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A Tale of Two Storms: The Evolution of Mixed-Phase Winter Weather in a Perturbed Global Warming Simulation

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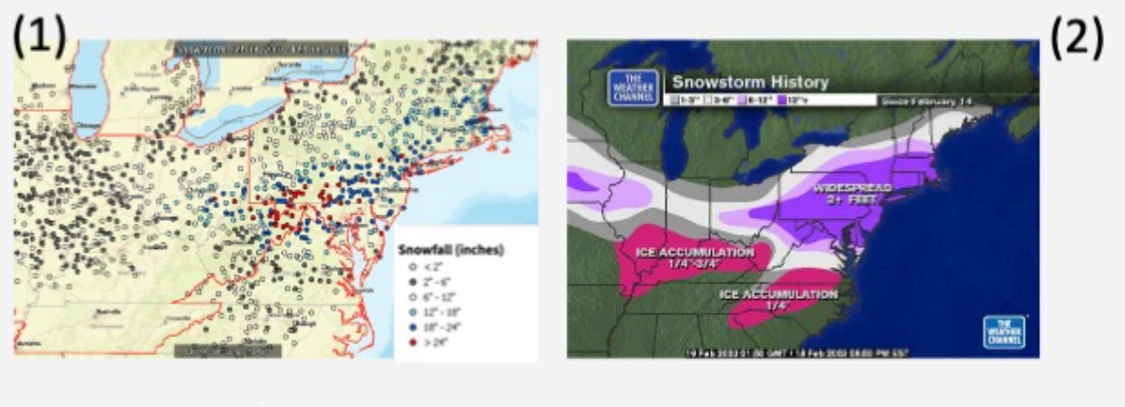
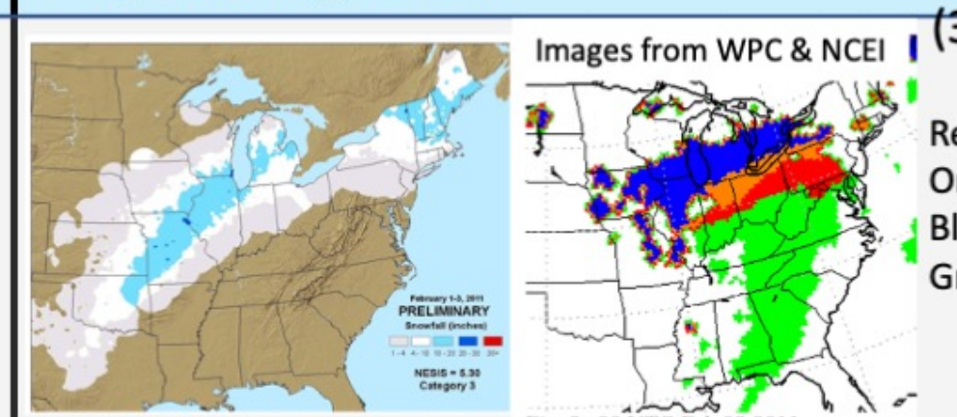
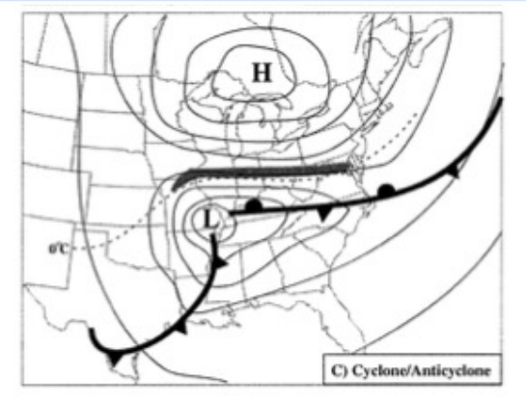
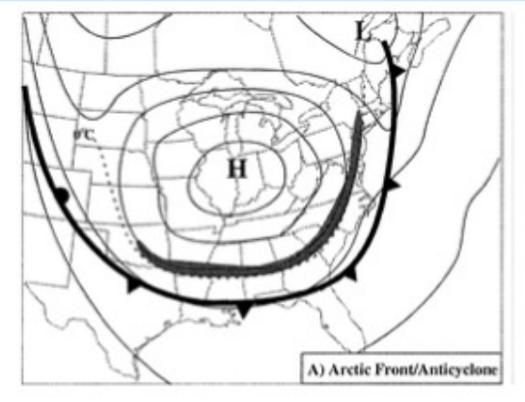
1. SETTING THE SCENE

How might mixed-phase winter weather change in a warmer climate? This poster addresses this question in a preliminary fashion through the example of two historical winter weather events, modified to a late 21st century climate under high greenhouse gas emissions. It is expected that a warmer climate will reduce winter weather extremes, and this has been demonstrated over the United States (e.g., Jeong et al. 2018), particularly for snowfall. However, what about marginal mixed-phase weather than relies on both cold AND warm air for its development?

The case studies we examine are two mixed-phase events occurring in the month of February, roughly 8-years apart. The table below highlights the key narratives for both cases.

	Case 1 – February 14-18 2003	Case 2 – February 1-3 2011
Antecedent Synoptic overview	Cold air in place from Canada to the Northeast. Lee cyclogenesis in the southern Rockies on the 14th, with the system moving northeastward. Strong temperature gradient and high pressure to the north slowed the movement of the surface low and provided persistent forcing for winter precip.	Cold air in place from Canada to the Plains. Upper ridge amplified over NE Pacific with troughing over Rockies – broad trough over the US through the event. Eventually a surface low developed and tracked northeast, south of the persistent strong temperature gradient.
Areas Impacted	 (1) (2) Estimated $50 million in damages, 10 deaths. Ice storm power outages lasted days – Kentucky FZRA & IP accumulations of 1-2 inches	 Images from WPC & NCEI (3) Red = FZRA Orange = IP Blue = SN Green = RA Estimated $43 million in damages, 1 death and several injuries. Most ice accumulation in IL, IN, OH, PA, with peak amounts 0.25-0.5 inches.
Rauber et al. (2001) freezing rain archetype	 Cyclone/anticyclone	 Arctic front – anticyclone (Rocky Mountain cold air damming – later development of cyclone/anticyclone

IP = ice pellets (sleet), FZRA = freezing rain, SN = snow, RA = rain

2. TECHNICAL APPROACH

Resource/Activity	Description/Specs
NCAR WRF 4 km (Liu et al. 2017)	WRF-ARW numerical model version 3.4.1. Explicit convection, 51 vertical levels, Thompson microphysics, YSU Boundary Layer scheme, and an updated Noah land surface model scheme. The model configuration was tested and optimized by Liu et al. (2017). The historical period is hourly output for surface variables, and three-hourly for upper air, from October 2000-2013. The Perturbed Global Warming (PGW) approach simulates the same historical period and its weather, only with a modified thermal initial and boundary conditions that reflect the mean CMIP5 model projection for 2071-2100 under an RCP8.5 (high emissions) pathway. *Variables used: Geopotential height, air temperature, surface air temperature, precipitation rate, humidity, surface pressure, air pressure.*
Precipitation Type Algorithm	This study uses the Bourgouin (2000) approach. This algorithm calculates areas of lower tropospheric 'positive' (warm) and 'negative' (cold) energy from pressure levels above the surface, which is determined from the equation: $c_p \lvert Area \rvert = c_p \overline{T_l} \ln\left(\frac{\theta_{top}}{\theta_{bottom}}\right)$ Where c_p is specific humidity, *Area* is above or below freezing areas, T_l the layer (wetbulb) temperature, θ_{top} the equivalent potential temperature at the uppermost warm/cold layer level, and θ_{bottom} the potential temperature at the lower boundary. These energies are proportional to the mean temperature of a layer above or below freezing, and the depth of that layer
Analysis Criteria (for case study figures)	**Fig. 2 and 7** – precipitation phase as derived from the Bourgouin algorithm **Figs. 3 and 8** – duration of warm layer and cold layer configuration (the warm-cold layer ratio here must be at least 2-1, and areas outside of the zones of freezing precipitation are not included). **Tables** – spatial area is defined as the number of grid points with precipitation of each type above 1 mm, while the accumulations are summed up over all applicable grid points for total event duration. **Figs. 5 and 10** – precipitation rates are the cumulative probability distribution of all precipitation rates over each hour for each grid point

Caveats and Limitations:

PGW – is this really a reasonable way to examine climate change? Perturbed global warming studies make a large assumption regarding future climate – that is, that synoptic events that were seen historically will also be distributed similarly in the future. While such simulations are helpful for examining a historical events in a warmer climate, they do not permit the large-scale atmosphere to freely evolve. Thus, while we focus on thermodynamic modification, PGW is a reasonable approach. However, we hope to examine dynamical changes using high resolution RCMs later in this work.

Isn't CMIP5 out of date? As of 2021, we have CMIP6, the latest suite of global climate models. However, while the specific specs and emissions scenarios have changed, the CMIP5 data is still a helpful tool in projecting future change, though it is but one arm of a vast array of datasets.

What about just using one precipitation type algorithm? Here we apply one technique, however there a numerous possible techniques ranging in complexity. We intend to evaluate multiple algorithms in due course, using a small ensemble (e.g., Mullens and McPherson 2017). It should be noted that additional uncertainty is contributed here by temporal mismatch between 3-hourly upper air data (needed for precipitation type estimation), and hourly surface precipitation. We assign a phase type to three hourly accumulated precipitation as a result.

3. CASE 1 – PRESIDENT'S DAY SNOWSTORM/BLUEGRASS ICE STORM (FEB 14-18 2003)

February 15 2003 12 UTC – WRF analysis (925 mb height, surface temperature)

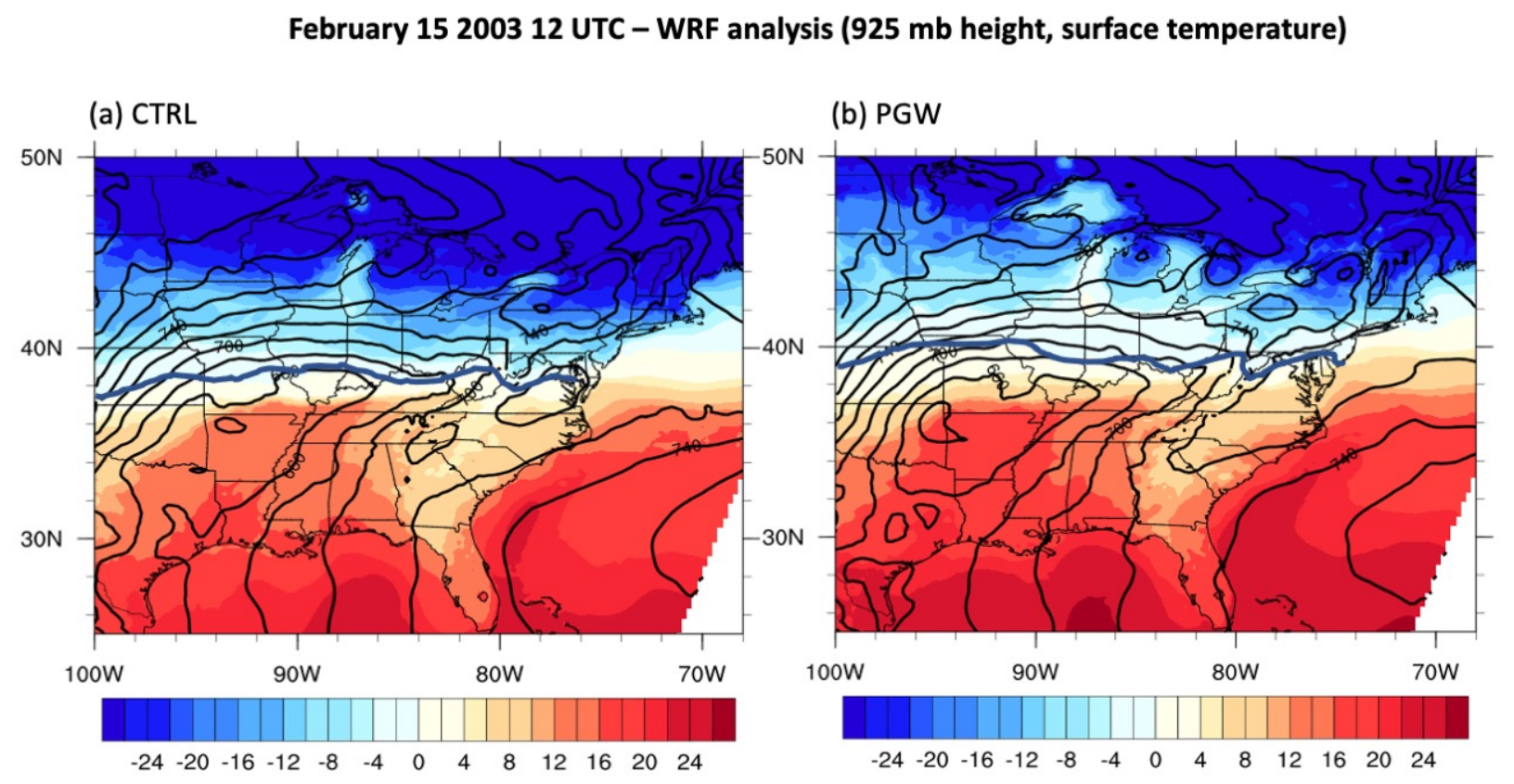
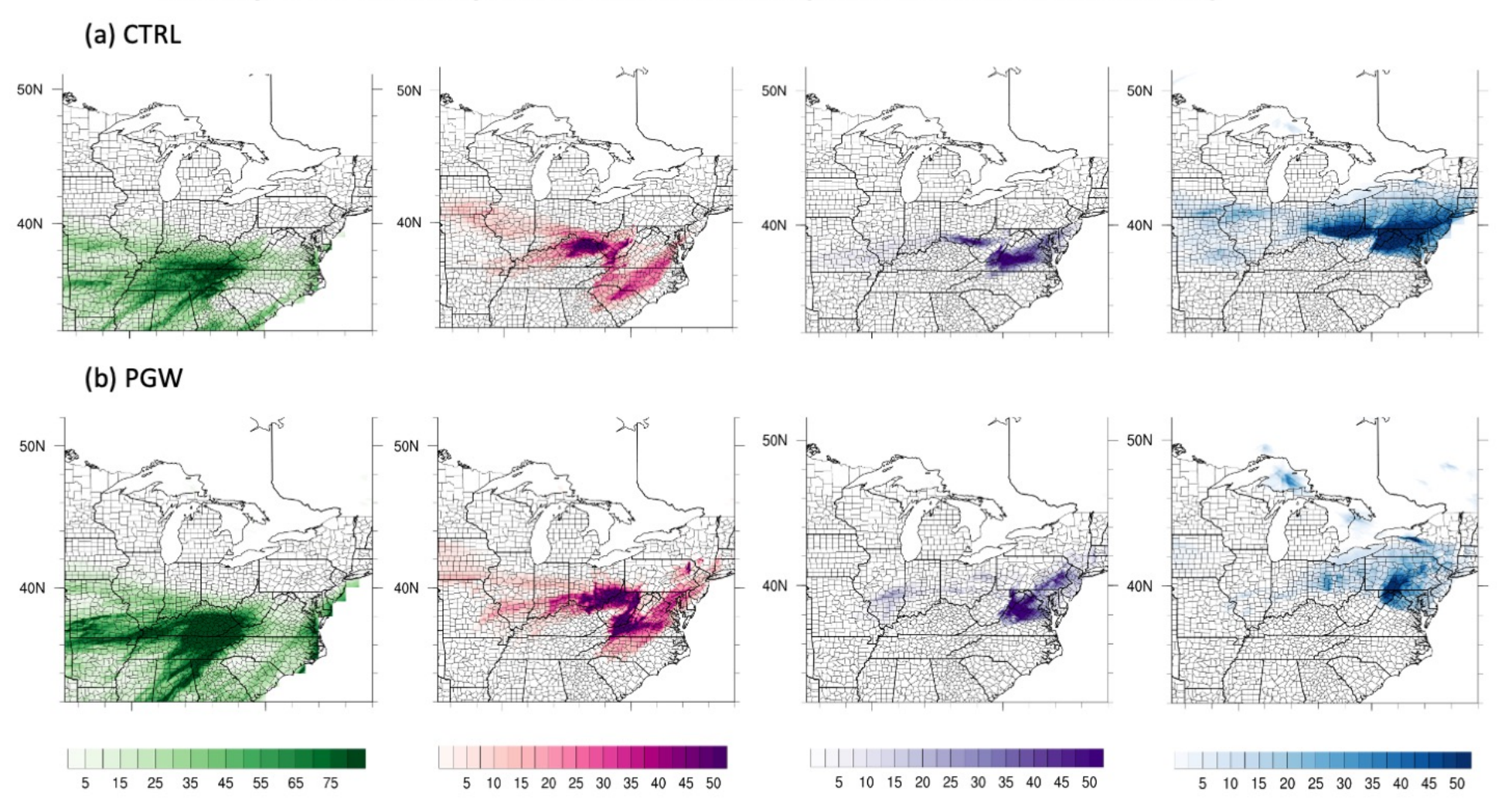
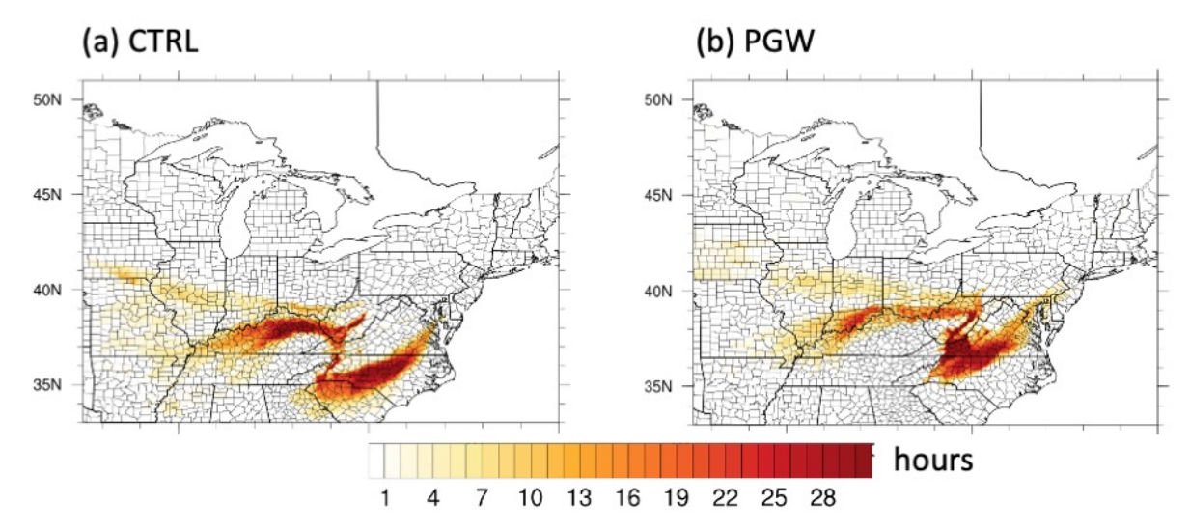


Figure 1 (left) reveals a slightly stronger low in the PGW case, while the 0˚C isotherm is shifted northward. The temperature gradient over the Midwest and mid-Atlantic weakens, but sub-freezing air is still present in these locations. Warmer air to the south provides potential for a deeper warm layer. The slight dip in heights associated with the developing low in (b) can be attributed to lower static stability in the warmer air. This low propagates to the east with a little more speed than in (a) (e.g., Mullens 2016)

February 14-18 2003 Precipitation Phase Distribution (event total accumulations in mm)



February 14-18 2003 Warm and Cold Layer Duration and Magnitude

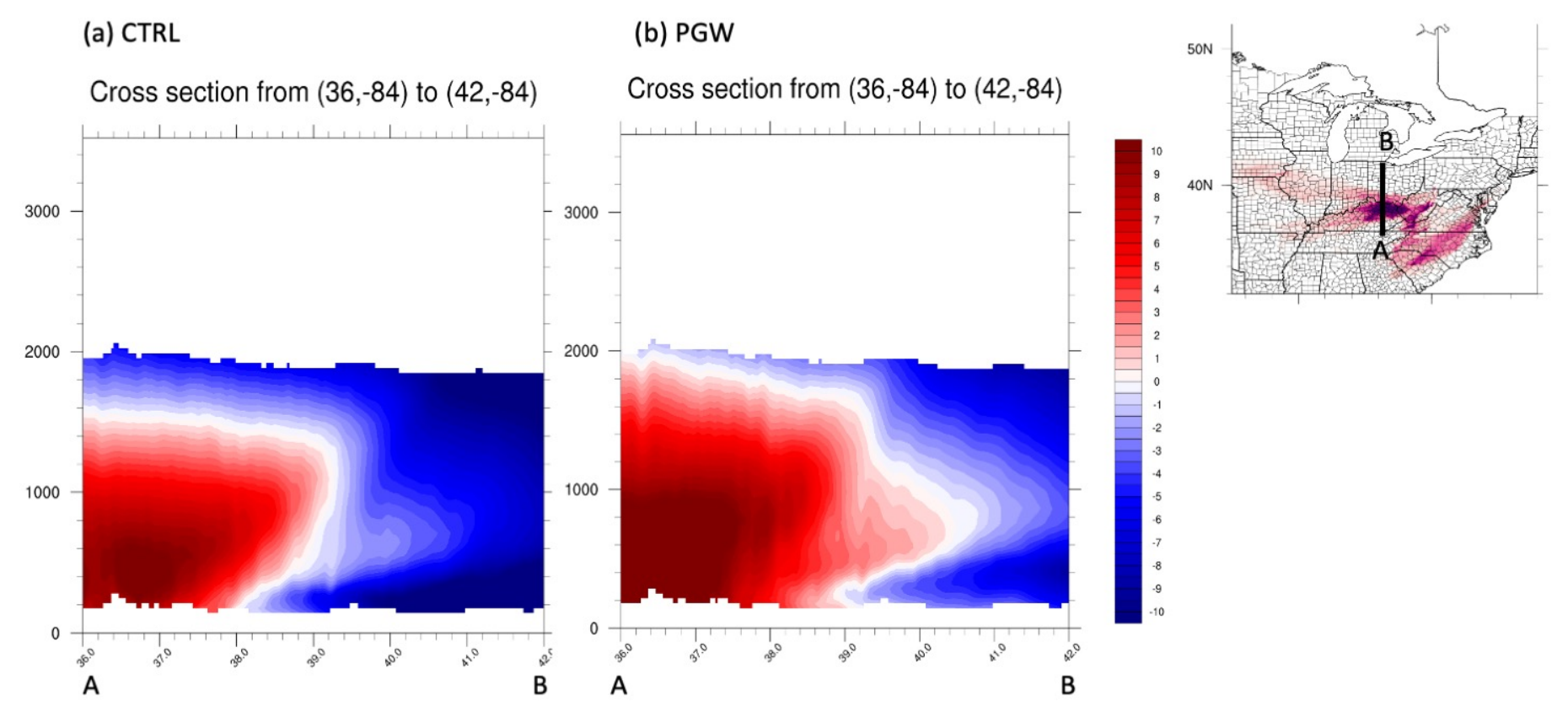


Feb-03	Rain	Snow	Ice Pellets	Freezing Rain	Metric
PGW-CTRL	0.49	-17.05	0.64	3.87	Domain cover
PGW-CTRL	22.0	-42.0	12.6	40.1	Accumulation

Percentage (%) changes in spatial area and total accumulation

Figure 2 (left, above) shows the phase types accumulated over the duration of the storm. Whereas the control case accurately depicts a major snow event in the mid-Atlantic, and a major ice event in Kentucky and parts of the Carolinas, the PGW adjustment considerably lowers snowfall amounts, and increases rainfall and freezing rain amounts, shifting both to the north and east. The Bluegrass ice storm of 2003 now becomes the bane of the Buckeye state and West Virginia, with mixed-phase precipitation sleet dominating the DC/Baltimore areas, while Kentucky and areas south receive potentially flood-producing rain. **Figure 3** (right, above) suggests that the overall duration of the appropriate warm over cold layer configuration reduces over the Midwest and increases to the east.

February 2003 Vertical Thermal Profile of the lower troposphere (averaged over the 16th)



February 14-18 2003 Precipitation Rate distributions

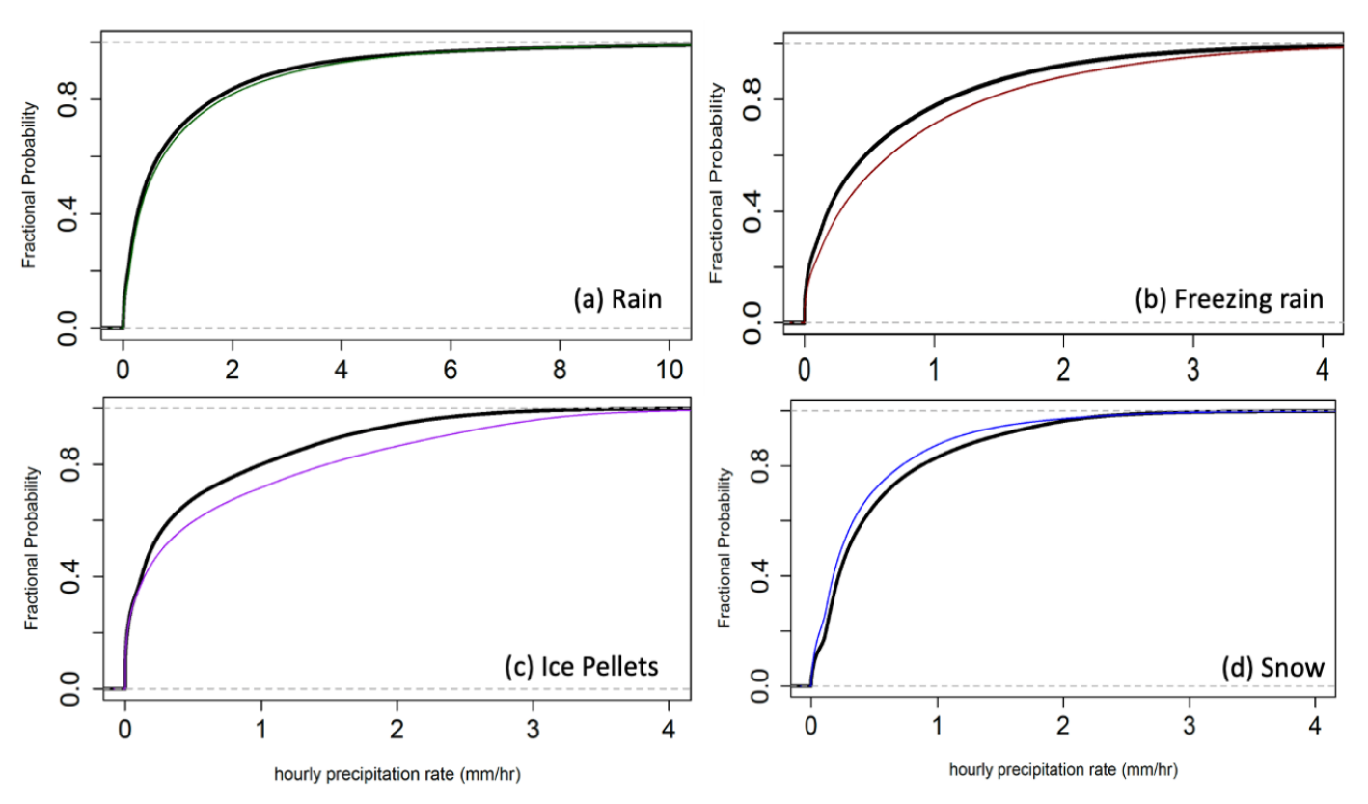


Figure 4 (left, above) is a cross-section of the lower tropospheric temperature (18 model layers). The northward shift of the freezing line is apparent, as is the reduction in the temperature gradient. Notably, the PGW case shows enhanced overrunning of warm air conducive to freezing rain. **Figure 5** (right, above) shows probability distributions of precipitation in each phase through the storm duration and spatial extent. While freezing rain and ice pellet rates are enhanced, snowfall rates decline. The higher amounts for freezing rain are thus a combination of a broader area of appropriate thermodynamics coupled with higher precipitation rates.

5. KEY FINDINGS

Despite differences in synoptic evolution, both case studies here show an increase in the mixed-phase portion at the expense of snow in a late 21st century, high emissions climate. These increases are the result of a deeper warm layer which is enhanced through advection of warmer air over subfreezing air. In both events, the initial subfreezing airmass was very cold, and some moderation of this cold air created an environment more suitable for freezing rain over ice pellets and snow (deep warm layer, shallow subfreezing cold layer). The expected northward shift of the axis of mixed-phase precipitation was evident, as was the notable increase in rainfall and rain rates, which extended to freezing rain.

Does this mean we get MORE ice in a warmer climate? No! These two case studies showed very cold arctic air being modified to be suitable for freezing rain, but many recent-past events are already more marginal for ice, and we hypothesize that historical events which either (a) lack a cold antecedent airmass, or (b) have a very shallow subfreezing airmass at event onset and/or weaker temperature gradient, will tend to show a decrease in the mixed-phase zone. **Therefore, the synoptic evolution of the historical event is critical to how a similar event would evolve in a warmer world, which we intend to explore further.**

4. CASE 2 – MIDWEST MIXED-PHASE MAYHEM (FEB 1-3 2011)

February 1 2011 12 UTC – WRF analysis (900 mb height, surface temperature)

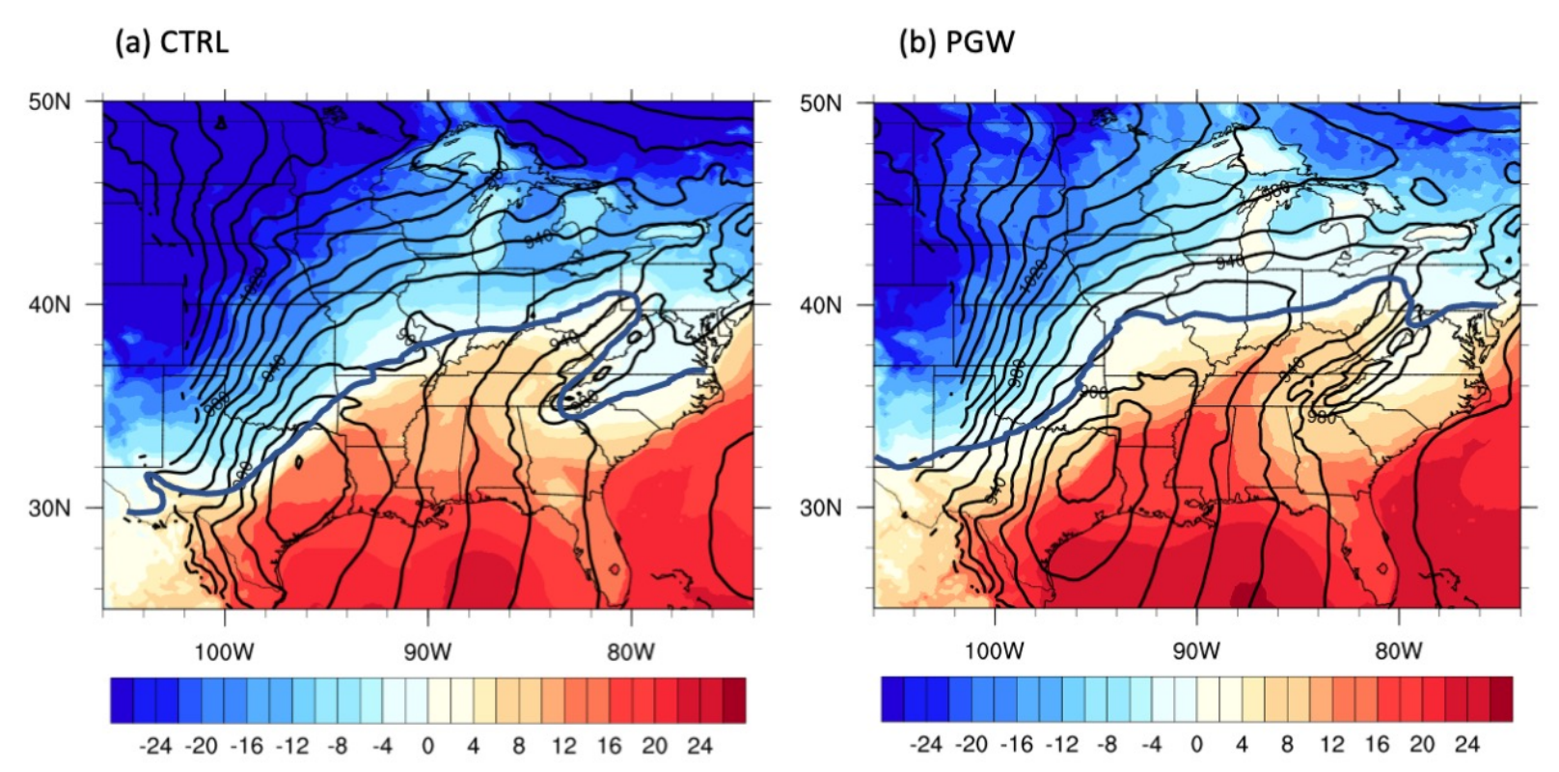
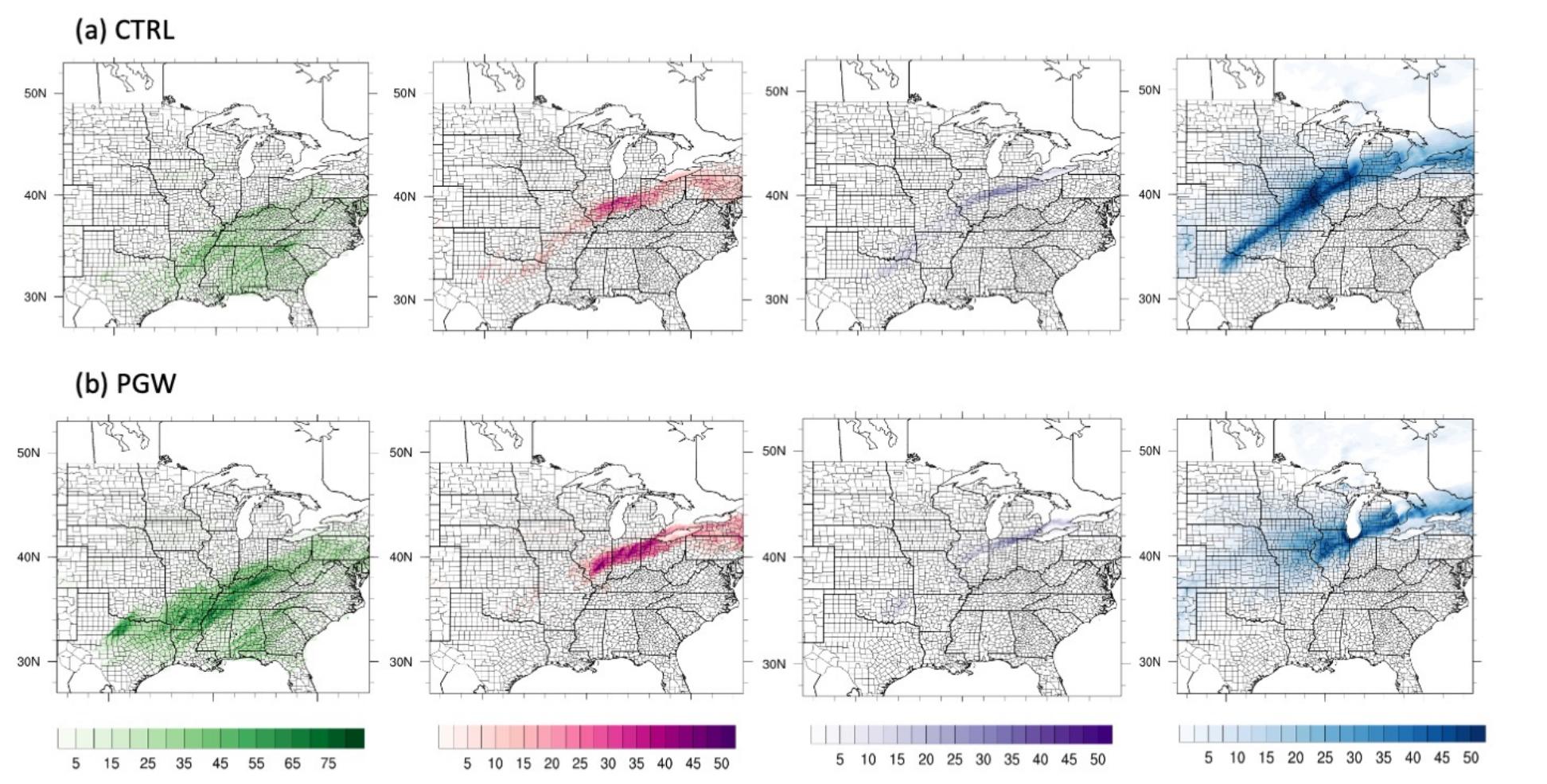
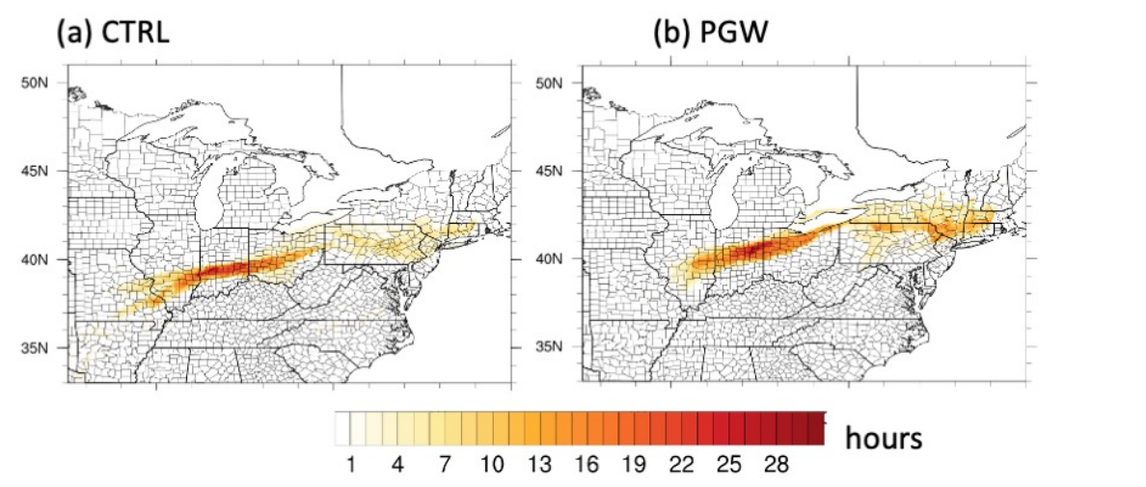


Figure 6 (left) shows that this storm began after cold air plunged south into the Great Plains in the lee of the Rockies. Very warm air was present to the south and east, with a second weaker area of cold-air damming east of the Appalachians. In the PGW case, these same features are present, but as in Fig. 2, the cold air is less cold, and the warm air is warmer. The lee Cyclone developing over the Southern Plains is also slightly stronger.

February 1-3 2011 Precipitation Phase Distribution (event total accumulations in mm)



February 1-3 2011 Warm and Cold Layer Duration and Magnitude

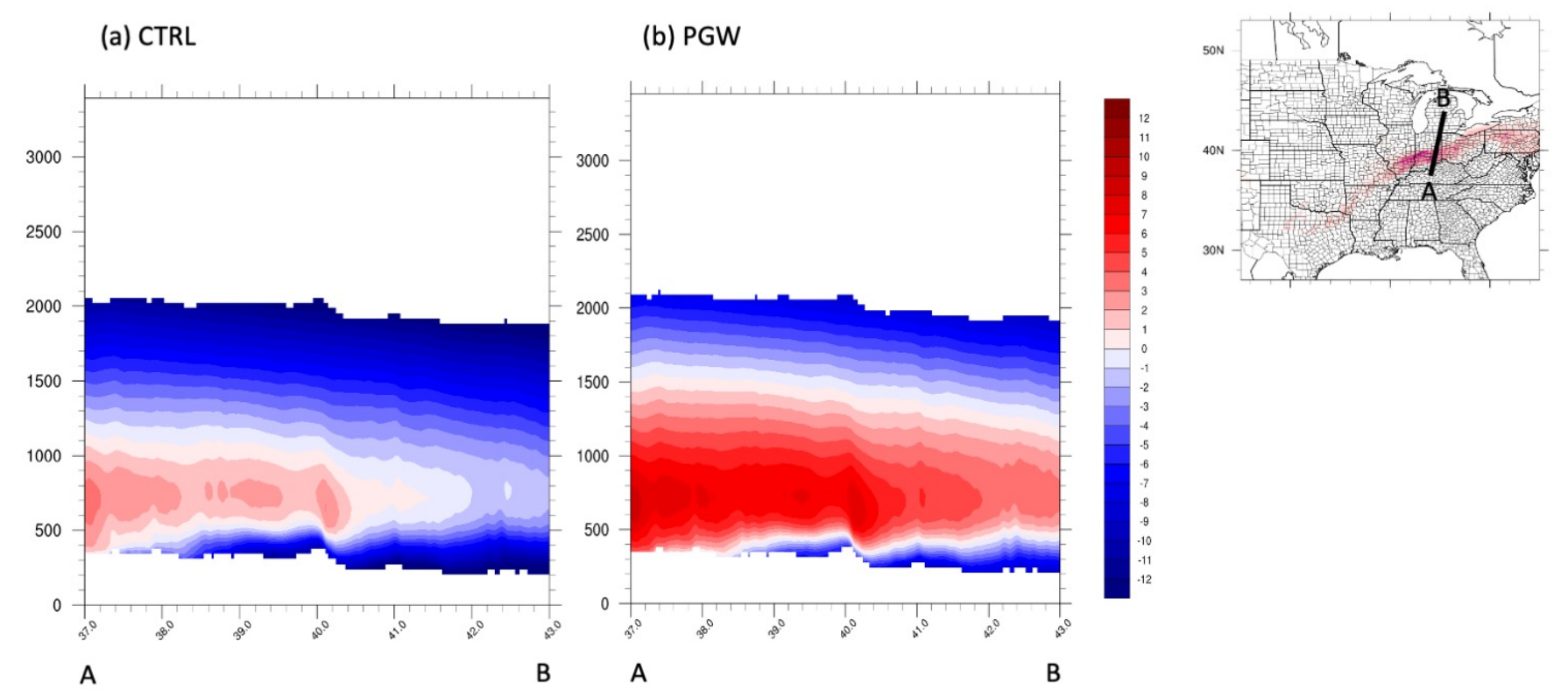


Feb-11	Rain	Snow	Ice Pellets	Freezing Rain	Metric
PGW-CTRL	1.2	-6.0	-5.6	-5.8	Domain cover
PGW-CTRL	55.8	-20.3	-14.5	35.9	Accumulation

Percentage (%) changes in spatial area and total accumulation

Figure 7 (left, above) is as Fig. 2. This event was known primarily for its snow, which impacted a large swath of the Plains northeastward as shown. Freezing rain and ice pellets produced a lower-end ice storm for southern Illinois and Indiana. The PGW adjustment reduces the sting of the snow, removing it almost entirely from the Plains and lowering the magnitudes for all but the Great Lakes region. Ice pellets show a northward shift and decline in amounts, while once again, rain and freezing rain show higher total accumulations, albeit less of a change in areal extent. **Figure 8** (right, above) suggests that the overall duration of the appropriate warm over cold layer configuration is unchanged over the Midwest, but shifted north, while it is increased in the east, just like Case 1.

February 2003 Vertical Thermal Profile of the lower troposphere (averaged over the 2nd)



February 1-3 2011 Precipitation Rate distributions

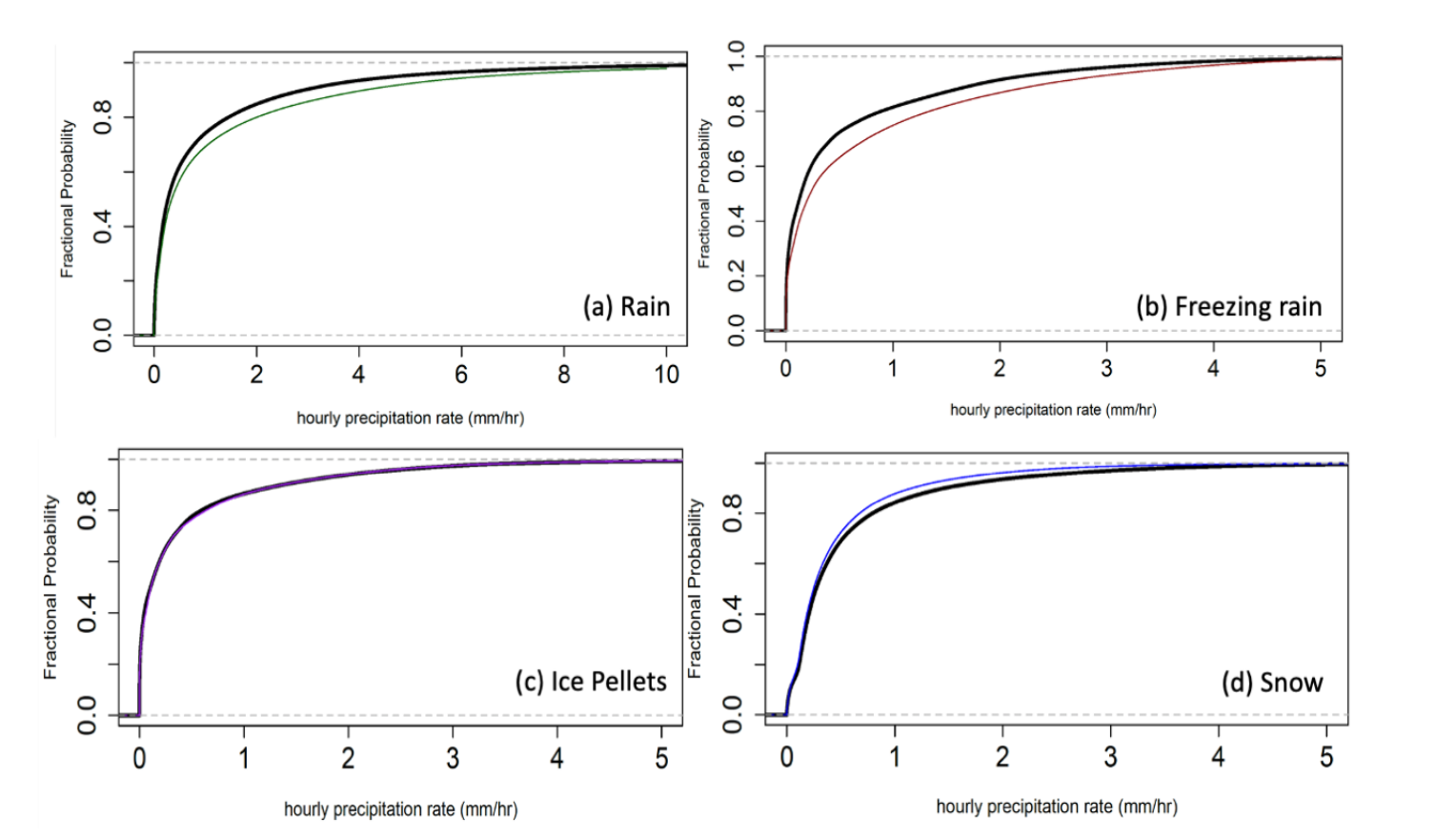
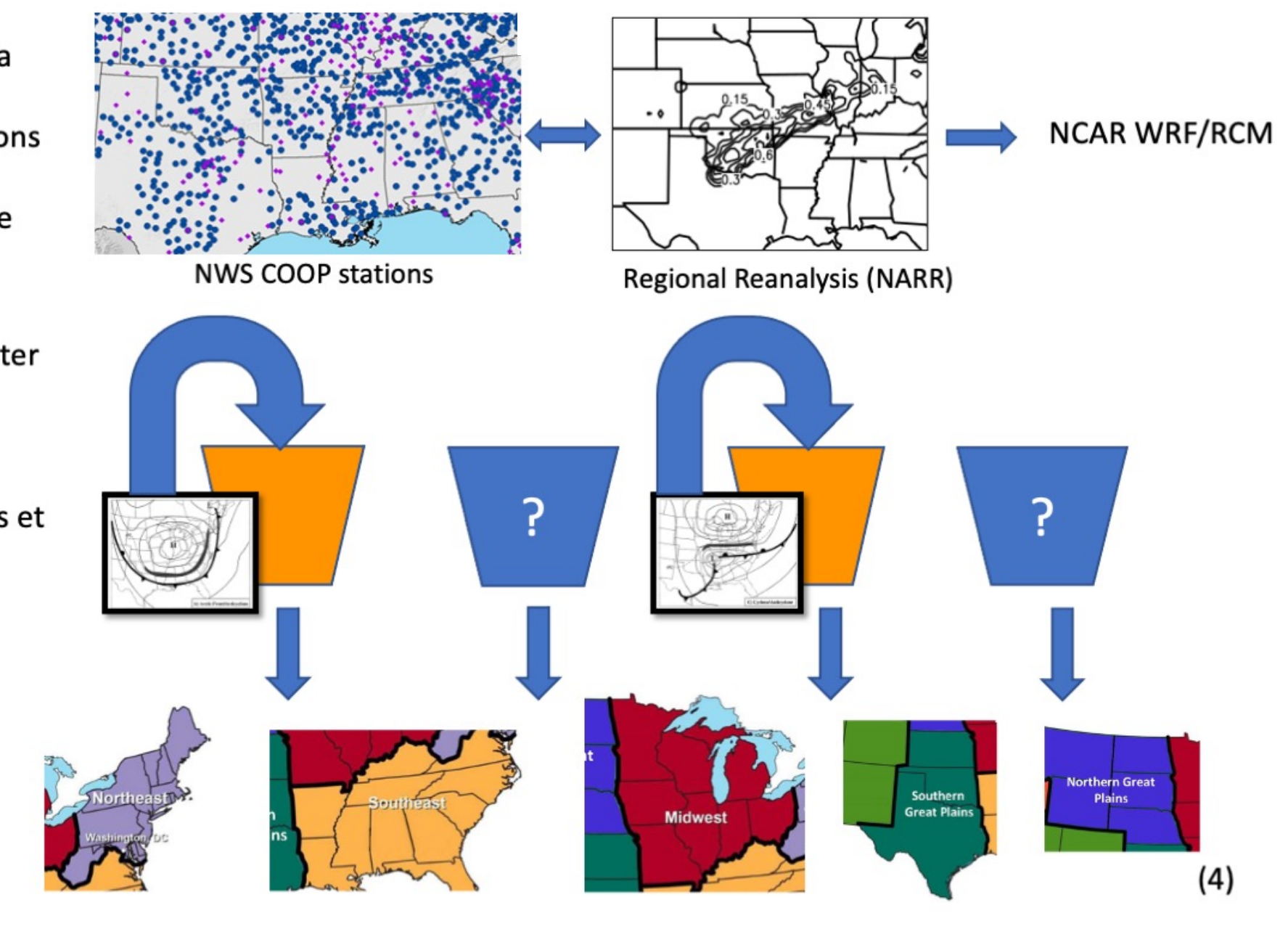


Figure 9 (left, above), as Fig. 4. In this case, there is a pronounced northward extension of the warm layer, and the overall warm layer magnitude and depth over this latitude range increases from a maximum of 4-9˚C, and ~600 m to 1km at 40N respectively. The freezing layer shrinks in vertical extent, and is removed south of about 38.5N, while the northern areas show favorability for mixed-phase. **Figure 10** (right, above) as Fig. 5. Rain and freezing rain rate distributions show increased probabilities of higher precipitation rates in the PGW case, while there is no change for ice pellets/sleet, and a decrease in snowfall rates.

6. WHERE ARE WE HEADING NEXT?

This project is part of NSF-funded work to examine thermodynamic changes to winter storms in a warmer climate. The process we will use to complete this work is shown below. The output of this analysis may be used by other researchers, stakeholders, and decision-makers to examine their potential risks to hazardous weather under climate change. However, there is still much we don't know about how the frequency of cold extremes (e.g., Polar Vortex breakdown, arctic cold air damming) may change in a warmer world, and the results of those studies will also have large implications on assessing future risk.



Stage 1: Developing/verifying a gridded 'ground truth' using reanalysis and point observations for events east of the Rocky mountains (illustrative example shown, exact data may vary).

Stage 2: Disaggregation of winter weather events into synoptic archetypes using machine learning/AI (initial archetypes based on Rauber et al, Mullens et al.)

Stage 3: Evaluation of typical thermodynamic and phase changes independently and regionally across archetypes using PGW and, if possible, high resolution GCM/RCM data

Magnitudes, spatial extent, displacement, duration, phase type(s), seasonality, accretion

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Select Figure References

[1] NCEI – regional snowfall index: https://www.ncei.noaa.gov/maps/rsi/
[2] The Weather Channel – depiction of approx. snow and ice totals
[3] Weather Prediction Center Event Summary: https://www.wpc.ncep.noaa.gov/storm_summaries/event_reviews/2011/Feb1-3_Central_Eastern_Winterstorm.pdf
[4] National Climate Assessment (2018) regional domains: https://nca2018.globalchange.gov/

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