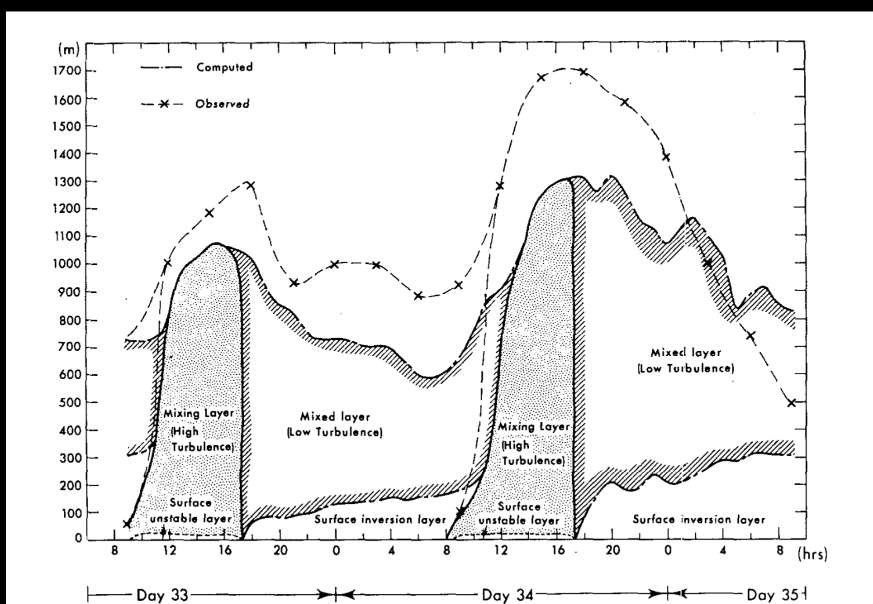
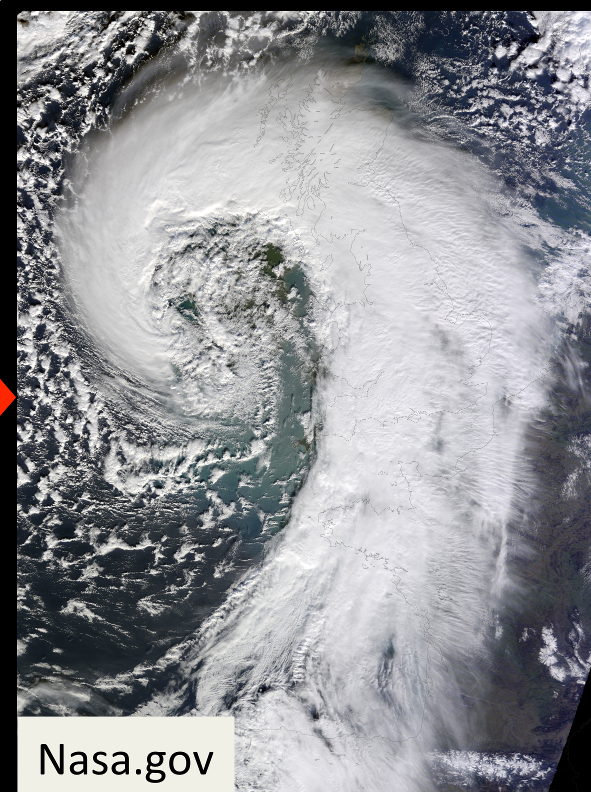


Fig. 33. Time evolution of the computed (basic case) and observed mixed layer height.

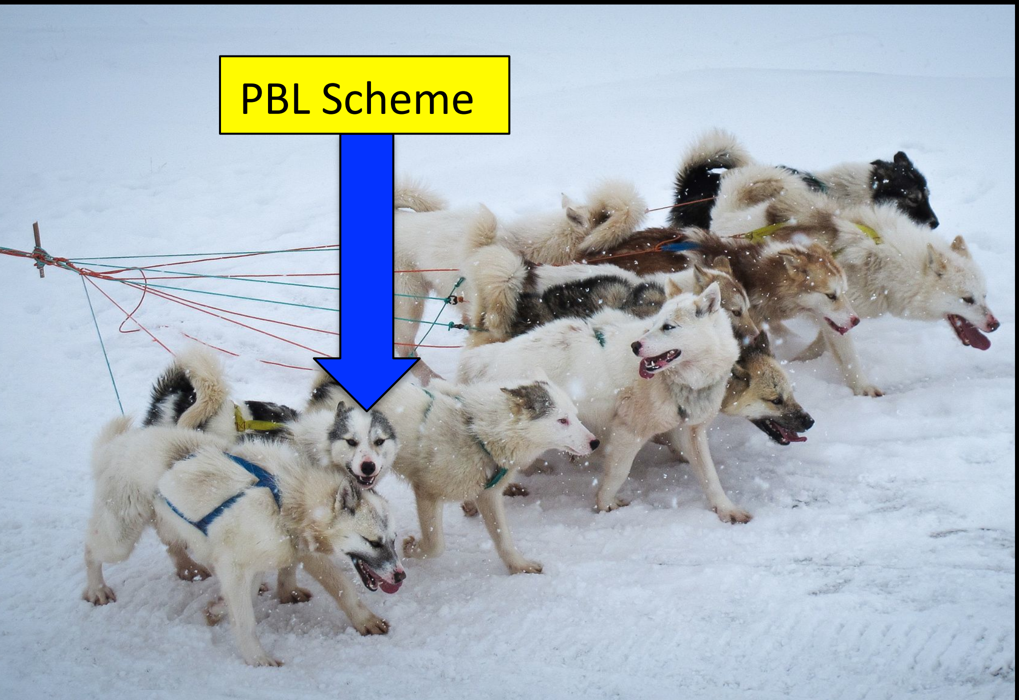
Yamada and Mellor (1975)

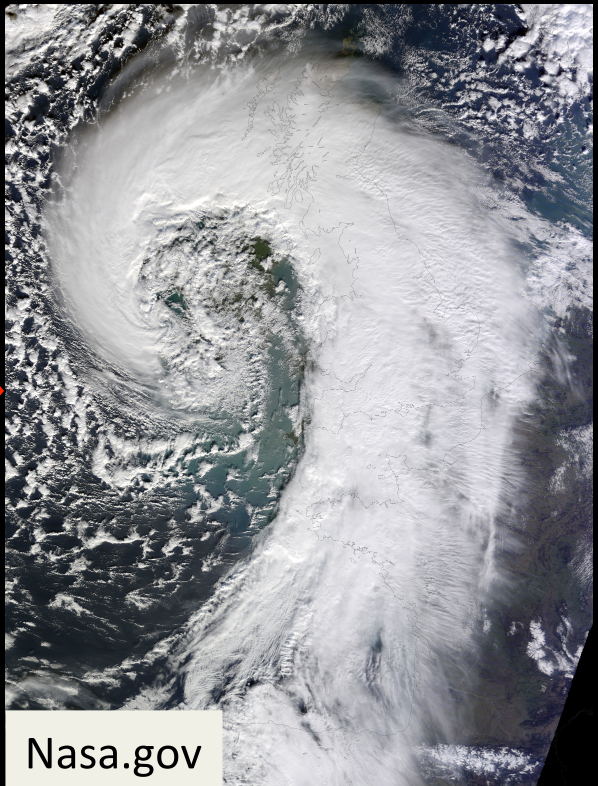


Nasa.gov

Motivating Question

- How do **boundary layer (PBL) turbulent mixing processes** impact the development and evolution of baroclinic cyclones?





Background

- How can the boundary layer affect cyclone development and evolution?

Background

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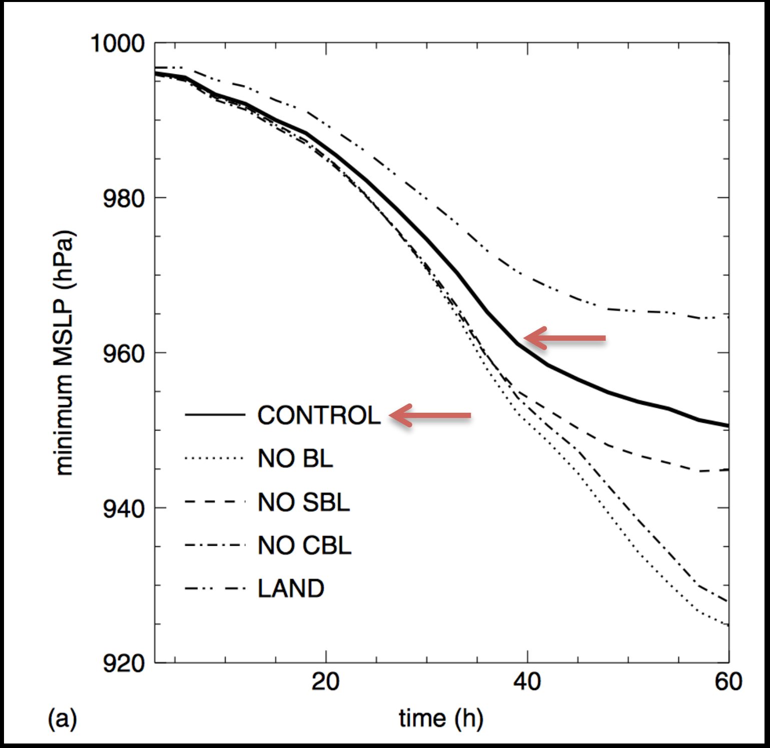
  - **Dry processes**
    - Ekman pumping and baroclinic PV generation processes (Beare 2007)

Background

- Beare (2007) found sensitivity to cyclone evolution through stable/unstable PBL mixing activation



Time series of the minimum mean-sea-level pressure over the cyclone for the coarse sensitivity experiment. (Beare 2007)

Background

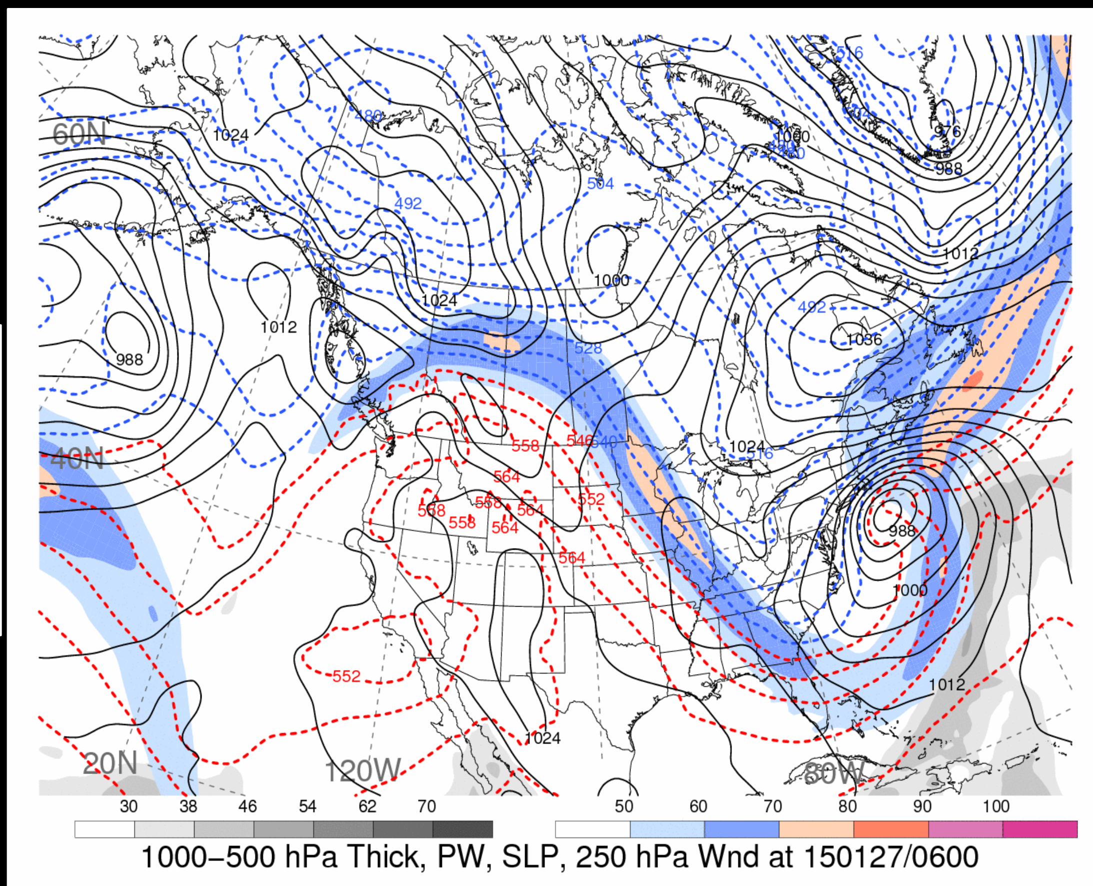
- How can the boundary layer affect cyclone development and evolution?
  - Dry processes
    - Ekman pumping and baroclinic PV generation processes (Beare 2007)
  - **Moist processes**
    - Latent heating from parcels within the PBL can alter cyclone behavior
      - ~70% of the low-level nondivergent circulation due to latent heating (Stoelinga 1996)

DO VARIATIONS IN PBL MIXING MATTER IN A REAL CASE?

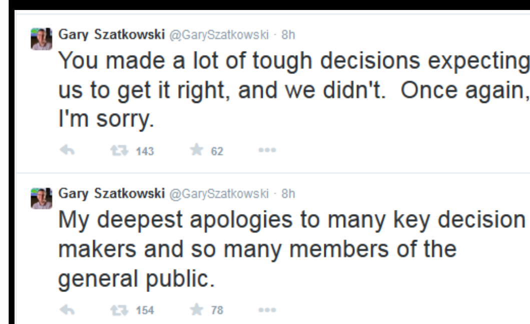
26–28 January 2015 Snowstorm

- Coastal extratropical cyclone impacting New England and parts of the Mid-Atlantic

0600 UTC 27 January 2015 “Twitter” snowstorm



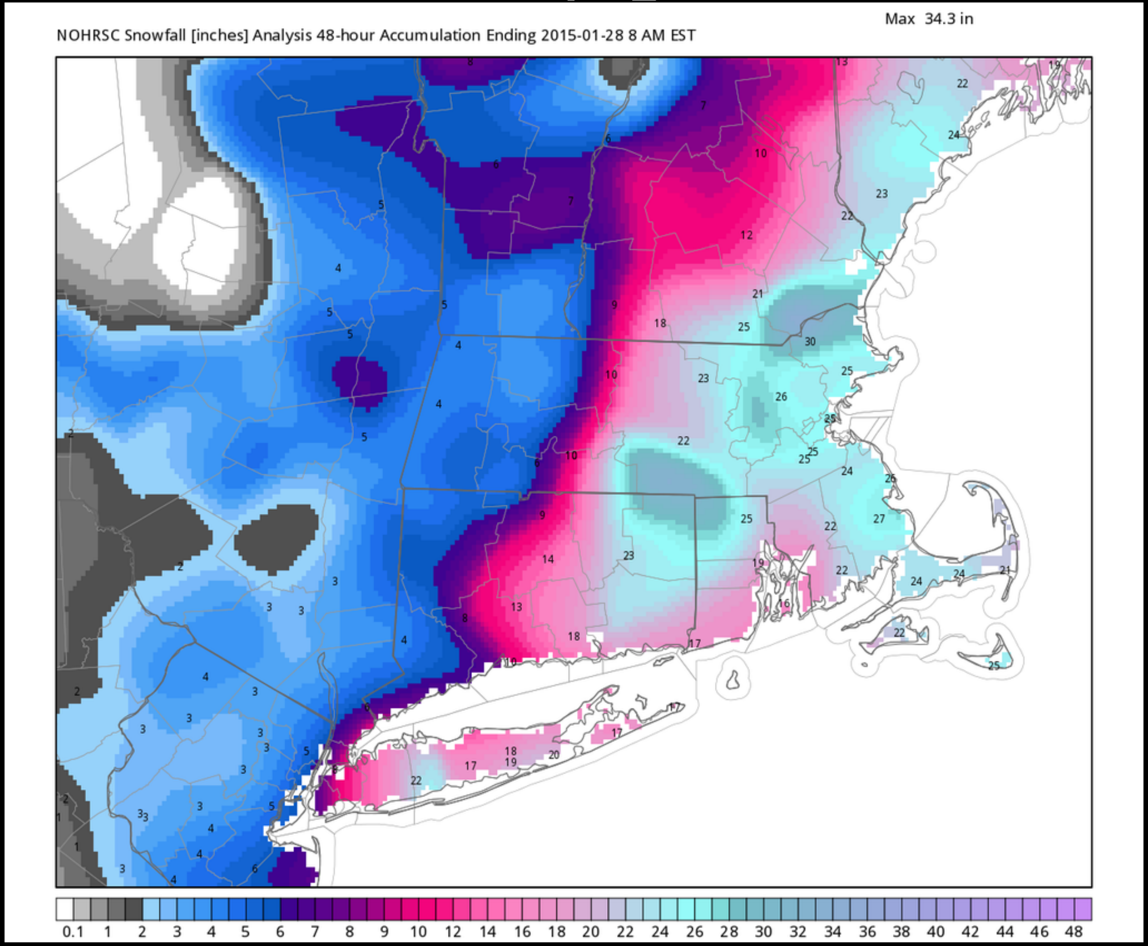
Apologetic tweets from New Jersey NWSFO Forecaster



Courtesy: H. Archambault

26–28 January 2015 Snowstorm

- Crippling snowfall over much of the Northeast. Sharp gradient on western flank



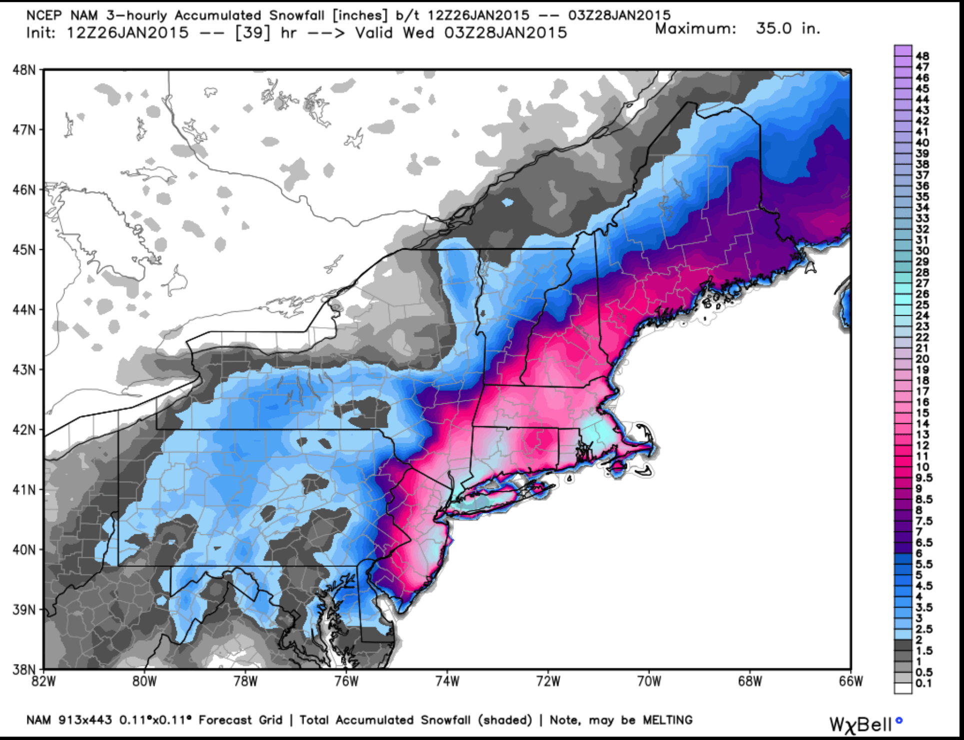
National Operational Hydrologic Remote Sensing Center 48-h snowfall accumulation (in., shaded) ending 1200 UTC 28 January 2015.

WeatherBell

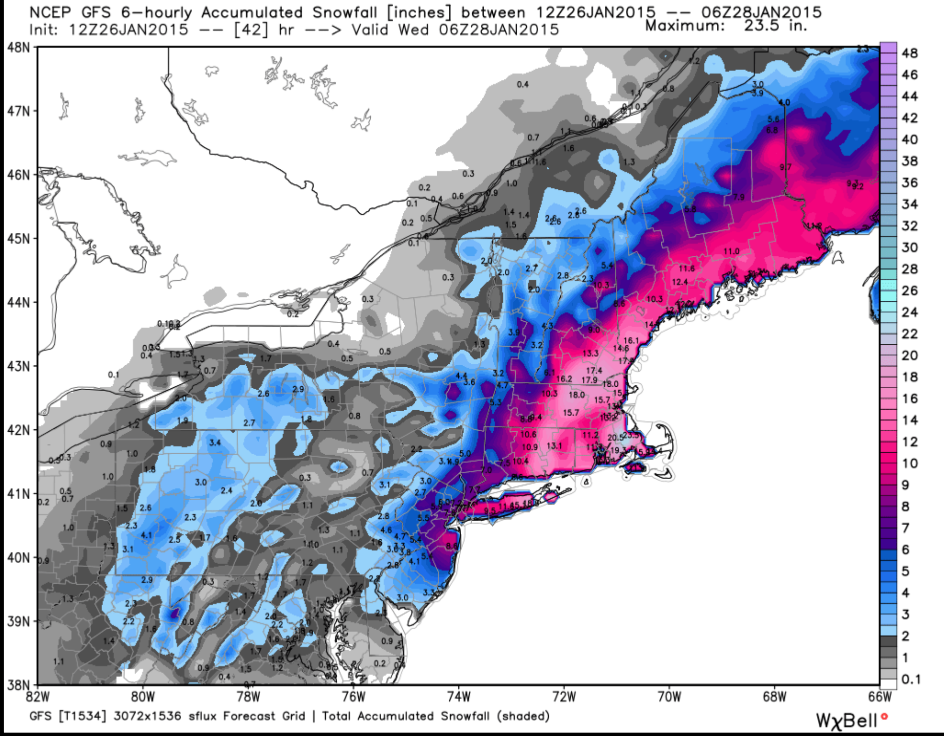
26–28 January 2015 Snowstorm

- Substantial spread within the models ~40 h out

NAM



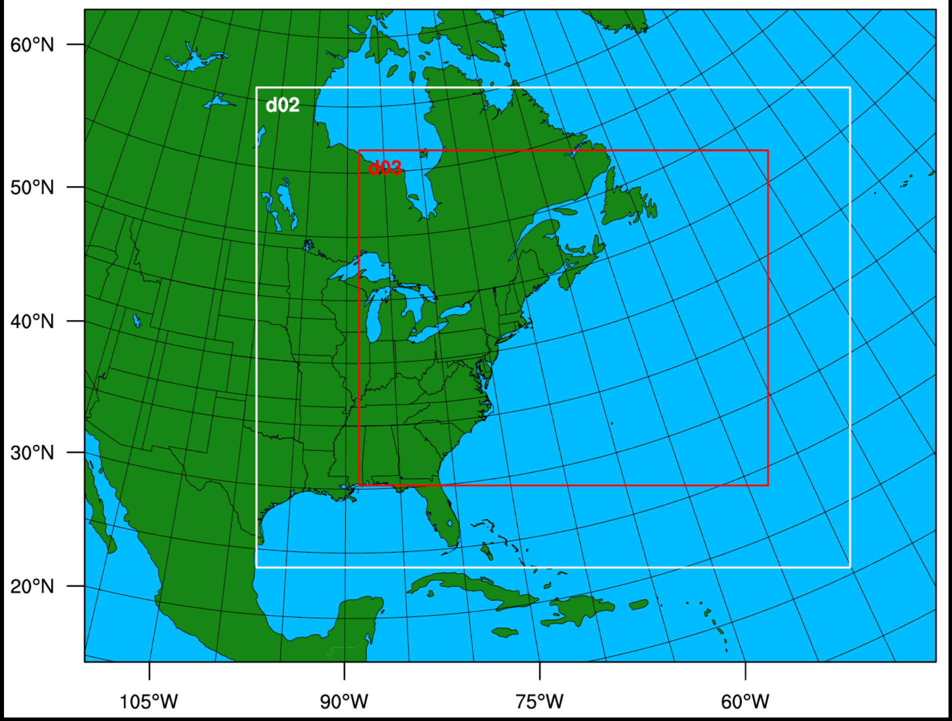
GFS



WeatherBell

WRF 3.7.1 Setup

- Initialized: 0000 UTC 26 January 2015
  - 72-h runtime
- Data: ERA-I
- 4-km inner domain
- **Tested various PBL schemes**

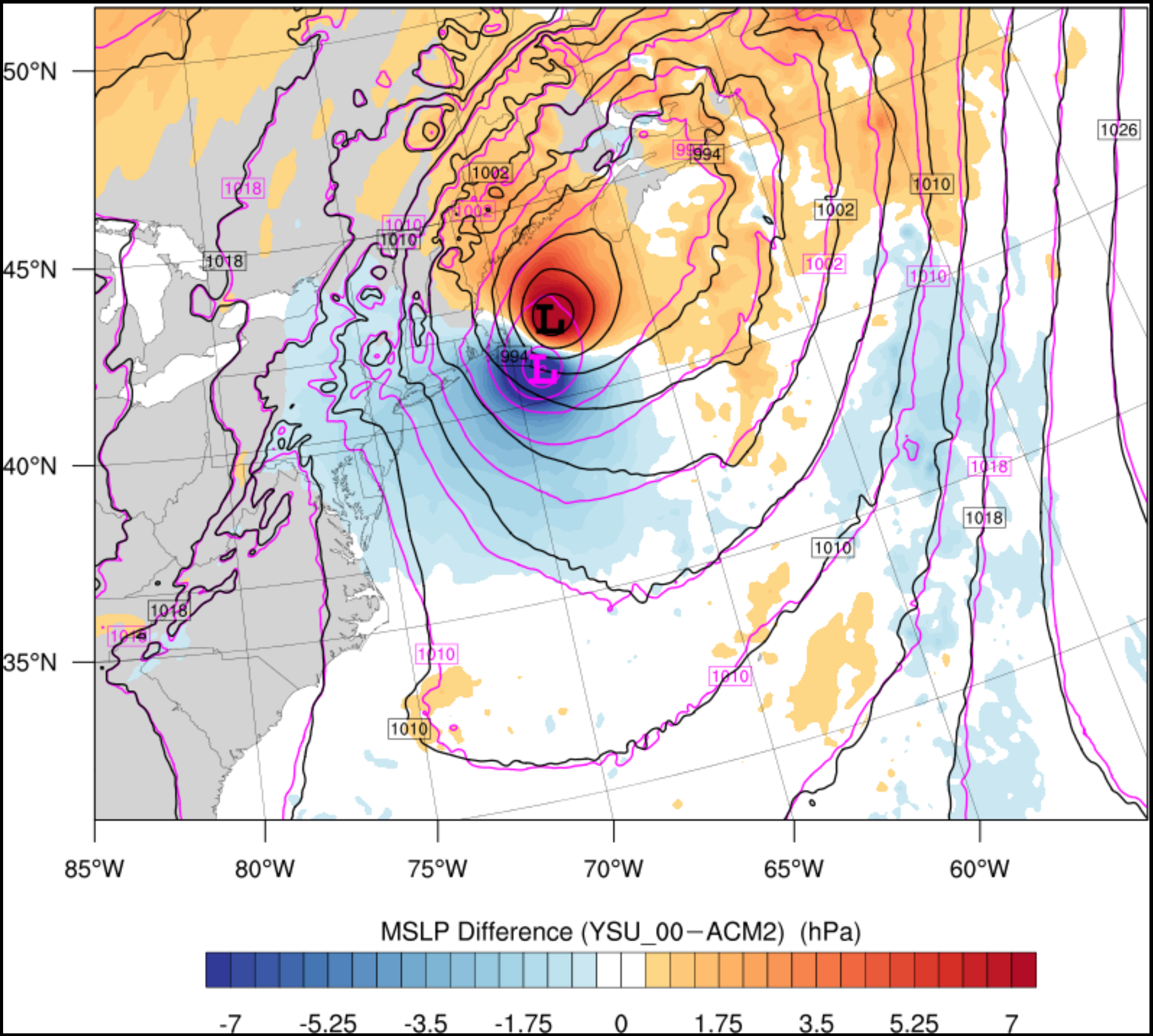


Microphysics	Longwave	Shortwave	Surface layer	Land surface	Cumulus (outer 2)
Thompson (8)	RRTMG	RRTMG	MM5	Noah	Tiedtke

RESULTS

YSU – ACM2

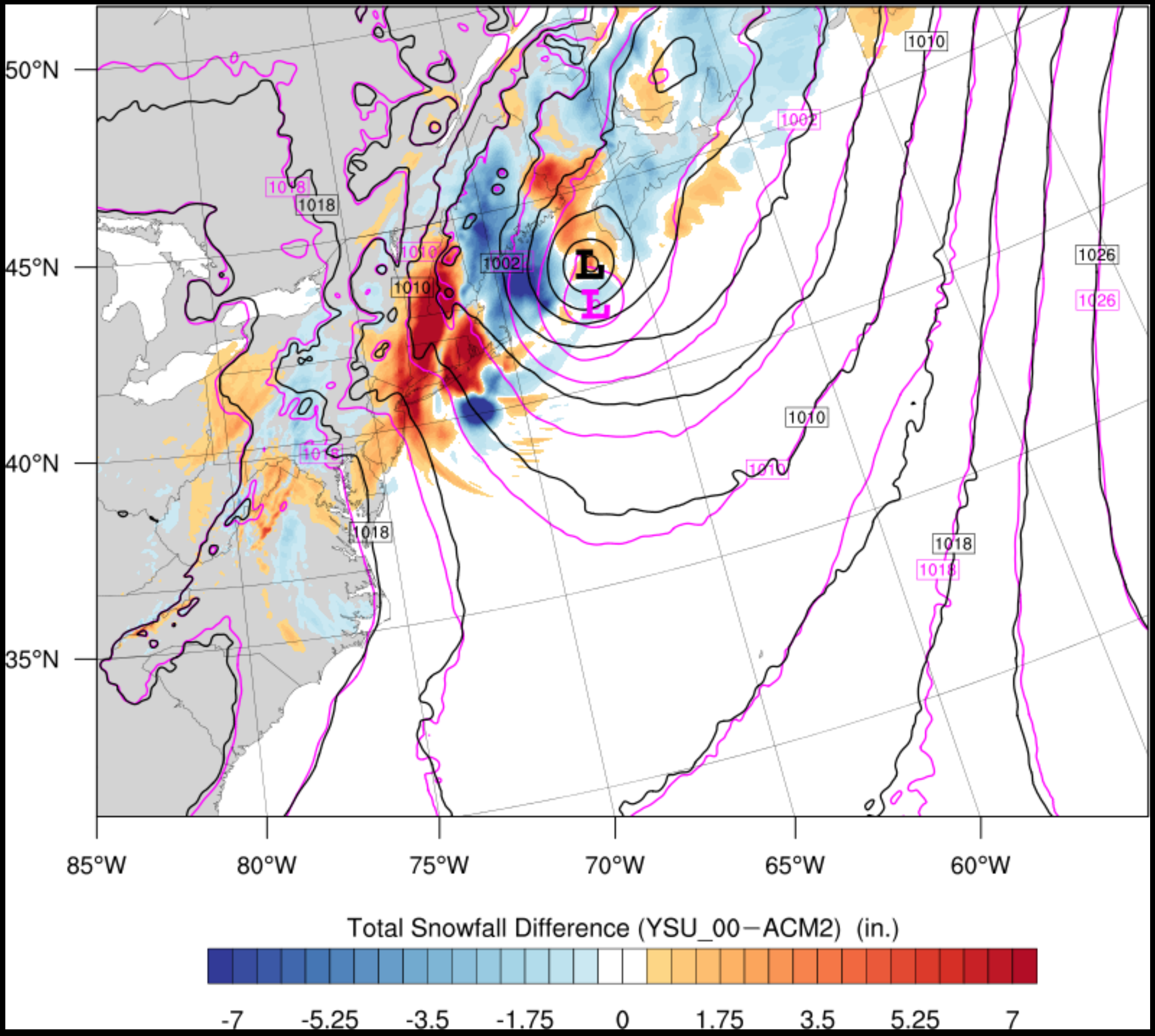
MSLP Difference (fill; YSU–ACM2) and MSLP



Valid: 0600 UTC 28 Jan 2015

YSU – ACM2

Snowfall Difference (fill; YSU–ACM2) and MSLP



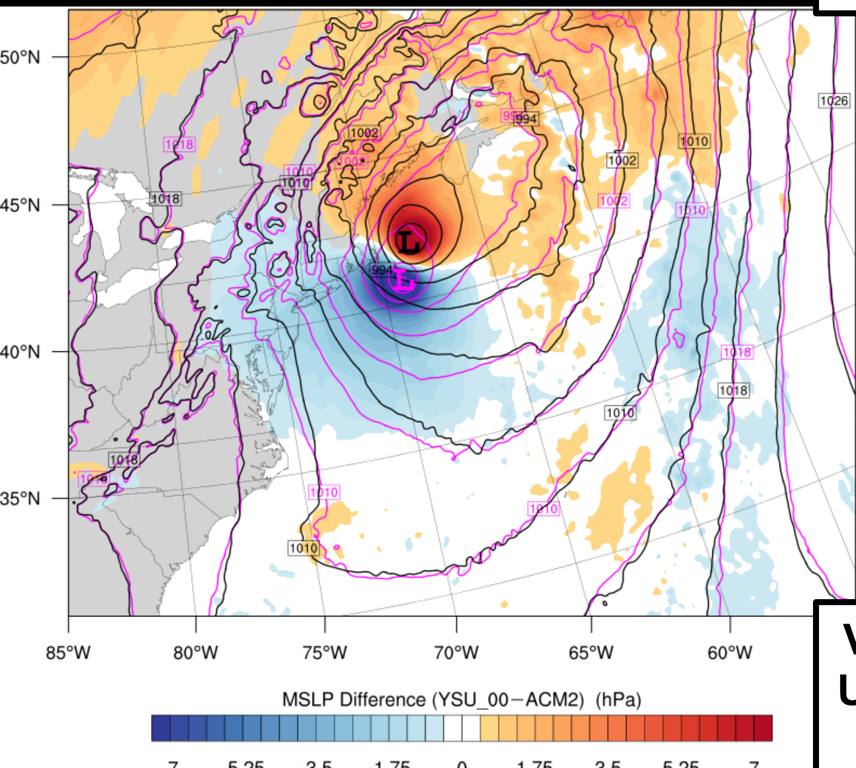
Valid: 1200 UTC 28 Jan 2015

YSU and ACM2

– YSU and ACM2 have many differences, **BUT** their methods for determining PBL height are similar

YSU_00 – ACM2

MSLP Difference



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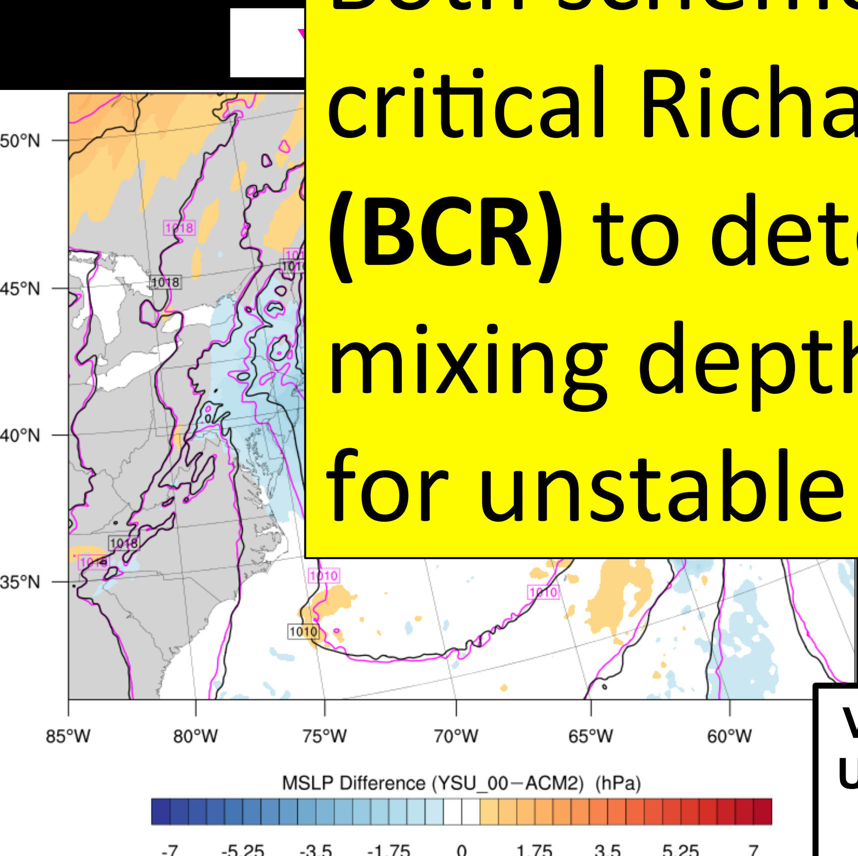


Both schemes use a bulk critical Richardson number **(BCR)** to determine the PBL mixing depth and strength for unstable surface layers

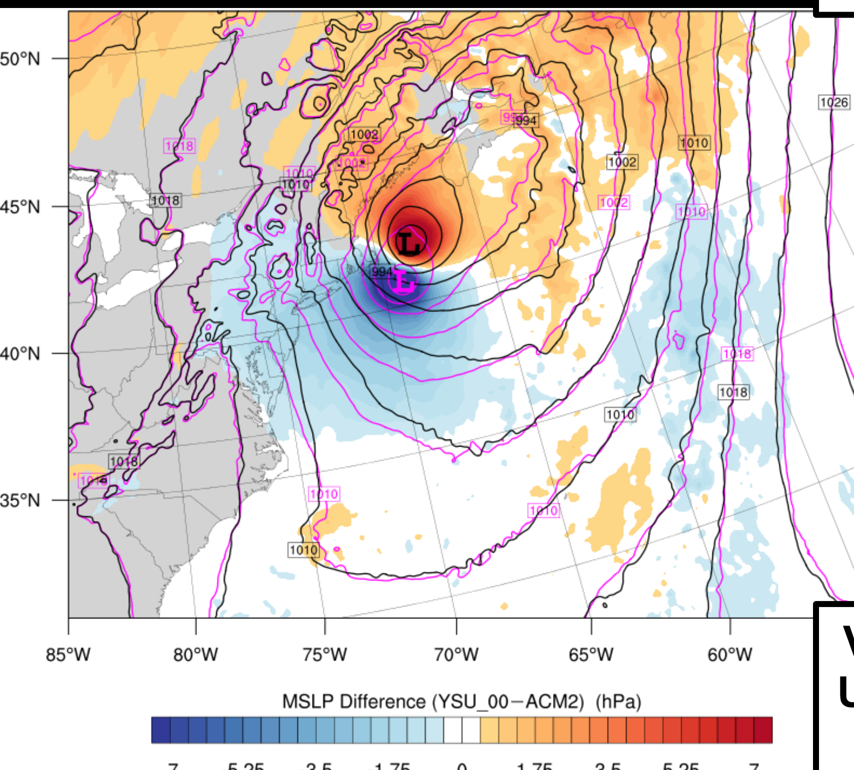
Valid: 0600 UTC 28 Jan 2015

YSU and ACM2

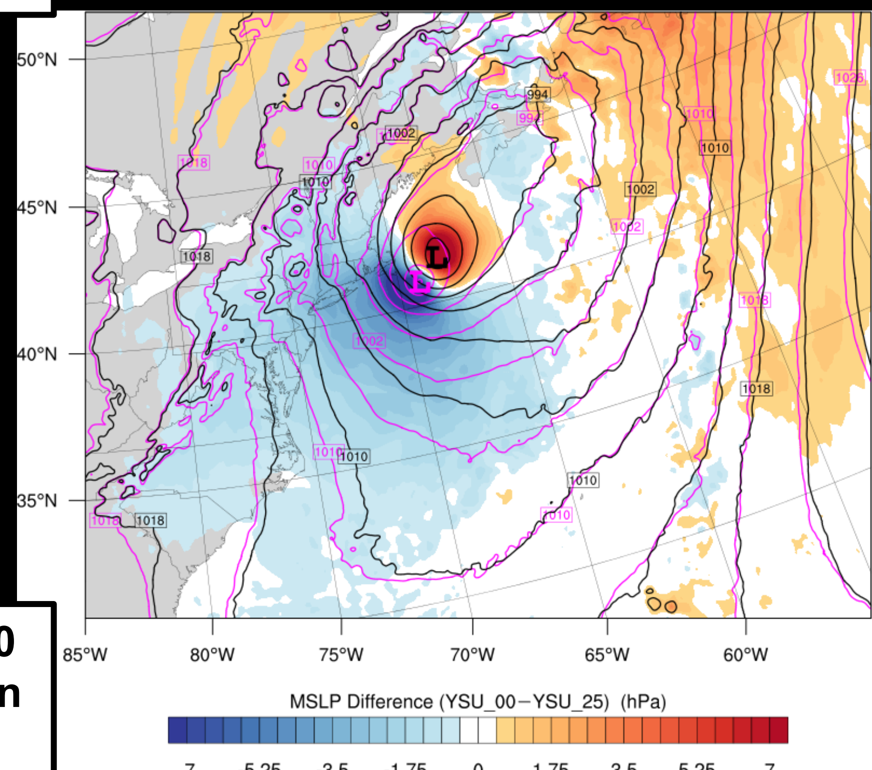
– Changing the BCR in YSU to the ACM2 value (0.25) yields similar cyclone evolution

MSLP Difference

YSU_00 – ACM2



YSU_00 – YSU_25



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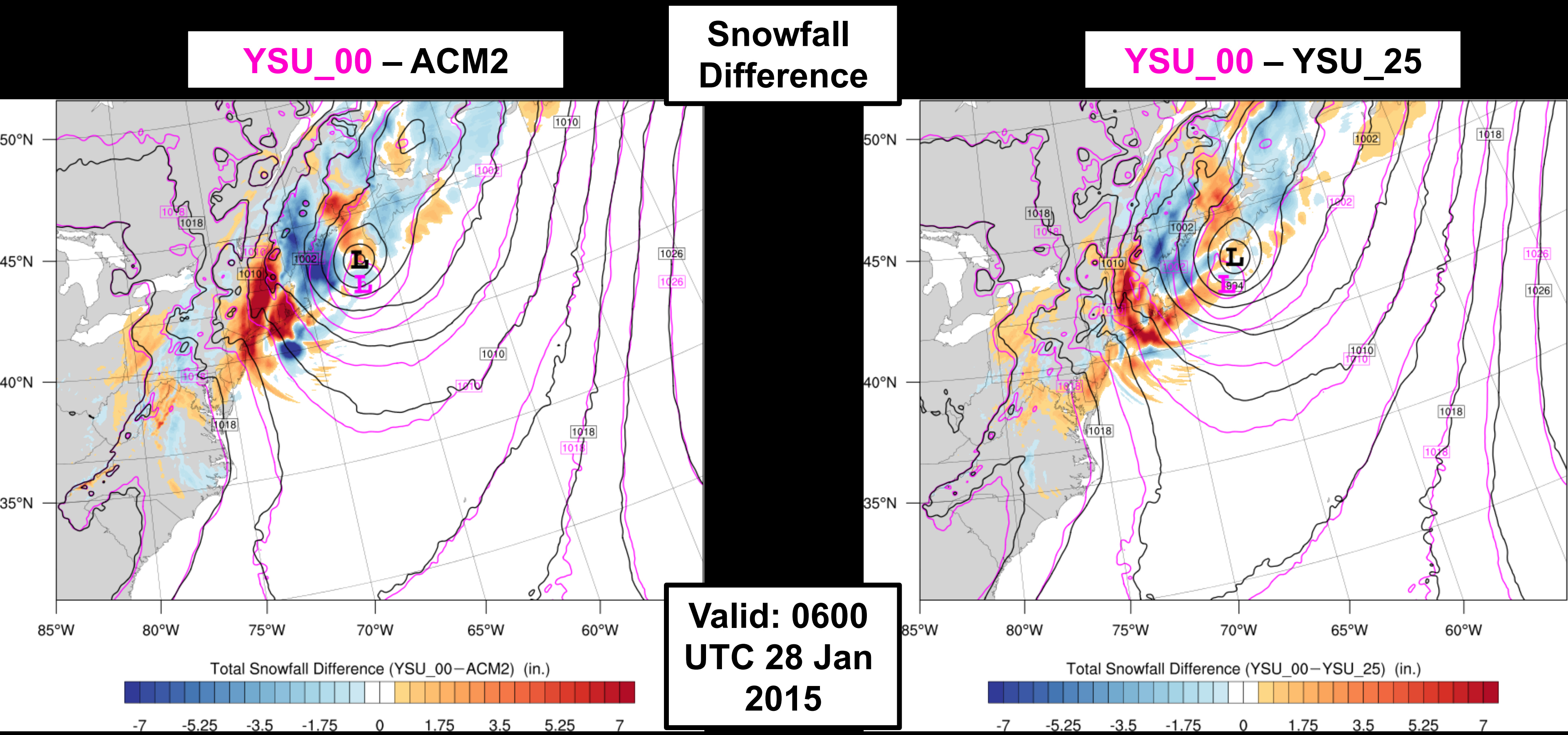


HOW DOES THE BULK CRITICAL RICHARDSON NUMBER WORK?

YSU Scheme

- YSU scheme estimates PBL height and imposes K-profile shape function

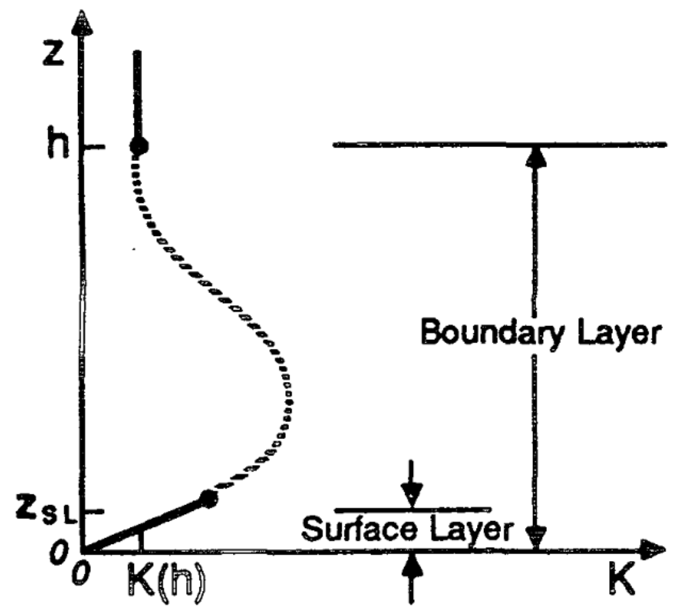


FIG. 1. Typical variation of eddy viscosity K with height in the boundary layer proposed by O'Brien (1970). Adopted from Stull (1988).

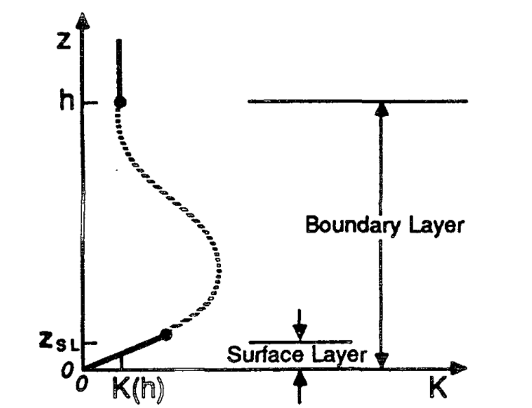
Hong and Pan (1996)

$$K_{zm} = \kappa w_s z \left(1 - \frac{z}{h}\right)^2$$

Hong et al. (2006)

YSU Scheme

- YSU scheme estimates PBL height and imposes K-profile shape function
  - First guess PBL height (h) is where the bulk Richardson number equals the bulk critical Richardson number (BCR)



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YSU Scheme

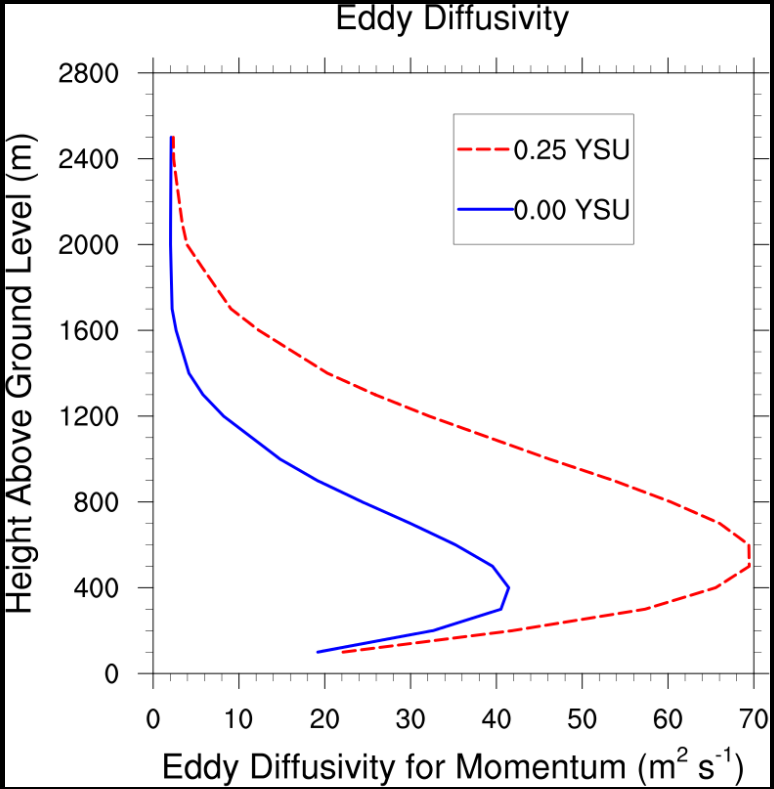
- Strength and height of PBL mixing are functions of BCR

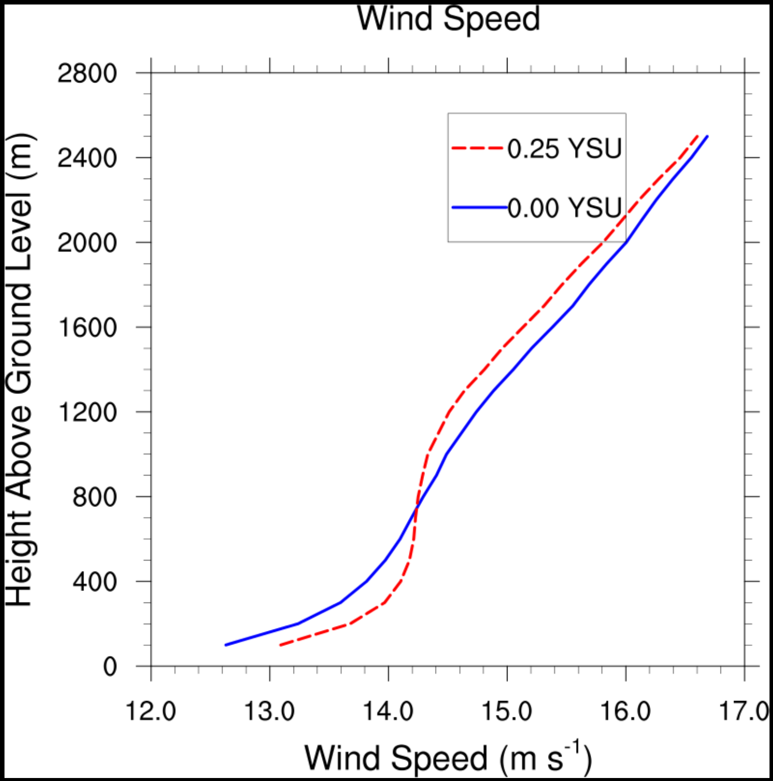
- **<u>Can leverage BCR to control mixing strength</u>**
  - Benefit of using YSU scheme for this study
    - Less mixing = 0.00 BCR
    - More mixing = 0.25 BCR

    - BCR changed for unstable surface layers only

Sample Vertical Profiles in the Warm Sector

– Enhanced eddy diffusivity in the warm sector results in expected changes to vertical profiles of wind speed and mixing ratio





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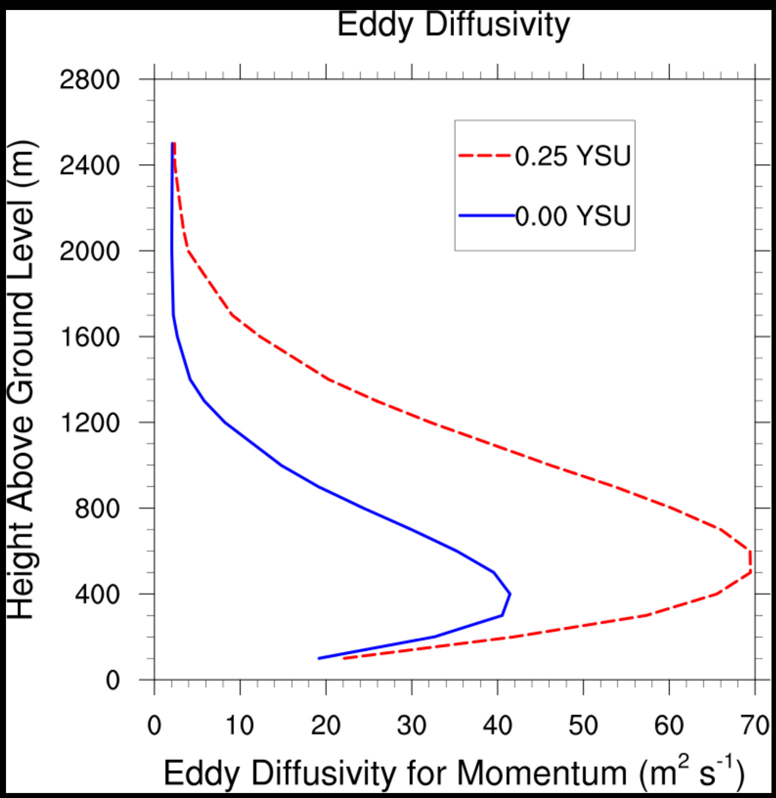
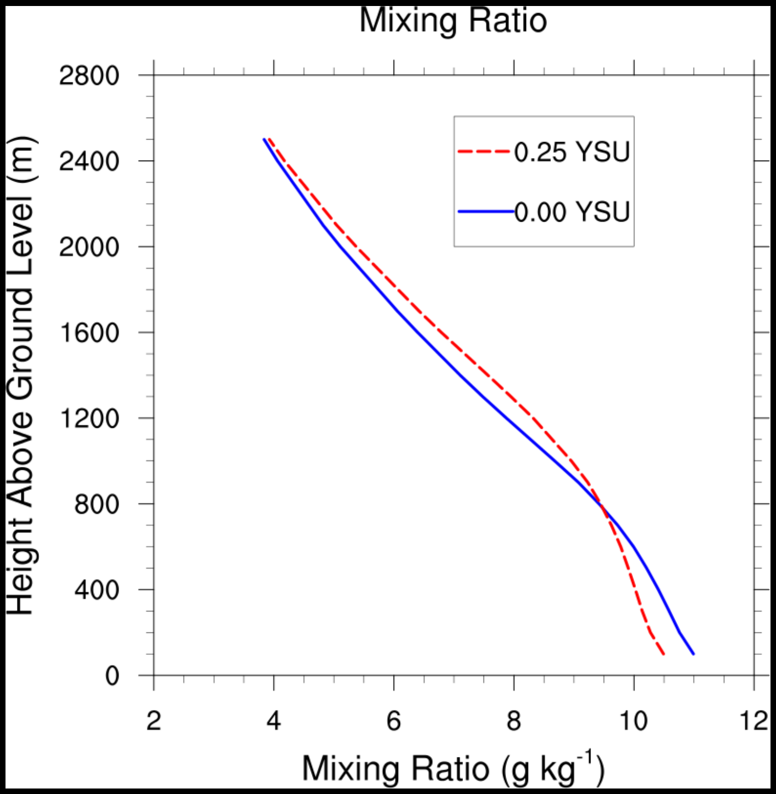
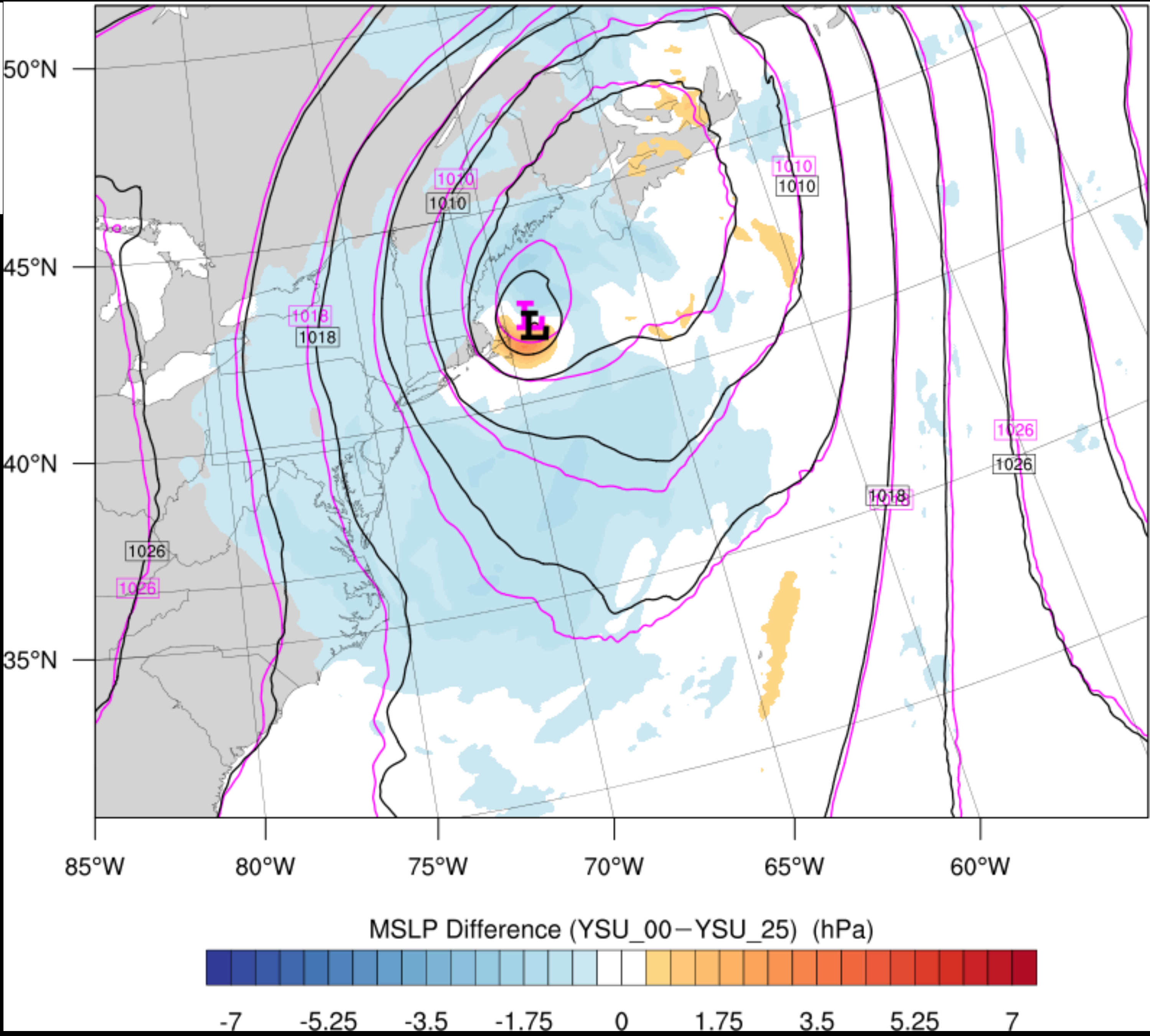




However, when latent heating was turned off…

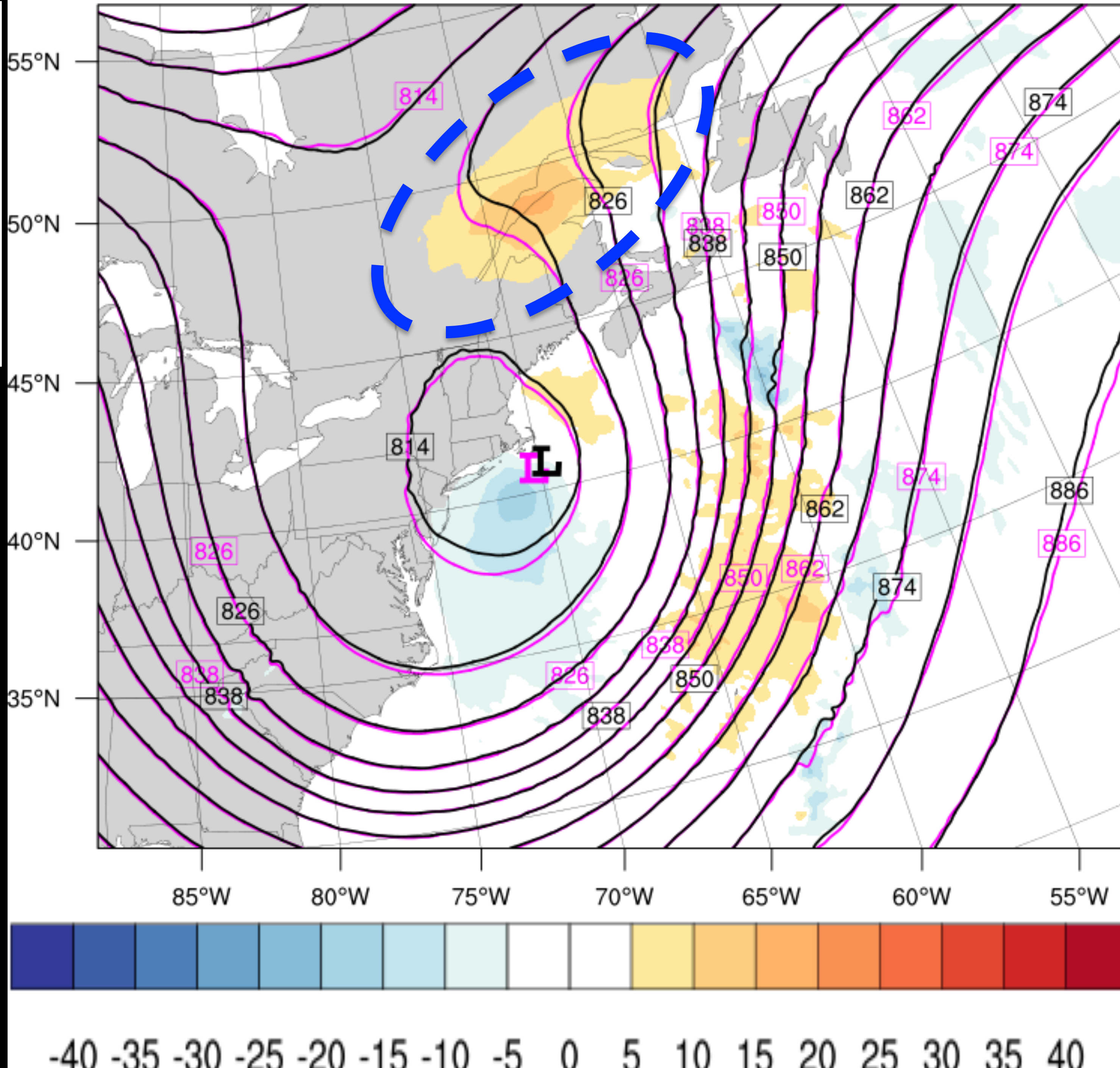
MSLP Difference (fill; less mixing– more mixing) and MSLP for ***NO LATENT HEATING***



0900 UTC 28 January

This suggests **moisture and latent heating differences** between the two mixing regimes may be responsible for the differences

500–200-hPa geo. height difference (m, shaded; less mixing – more mixing) and 300–200-hPa geo. heights (dm, contoured). MSLP minima = “L”



0000 UTC
28 January

26–28 January Snowstorm

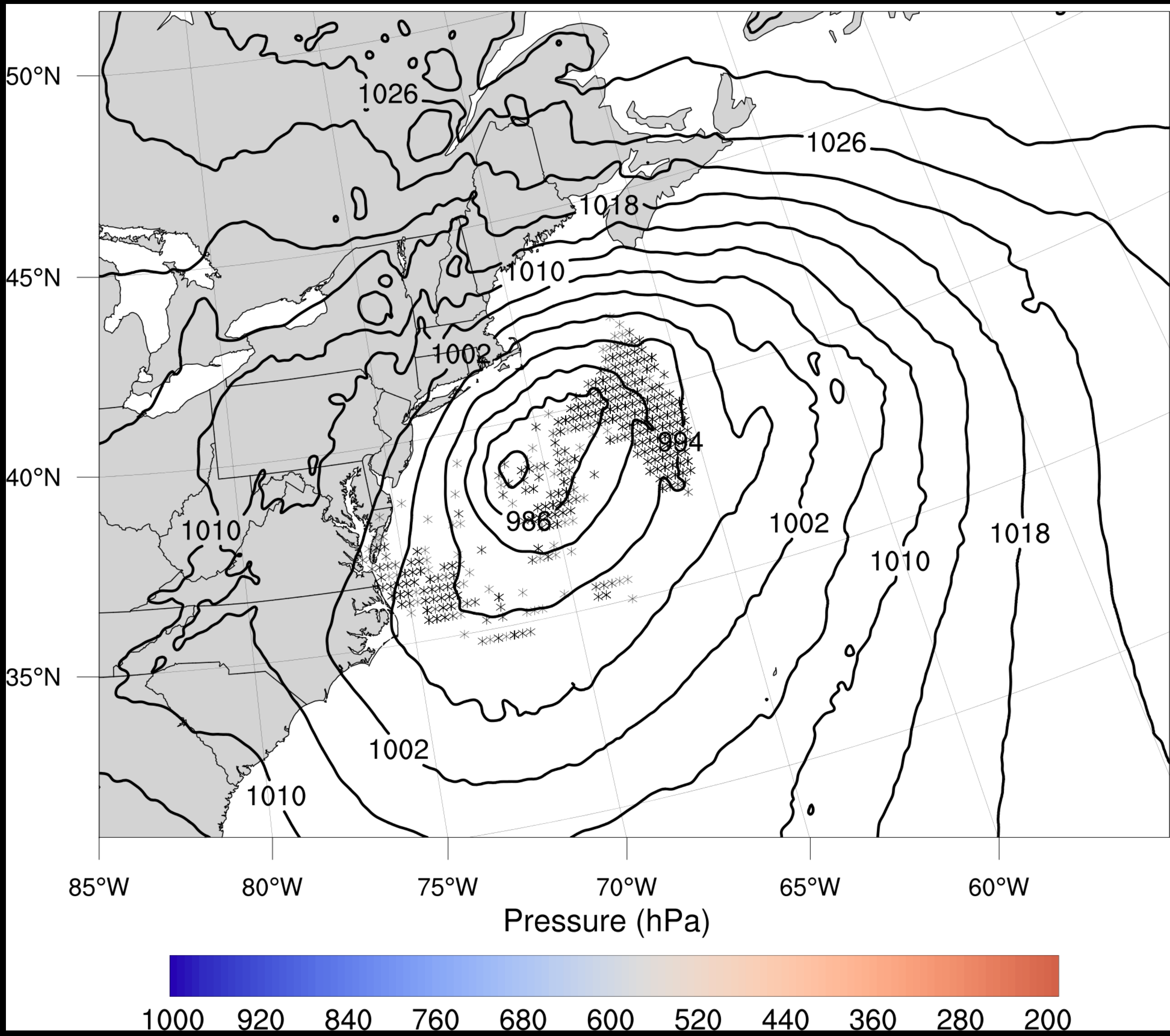
- ***<u>Less mixing</u>*** surface cyclone has higher upper-level heights downstream and a deeper trough

- We investigate the ascending air parcels using LAGRANTO (Sprenger and Wernli 2015)

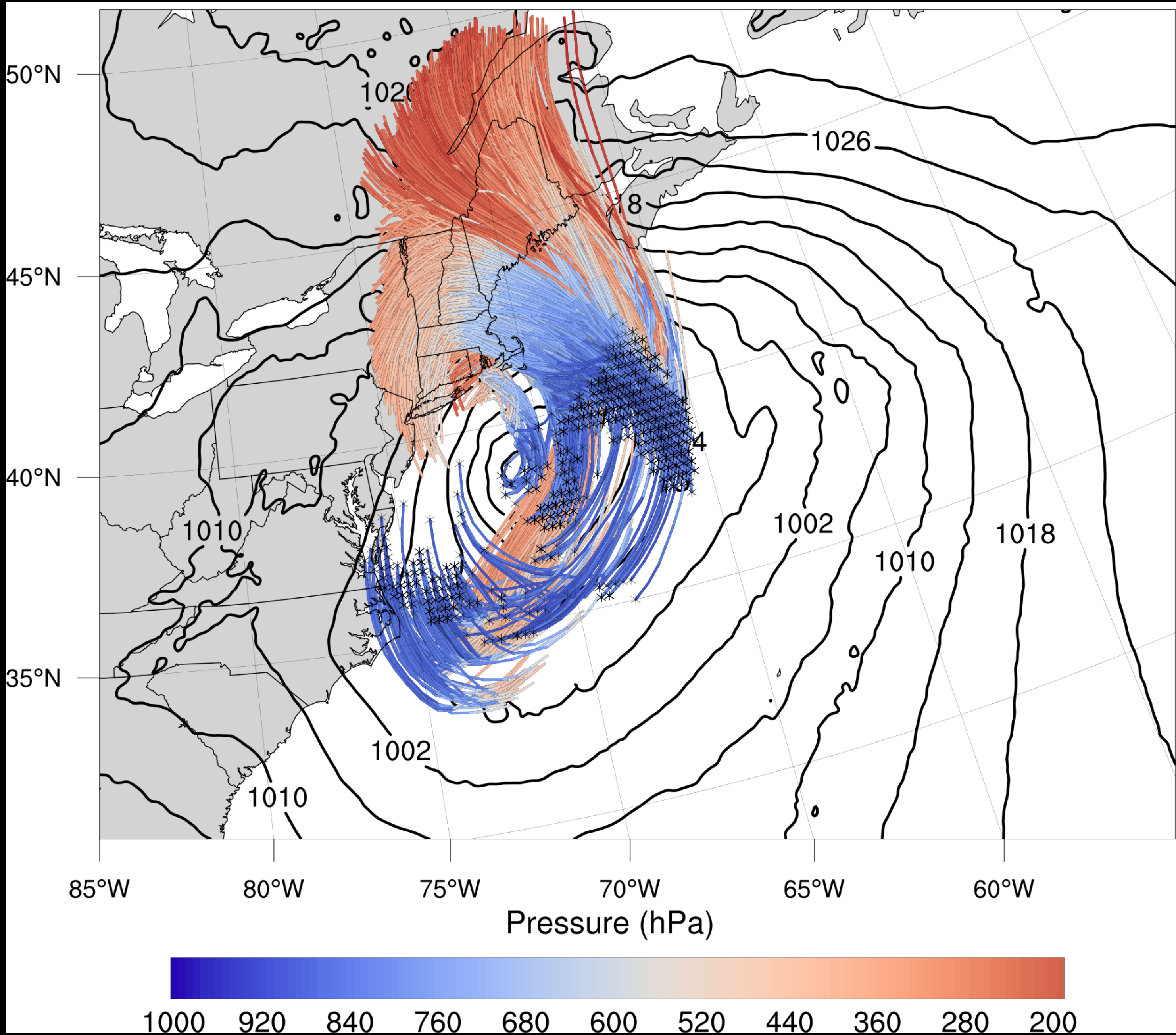
26–28 January Snowstorm

- Launched 12-h forward trajectory swarm from the lowest 1 km within 500 km of the surface cyclone at 0900 UTC 27 January 2015
  - Selected top 10^{th} percentile of ascending parcels

Starting positions of the top 10th-percentile ascending 12-h forward trajectories for the less mixing run ending 2100 UTC 27 Jan and MSLP (contoured) valid 0900 UTC 27 Jan.



Pressure (hPa, shaded) of the top 10th-percentile ascending 12-h forward trajectories for the less mixing run ending 2100 UTC 27 Jan and MSLP (contoured) valid 0900 UTC 27 Jan. Black X's mark trajectory starting points.



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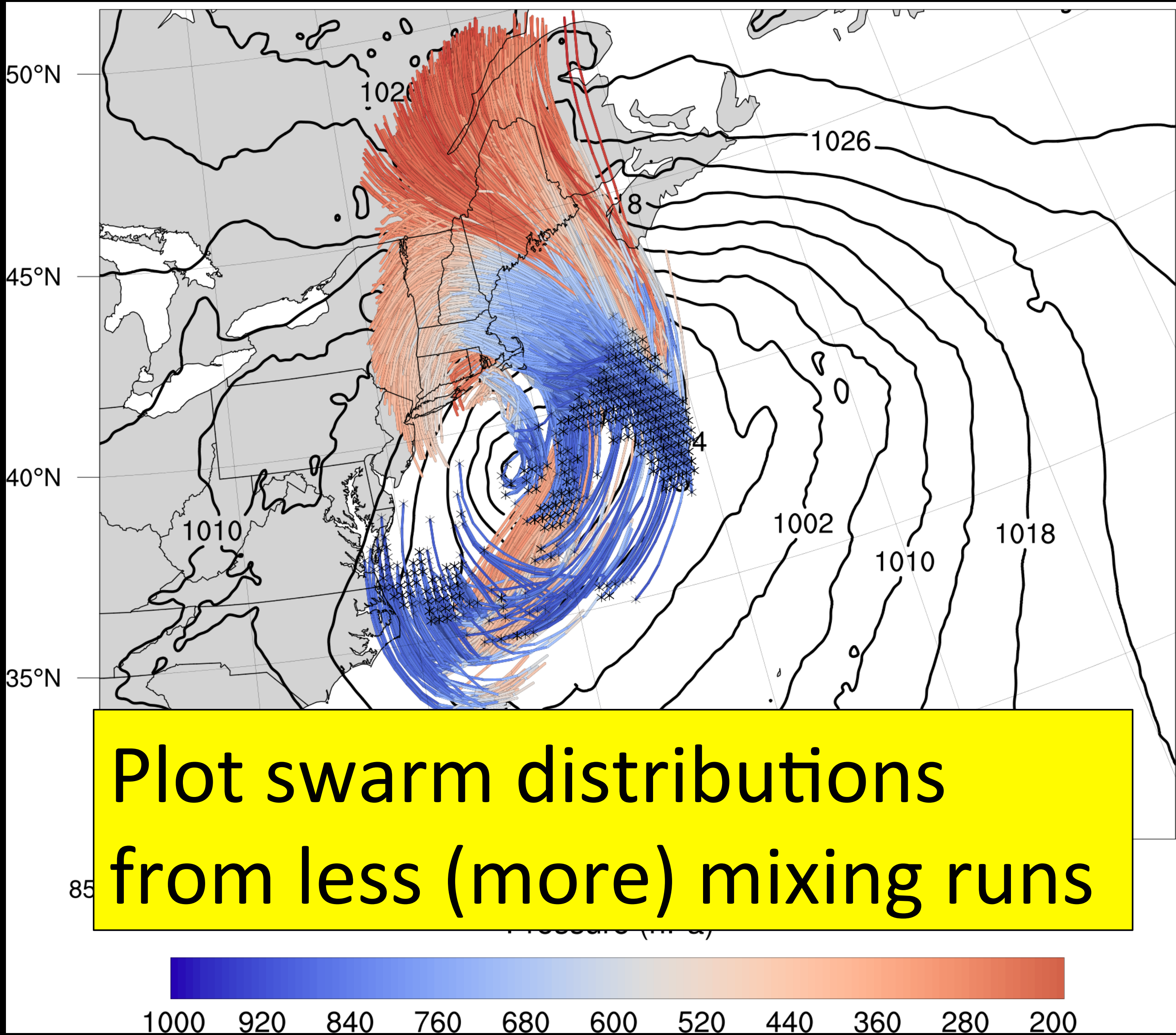
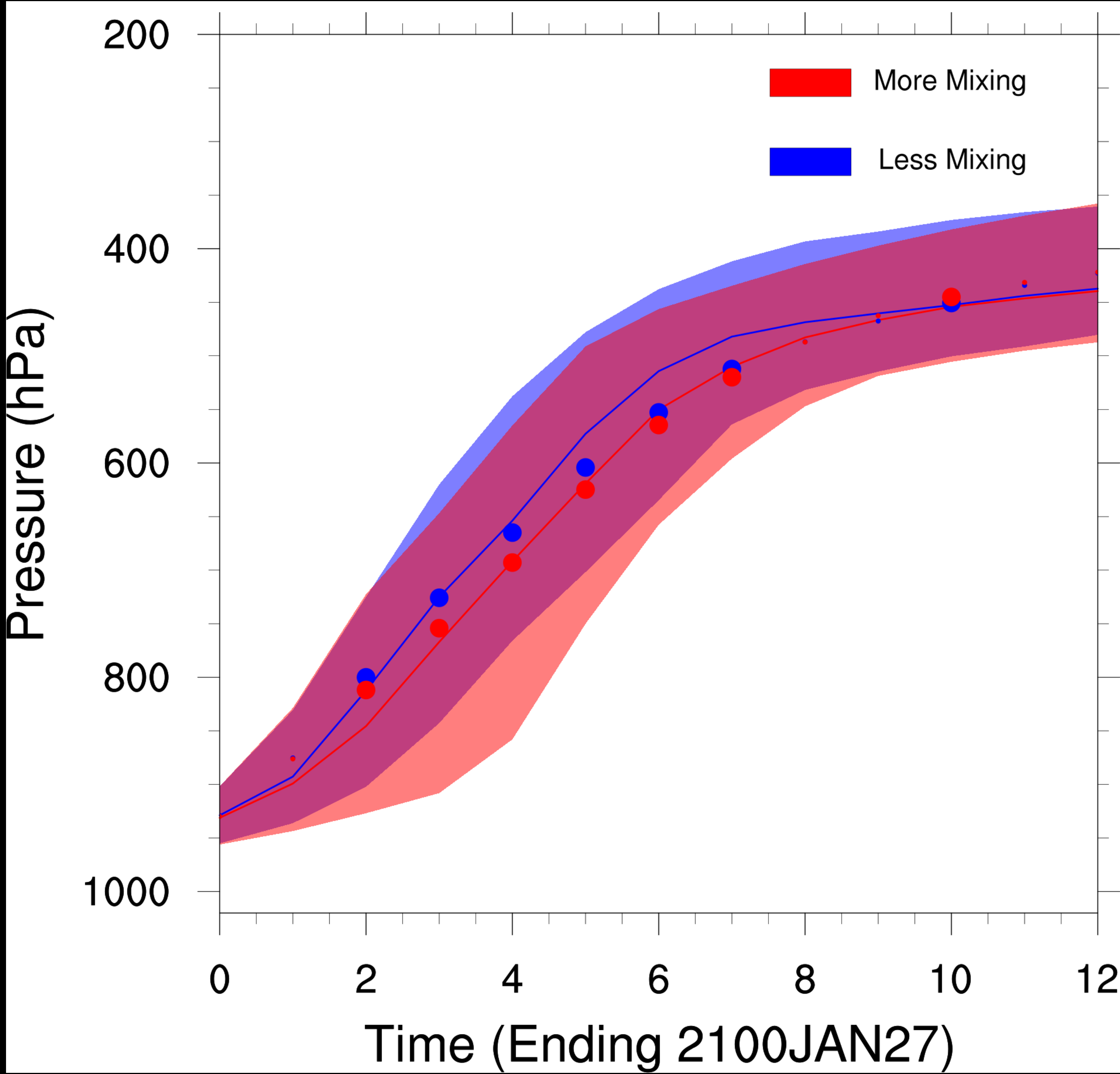
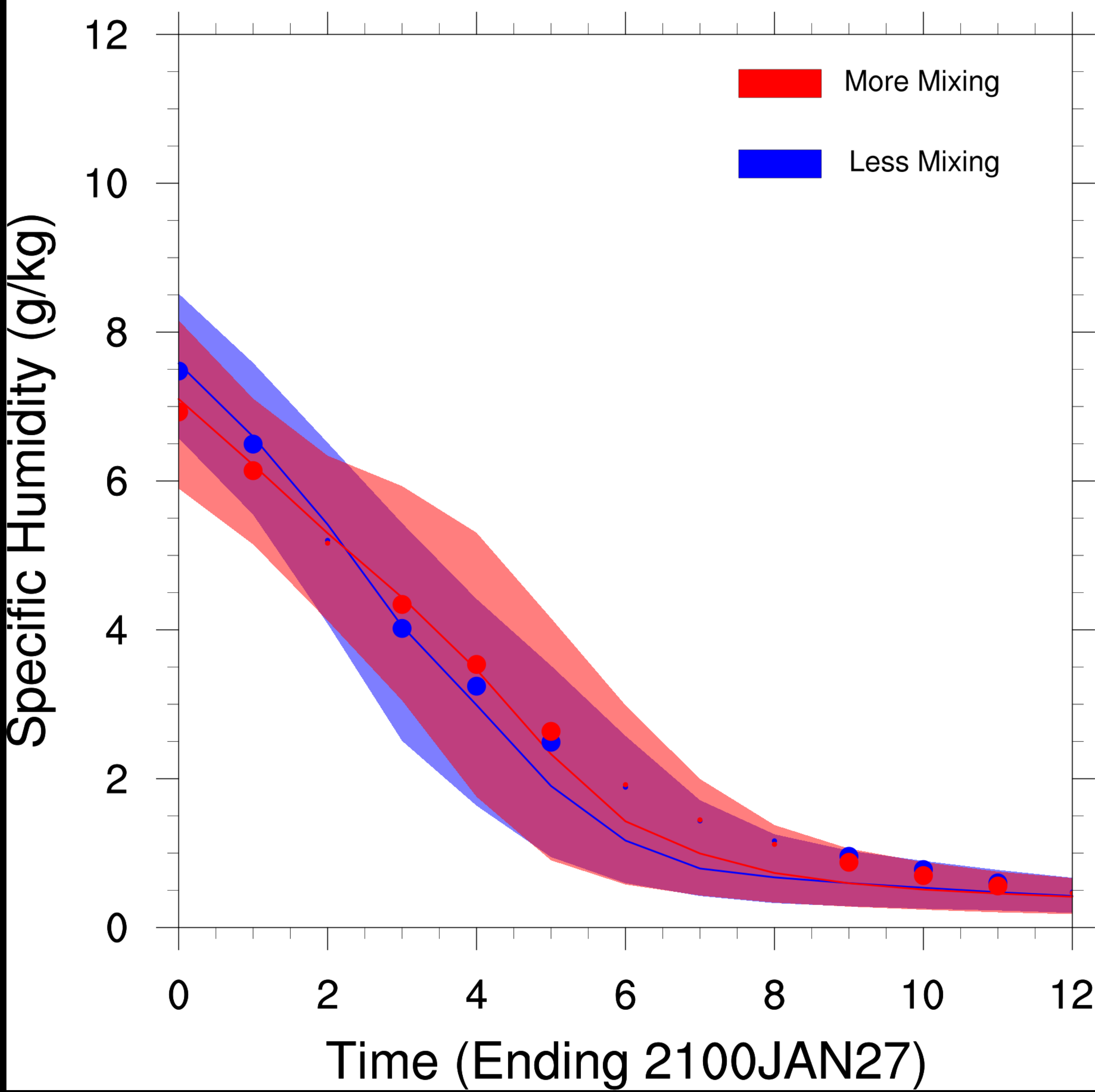


Plot swarm distributions from less (more) mixing runs

Distributions of top 10th-percentile 12-h ascending trajectories ending 2100 UTC 27 January for pressure. The distribution median (solid lines) along with interquartile range (shading) and distribution mean (dots) are plotted. Bold dots indicate statistical significance at the 95% confidence level.



Distributions of top 10th-percentile 12-h ascending trajectories ending 2100 UTC 27 January for specific humidity. The distribution median (solid lines) along with interquartile range (shading) and distribution means (dots) are plotted. Bold dots indicate statistical significance at the 95% confidence level.



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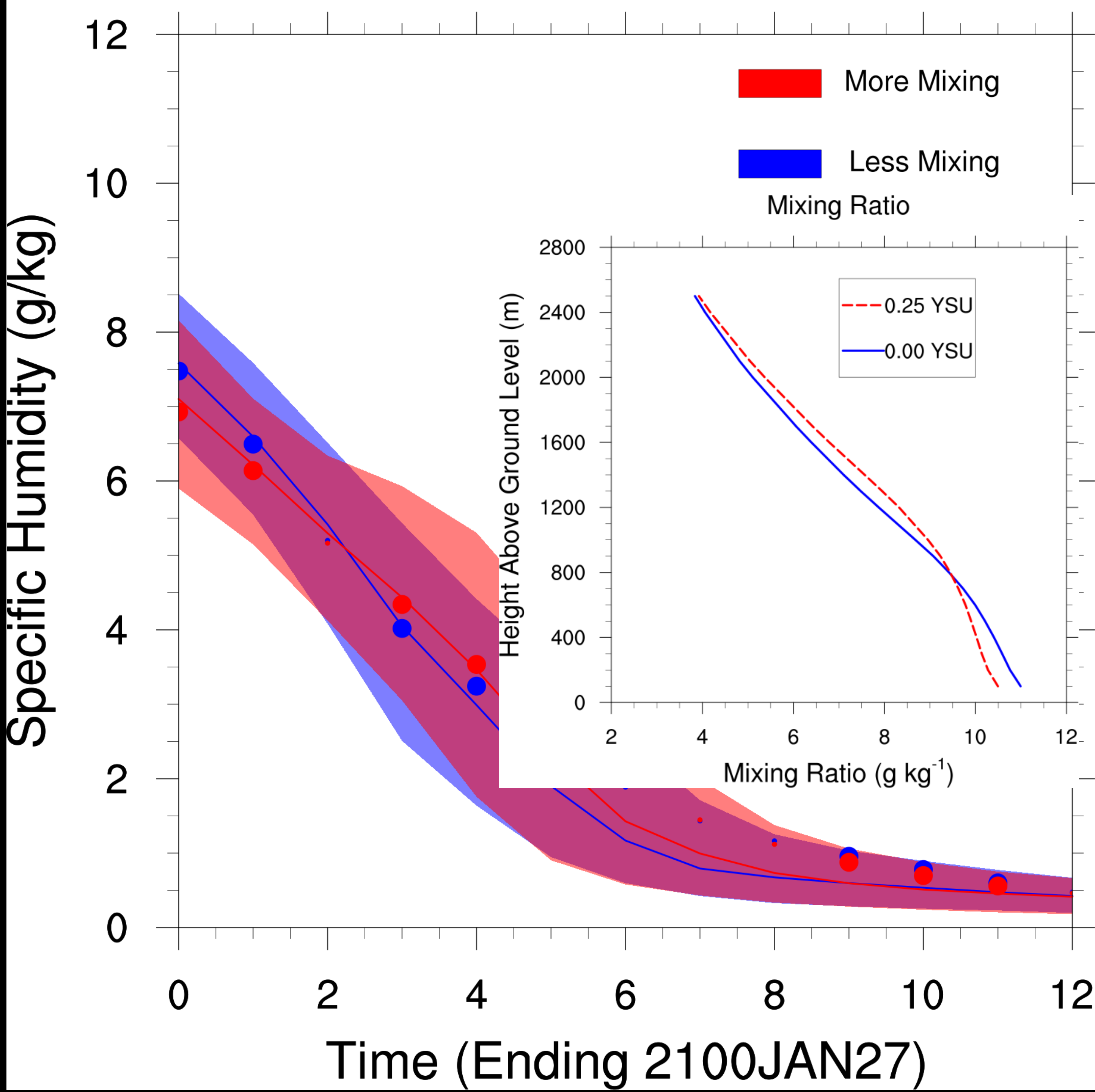
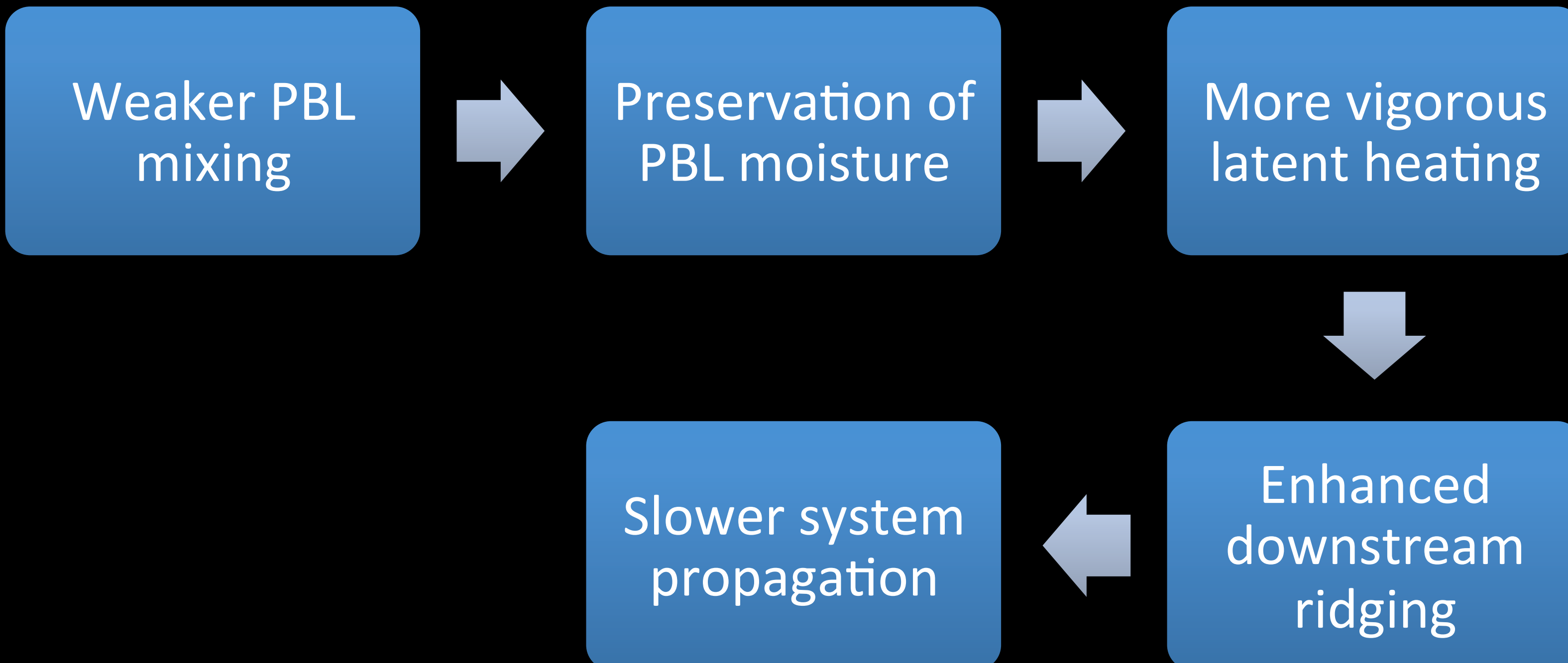


26–28 January Snowstorm

- The ascending parcels in the less mixing case experience more vigorous ascent and lose more water vapor
- This suggests the less mixing case, through preservation of PBL moisture, experienced more latent heating
  - More amplified upper-level flow pattern
  - Reduced downstream propagation

Email: mvaughan@albany.edu

Concluding Remarks



– Test using an idealized cyclone in various moisture environments

I was supported by the Department of Defense (DoD) through the National Defense Science & Engineering Graduate Fellowship (NDSEG) Program.

Overtime Slides

- ***<u>Less mixing</u>*** surface cyclone lags behind more mixing surface cyclone
  - More snowfall on western flank with less mixing
- Robust with regard to:
  - Terrain
  - Surface friction
  - Random noise perturbations
  - Microphysics

Poor Man's Warm Sector

- Used layer-averaged 950–800-hPa theta to compute anomalies for each time-step within the domain
- Used positive anomalies for designating the warm sector