High Resolution WRF Simulation of an Extreme Winter Storm (Blizzard) in Colorado in a Current and Future Climate

Roy Rasmussen, Kyoko Ikeda and David Gochis
National Center for Atmospheric Research
Boulder, Colorado
February 12, 2014

Objective and Key Questions Explored

- **The IPCC report indicates that extreme events will become more extreme in the future.**

- **Due to the coarse resolution of most global and regional models, the exact manifestation of these events in the future is uncertain.**

- **Recent high resolution WRF simulations for eight years current and an 8 year future Pseudo Global Warming (PGW) experiment has allowed us to explore the likely impacts of a well observed heavy snow (blizzard) event along the Colorado Front Range (March 18-20, 2003) if it instead occurred under a future global warming scenario.**

Objective and Key Questions Explored

- **Key questions:**

1. **What are some changes in microphysical and mesoscale features due to the warmer climate? (e.g., vapor and condensate mixing ratio profiles; horizontal distribution of surface precipitation, amount of surface precipitation)**
2. **Were there any changes in vapor flux into a particular mountain range?**
3. **Did the vertical velocity of the storm change?**
4. **Were there any changes in horizontal wind speed and direction?**
5. **Any changes in the atmospheric stability?**

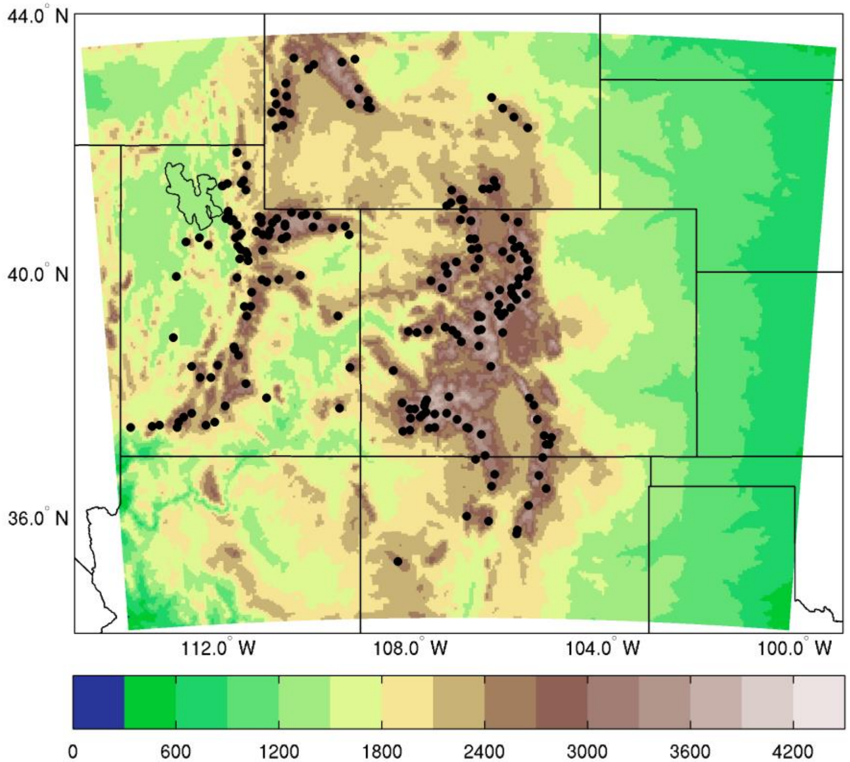
WRF Model Setup and Simulations

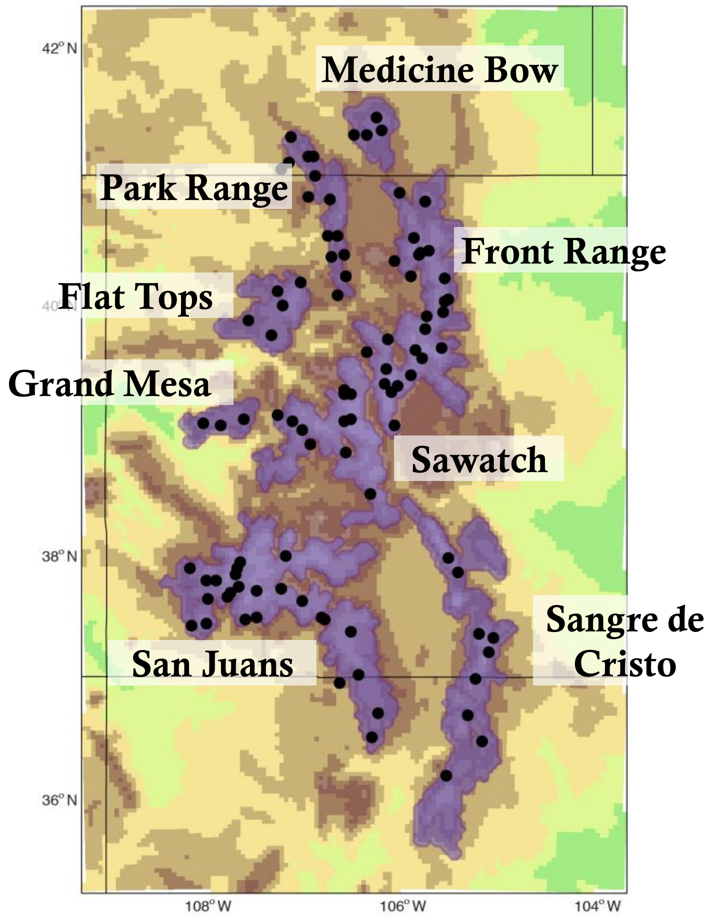
- **Model Setup: WRF V3.1**
  - Single domain: 1200km x 1000km, 45 vertical levels
  - Boundary layer : Mellor-Yamada-Janjic
  - Radiation : The NCAR CAM radiative transfer scheme
  - LSM : Noah land-surface model with snow physics improvements based on Barlage et al. (2010, JGR)
  - Microphysics : Thompson et al. (2008) mixed-phase microphysics
  - No Cumulus parameterization used, assumed explicit
- **Forcing data**
  - 3-hourly North American Regional Reanalysis data with 32 km grid resolution at the model boundary and initial time.

WRF Model Setup and Simulations

- **Simulations Performed**
  - **Present- (control) and future- (PGW) climate simulations from 1 October 2000 to 31 December 2008**
  - **Treat the first year as spin-up. Evaluate model performance for data starting on 1 January 2001**

Model Domain and Major CO Mountain Ranges





- Dots are SNOTEL sites.
- SNOTEL typically located at elevations between 2600 and 3600 m

Pseudo-Global Warming Simulation to study impact of increased temperature (2˚C) and moisture (15%) on the Headwaters water cycle

Approach

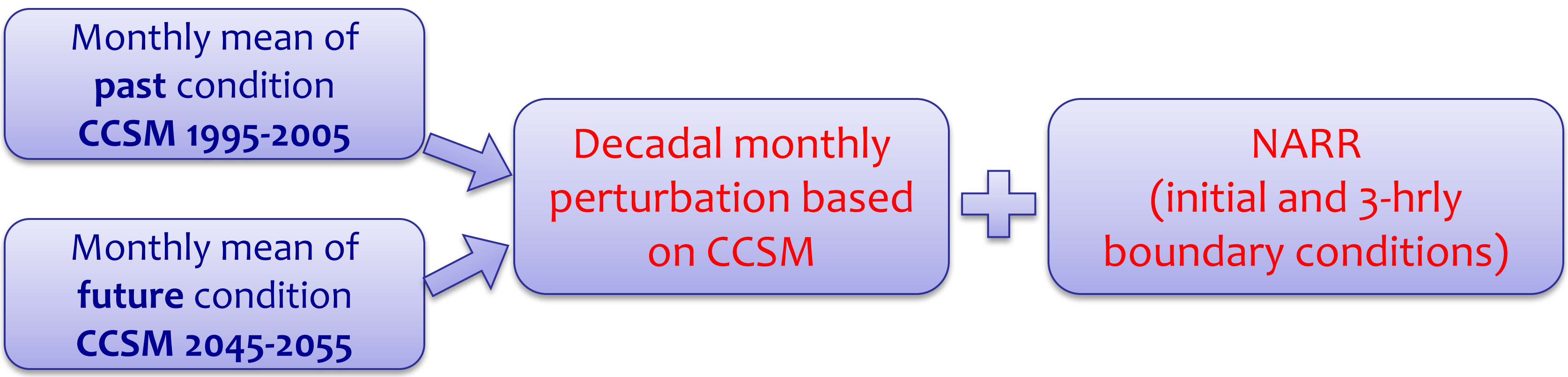
Add mean 10 year average pertubation from current to future climate from NCAR CCSM3 50 year A1B simulation to North American Regional Reanalysis boundary conditions and use to drive the WRF model

Rasmussen et al, J. Climate, 2011

“Pseudo-Global Warming” (PGW) Methodology

Schär et al (1996), Sato et al. (2007), Hara et al. (2008), Kawase et al. (2009)

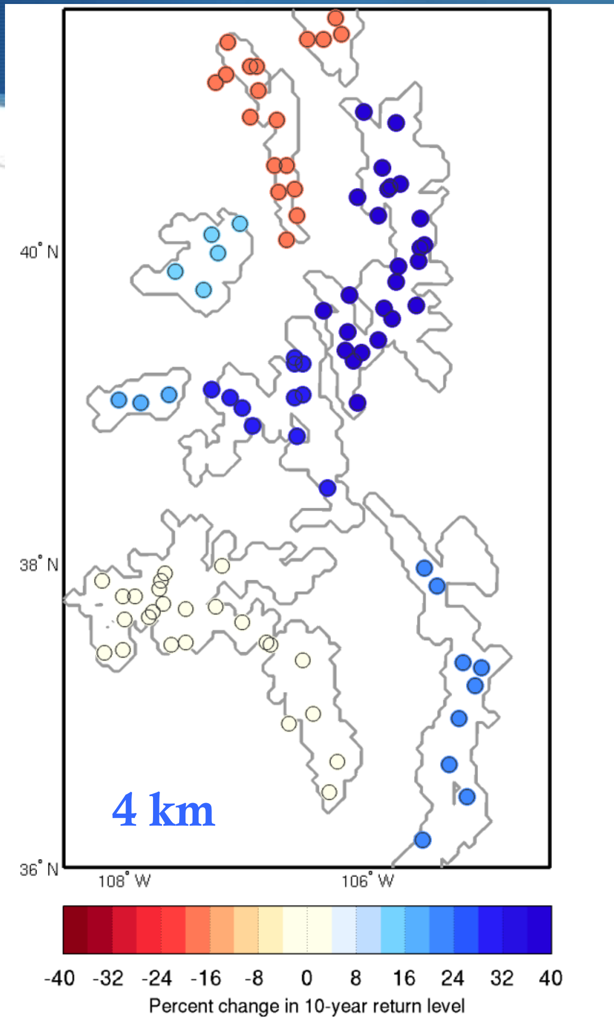
1. Calculate perturbation in 10-yr monthly mean values of **U, V**, **T**, **geopot. hgt**., $\mathbf{P_{sfc}}$ and $\mathbf{Q_v}$ between current and future climate periods from a Climate Global Circulation Model. (SRES-A2 from NCAR CCSM3 CCGM).
2. Add perturbation to current analyses of atmospheric conditions (North American Regional Reanalysis, 3-hrly) and extract regional model initial and lateral boundary conditions



Notes:

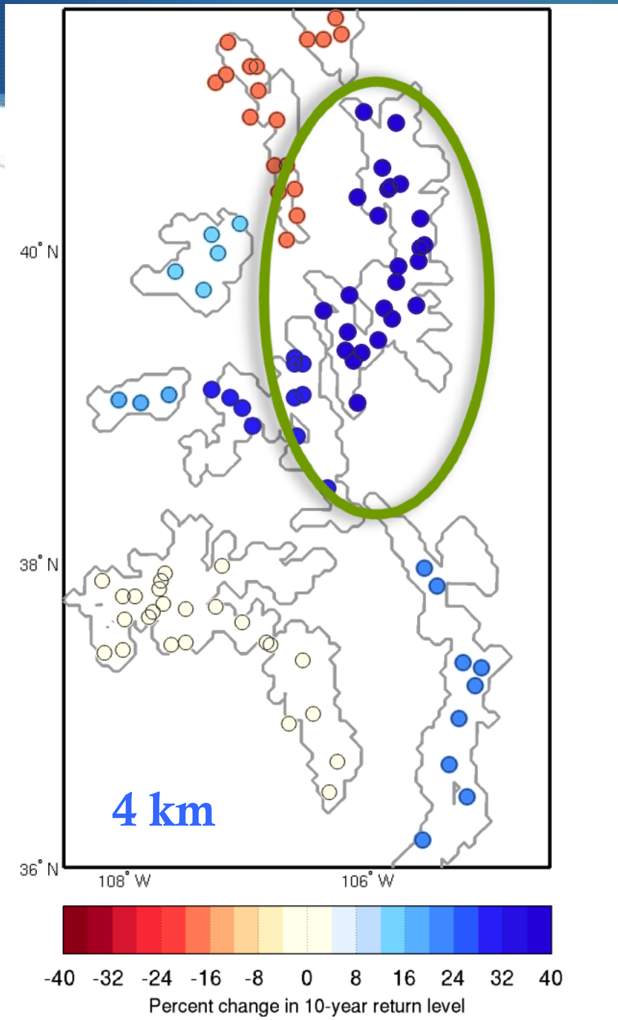
- Sub-monthly phenomenon such as extra-tropical storms not captured except in their mean effect. Monthly phenomenon are, such as the Hadley Cell. No change in storm tracks, and thus transient spectra the same (i.e. same climate variability in the future except for intensification of storms within the domain)

Percent difference in the 10-year return level for March-May daily precipitation



Based on a Generalized Extreme Value analysis on daily precipitation amounts, the 10-year return level of the MAM storms showed 52% increase in the 10-year return level for the Front Range mountain range.

Percent difference in the 10-year return level for March-May



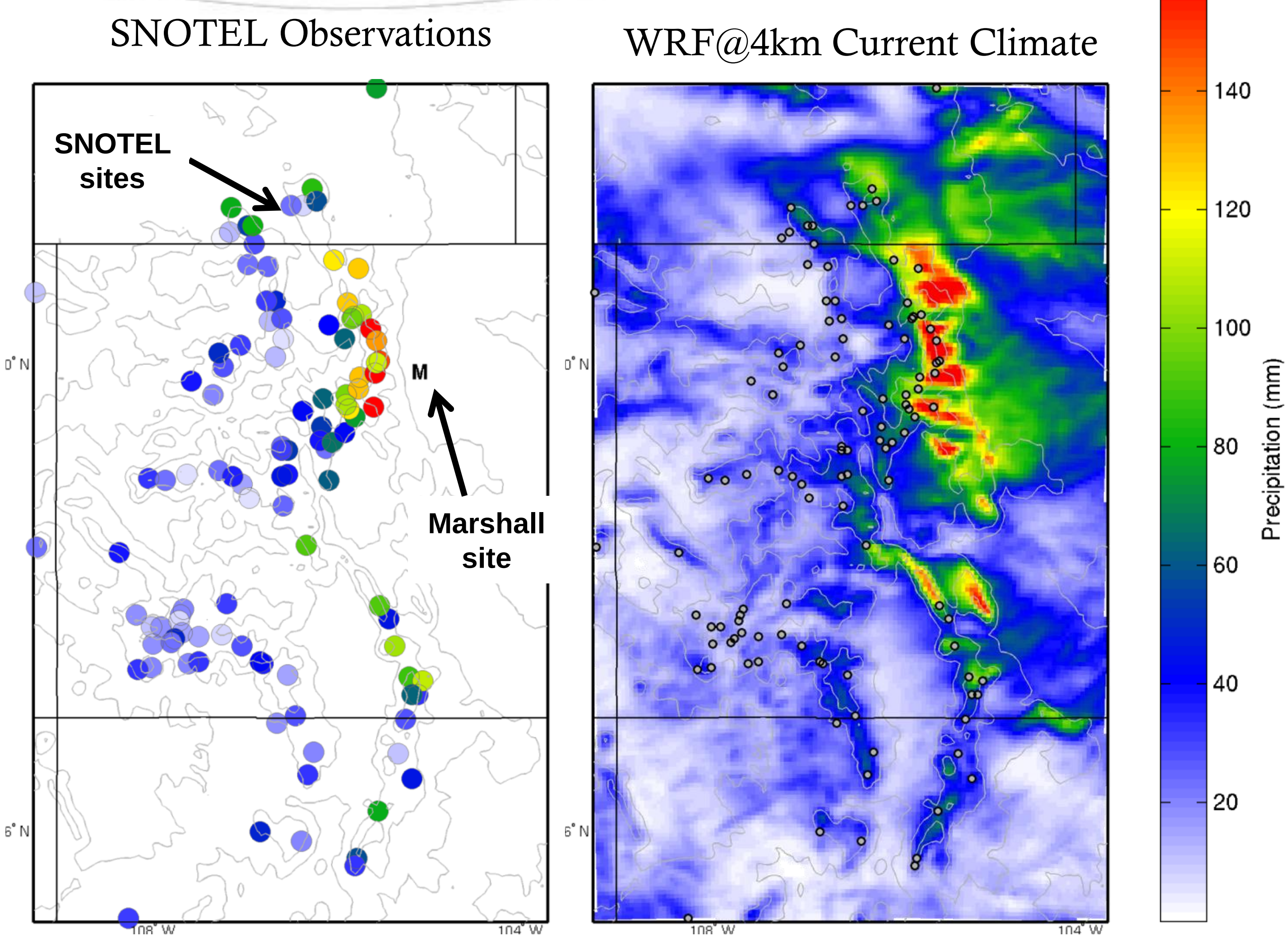
Based on a Generalized Extreme Value analysis on daily precipitation amounts, the 10-year return level of the MAM storms showed 52% increase in the 10-year return level for the Front Range mountain range.

Front Range Blizzard:
18 March 2003 – 20 March 2003

Comparison between observations and Current-climate WRF simulation

Evaluation of the WRF model performance

Total precipitation : 17 – 21 March 2003



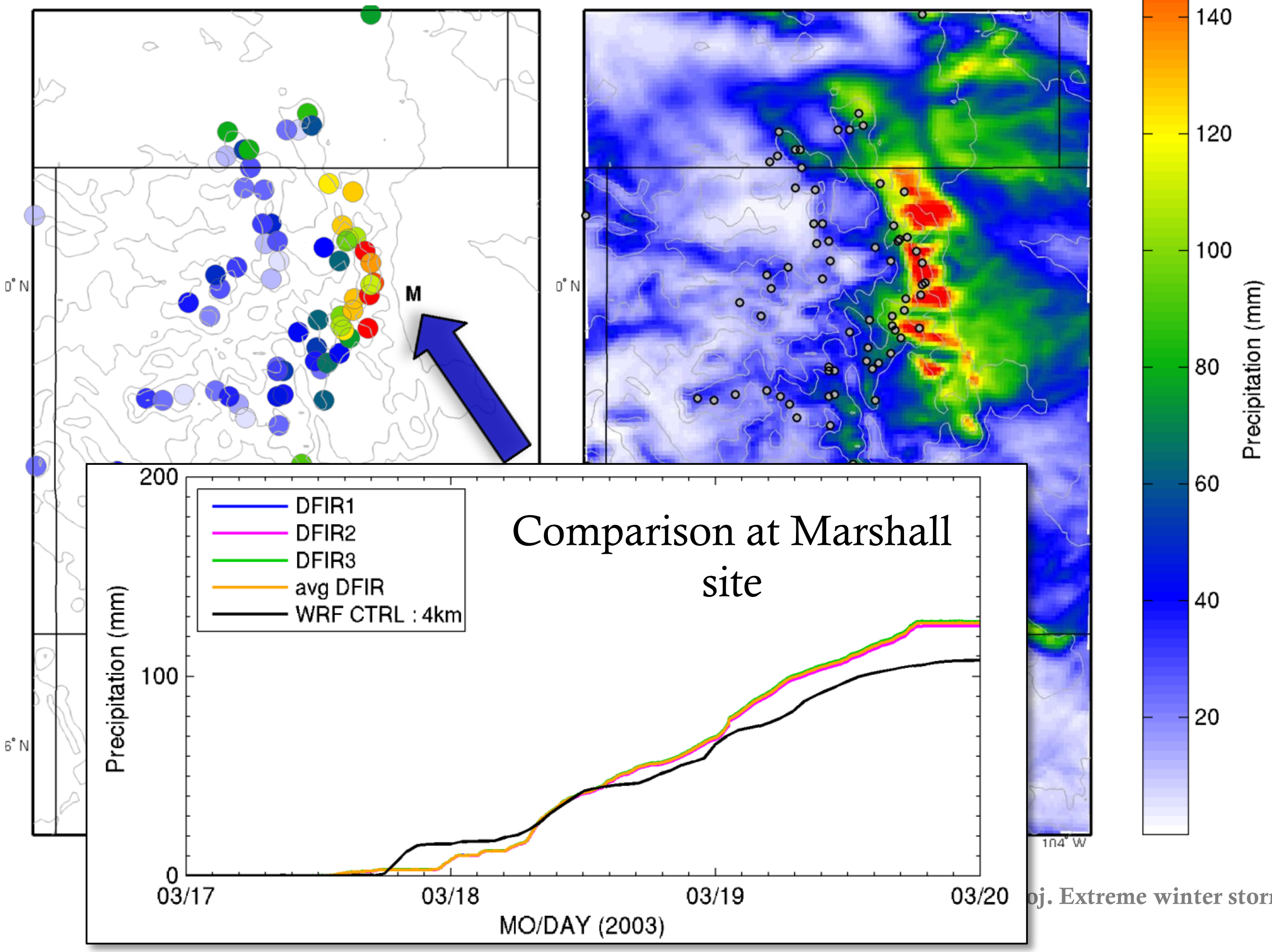
1 meter of snow at the Marshall field site

Evaluation of the WRF model performance

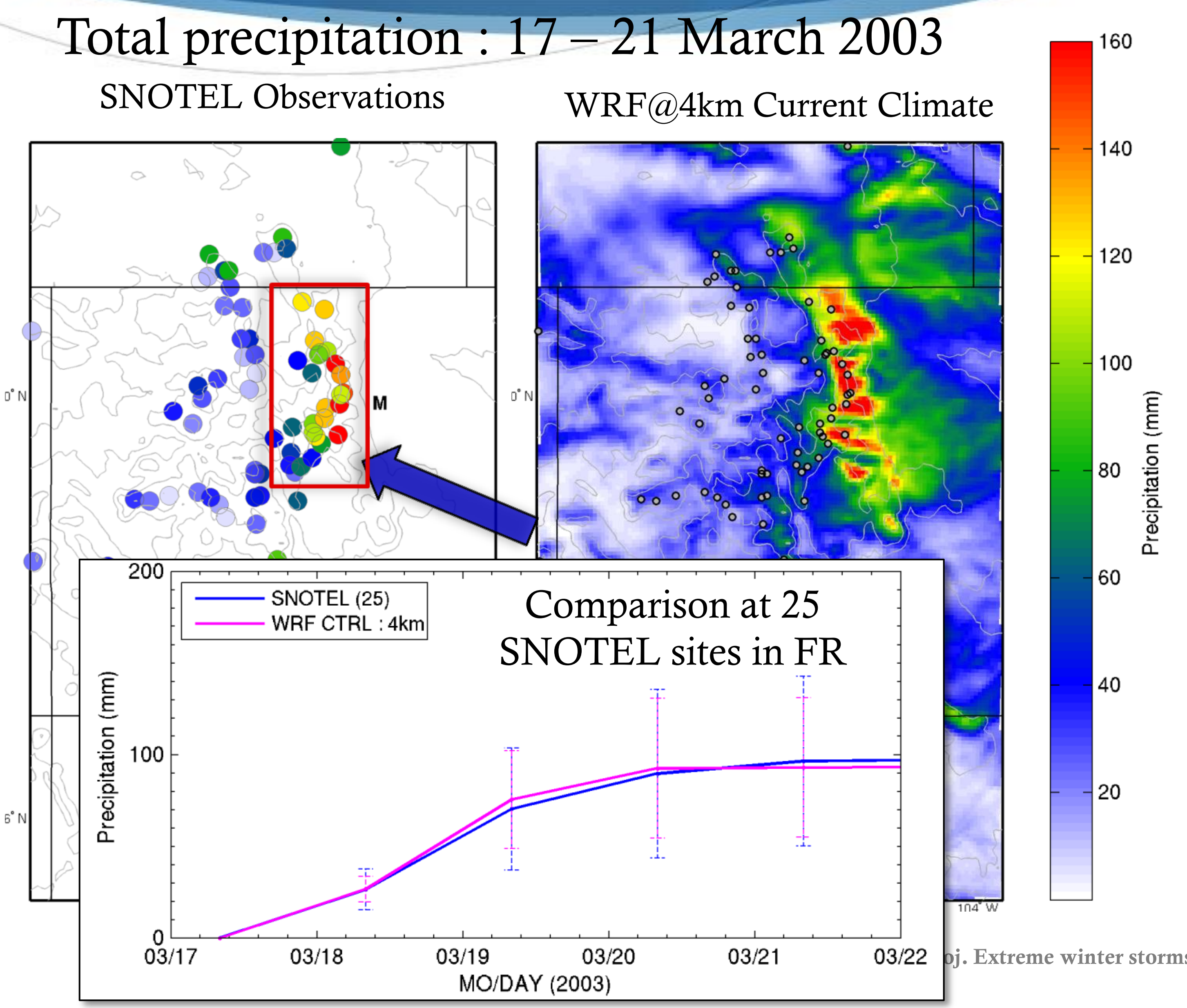
Total precipitation : 17 – 21 March 2003

SNOTEL Observations

WRF@4km Current Climate

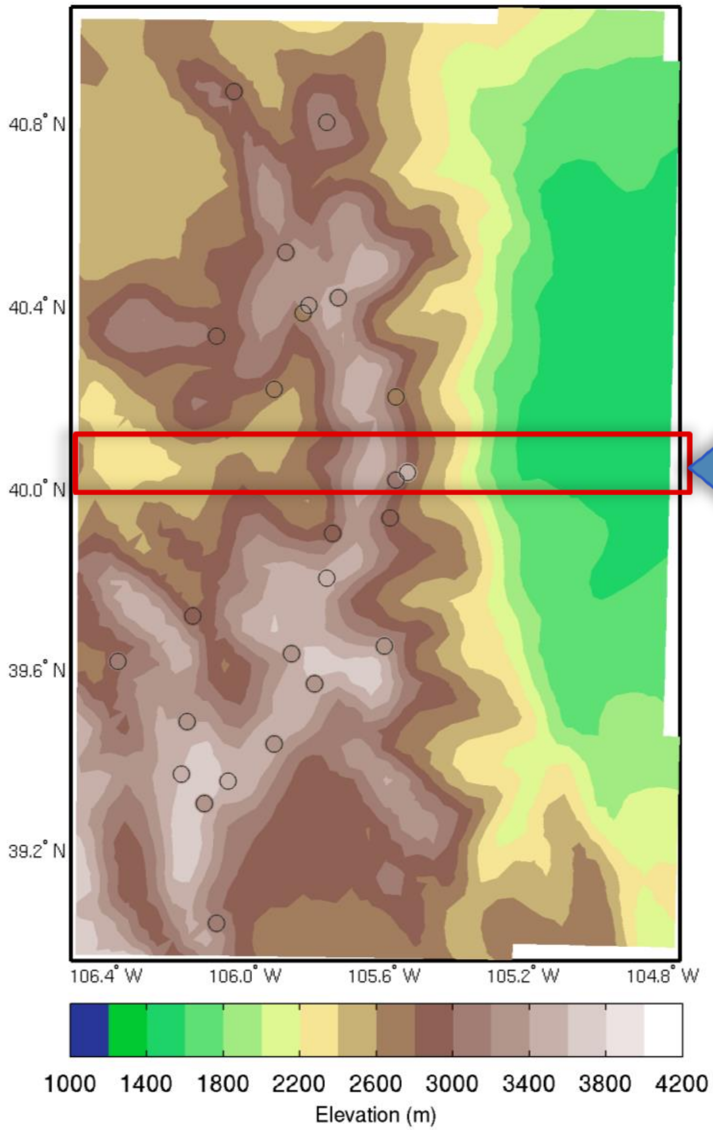


Evaluation of the WRF model performance

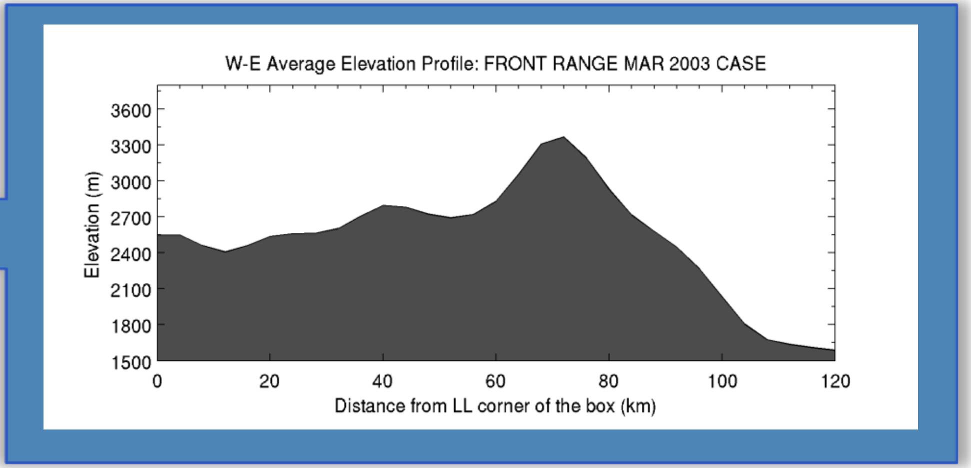


Comparison between the Current and Future Climate Simulations

Front Range Region and Terrain Profile

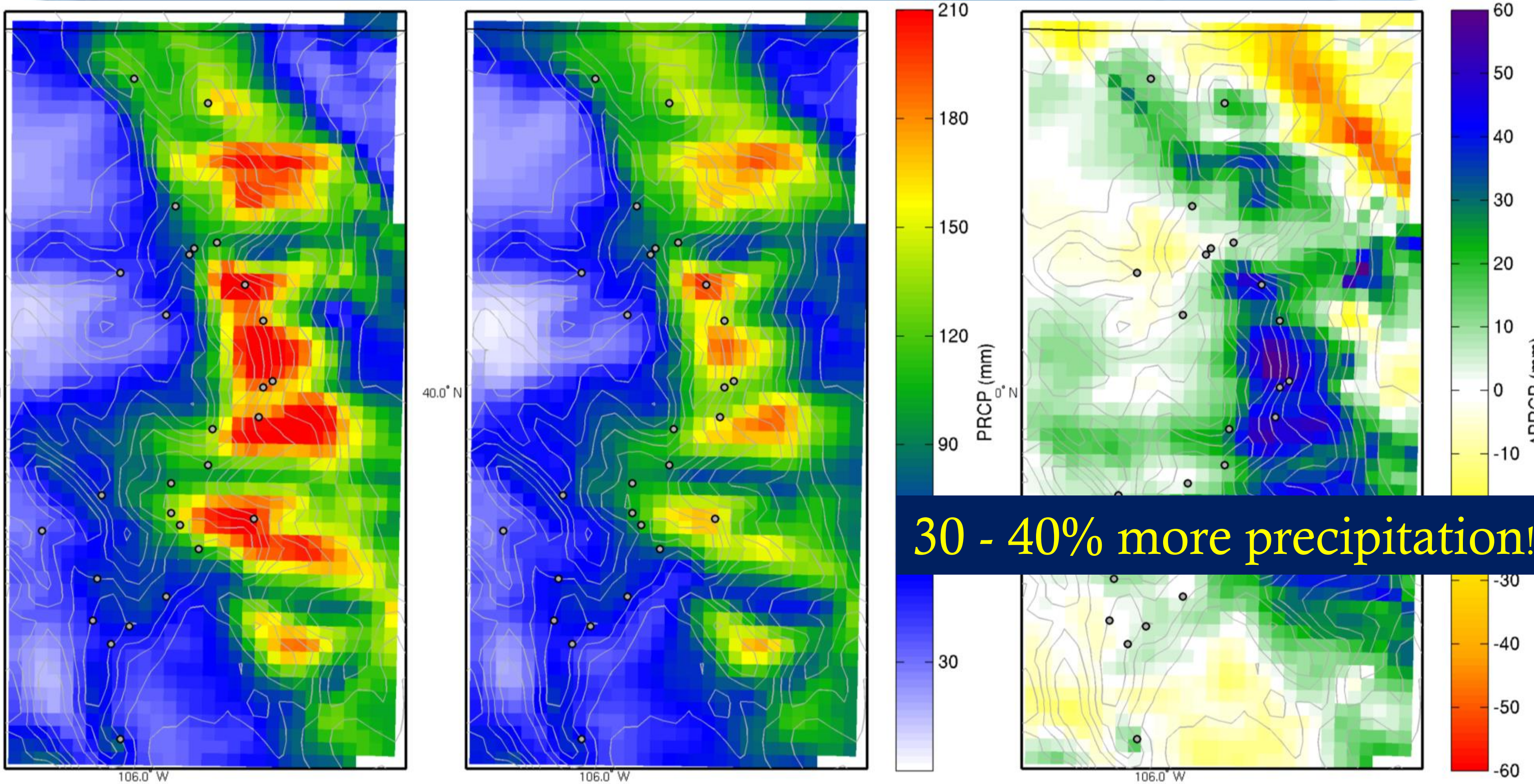


Elevation profile : averaged 24 km in the N-S direction



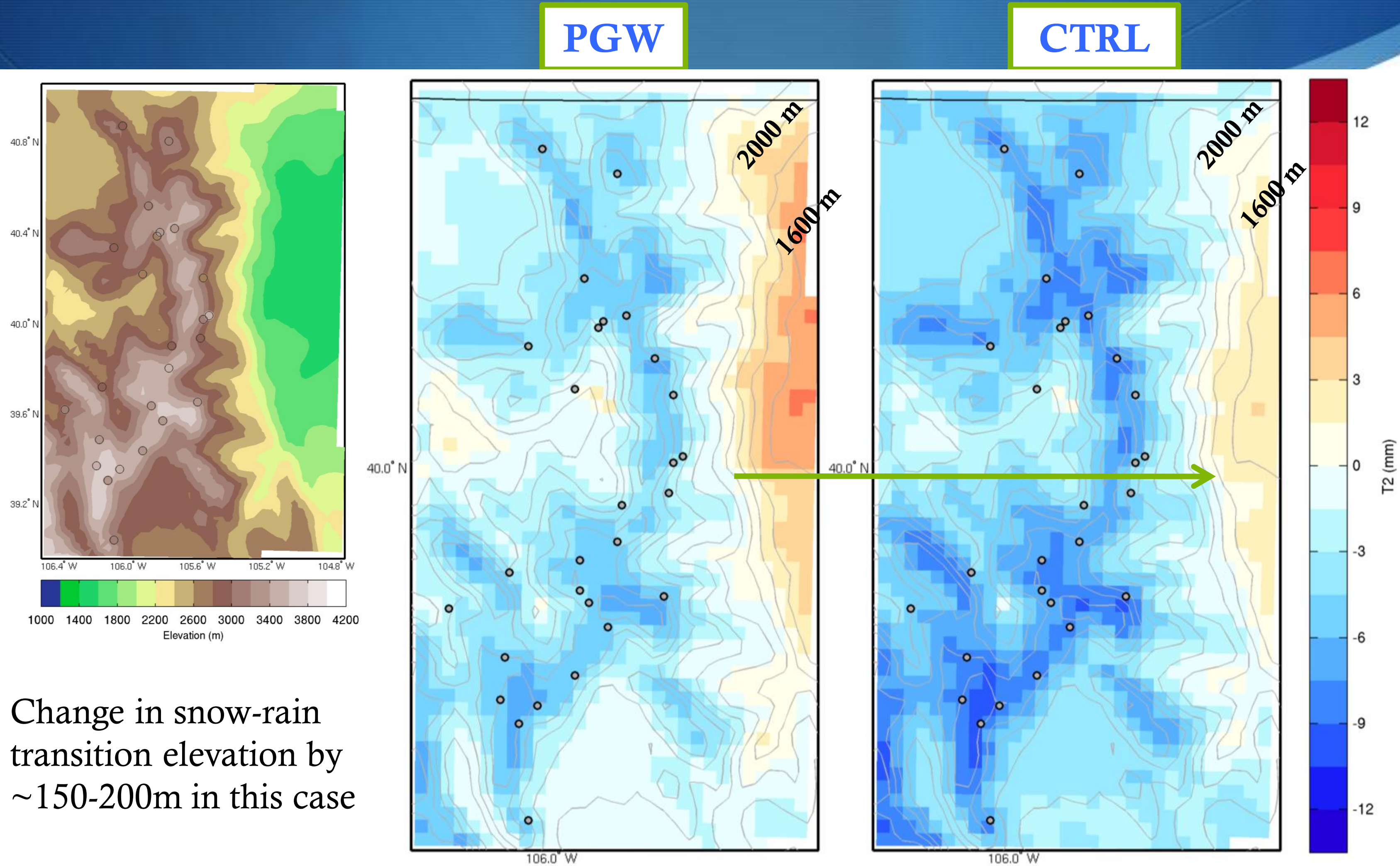
Total Precipitation:
15 UTC 17 March 2003 – 00 UTC 20 March 2003

PGW **CTRL** **PGW - CTRL**



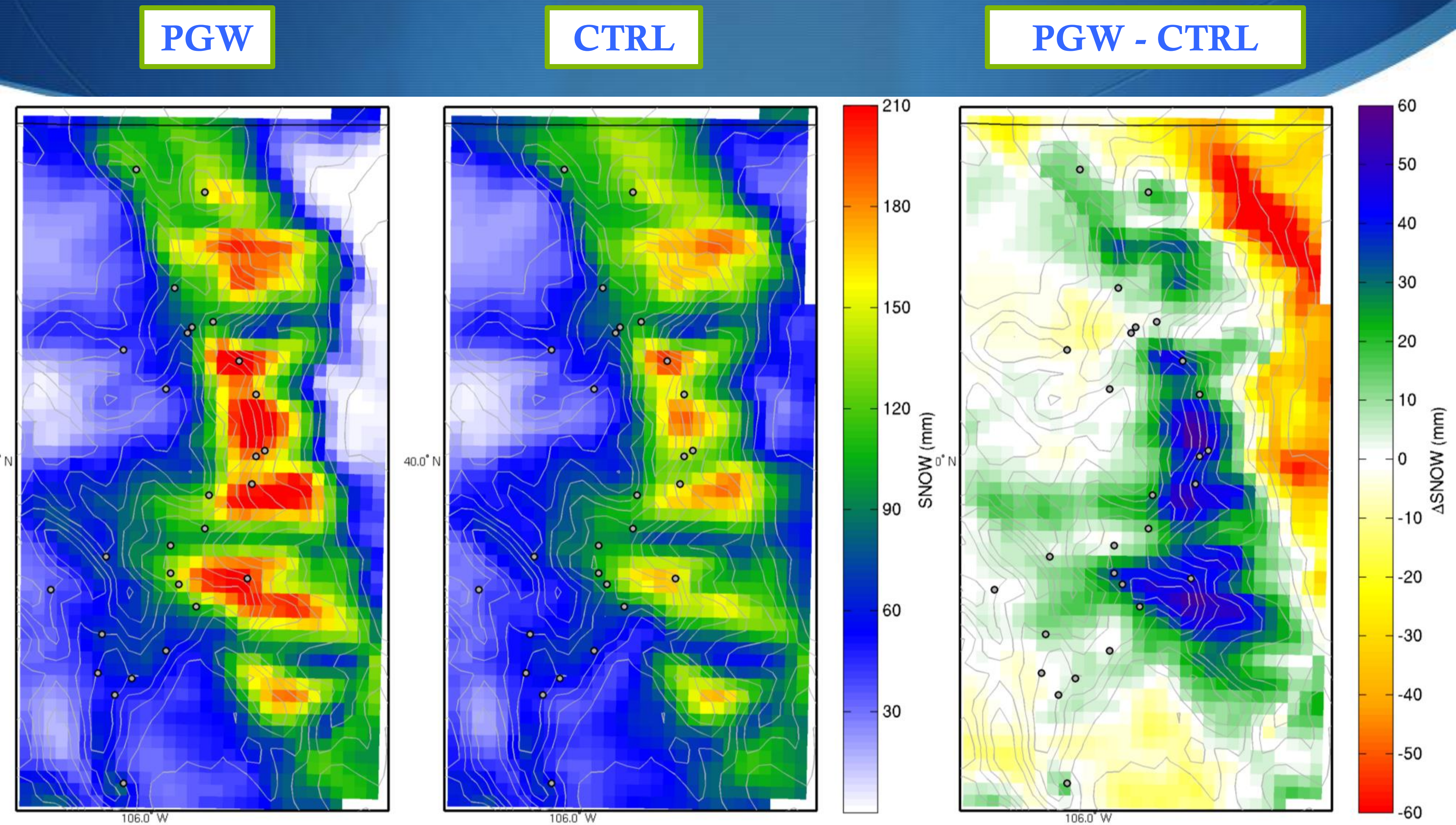
30 - 40% more precipitation!

Average near surface temperature : 15 UTC 17 March 2003 – 00 UTC 20 March 2003



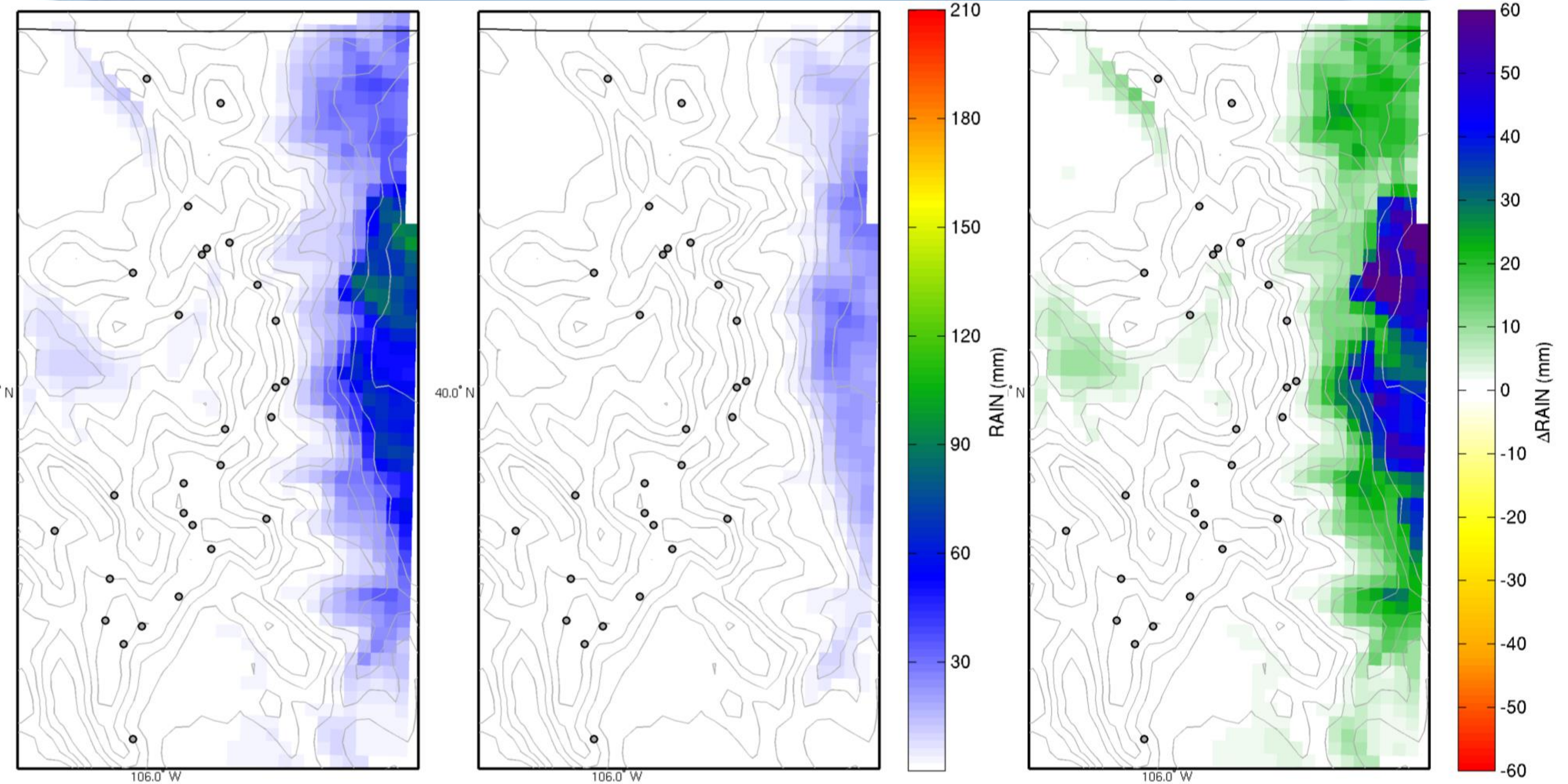
Change in snow-rain transition elevation by ~150-200m in this case

Total Snow:
15 UTC 17 March 2003 – 00 UTC 20 March 2003



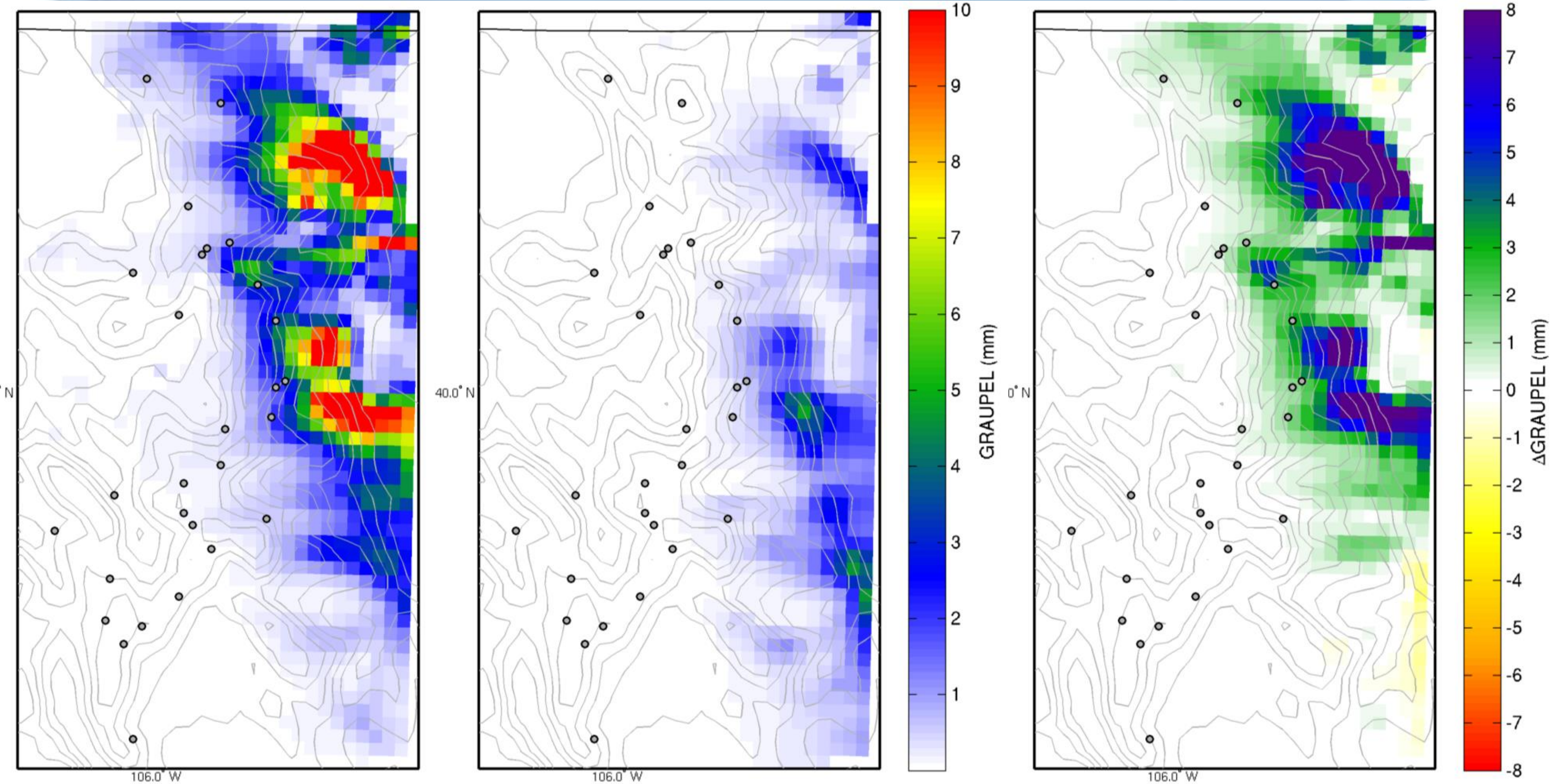
Total Rain:
15 UTC 17 March 2003 – 00 UTC 20 March 2003

PGW **CTRL** **PGW - CTRL**

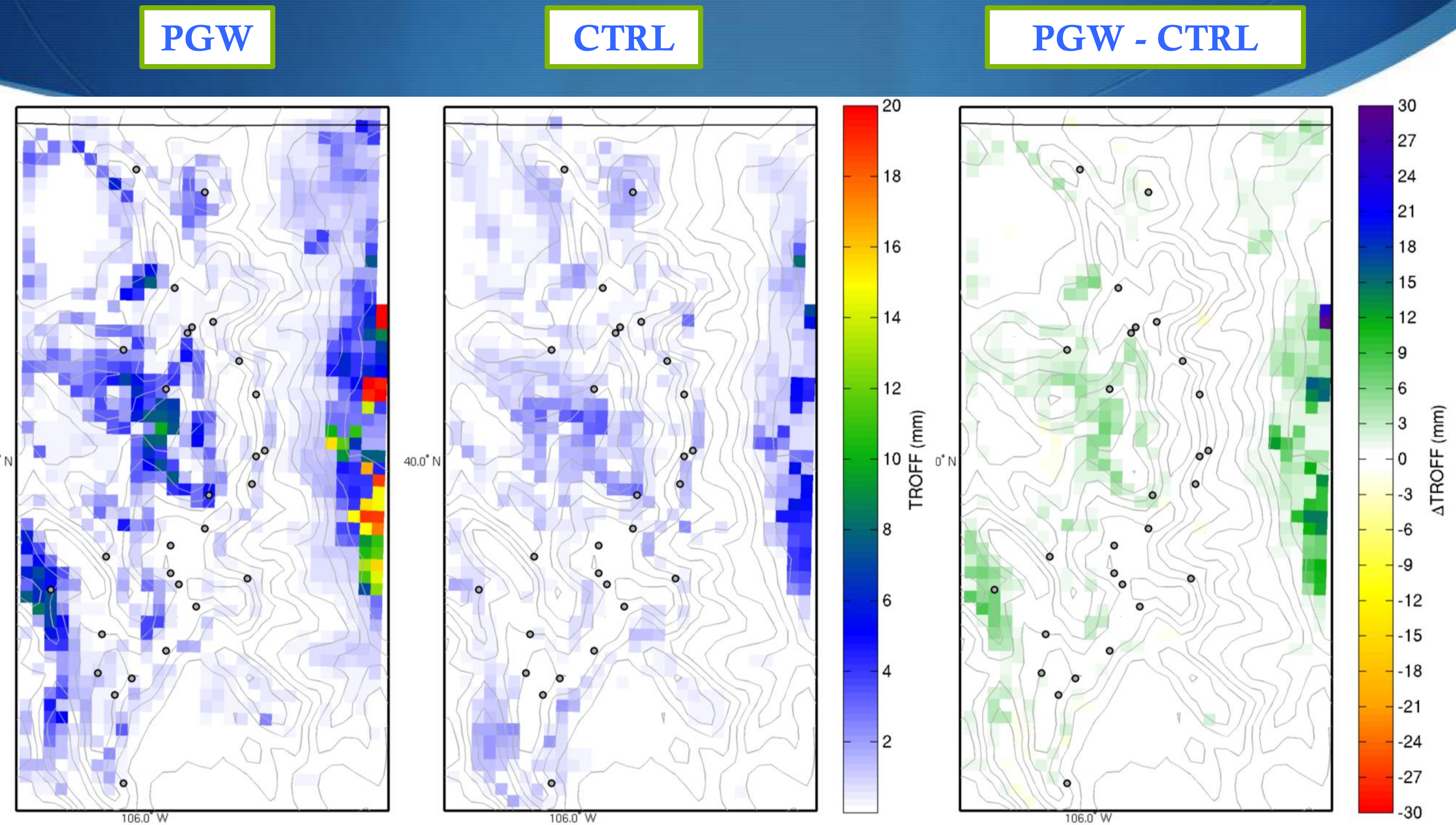


Total Graupel:
15 UTC 17 March 2003 – 00 UTC 20 March 2003

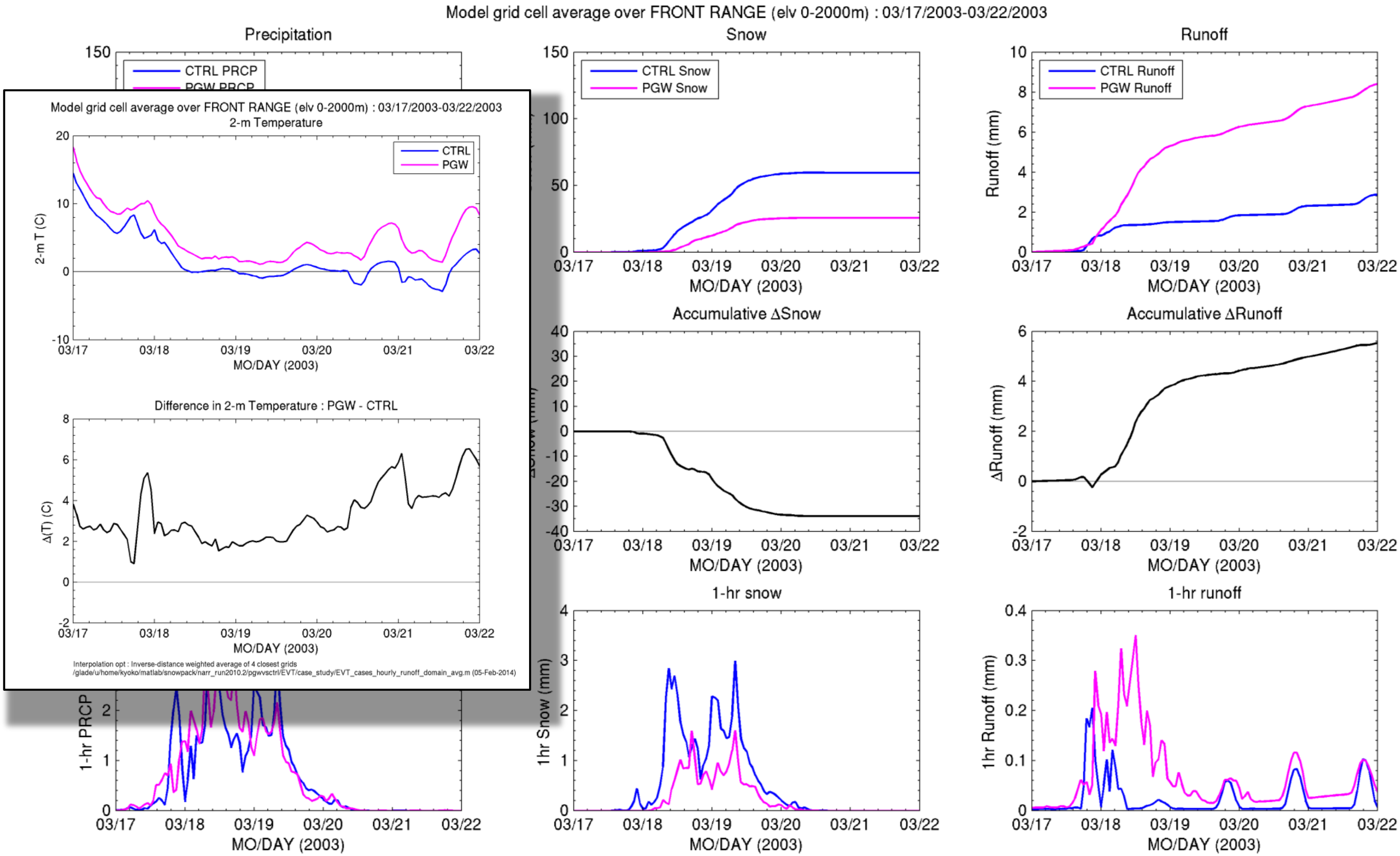
PGW **CTRL** **PGW - CTRL**



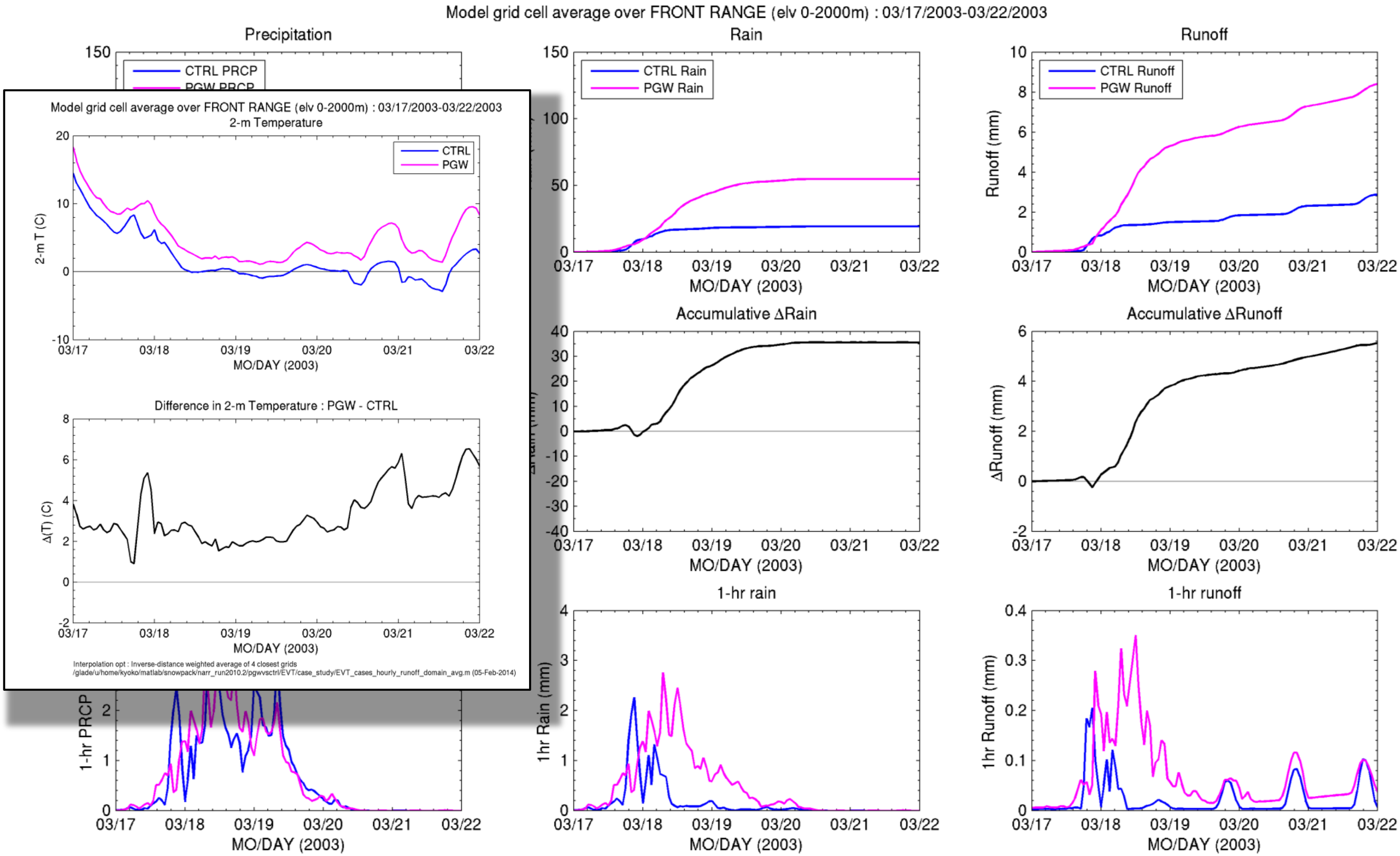
Runoff :
15 UTC 17 March 2003 – 00 UTC 20 March 2003



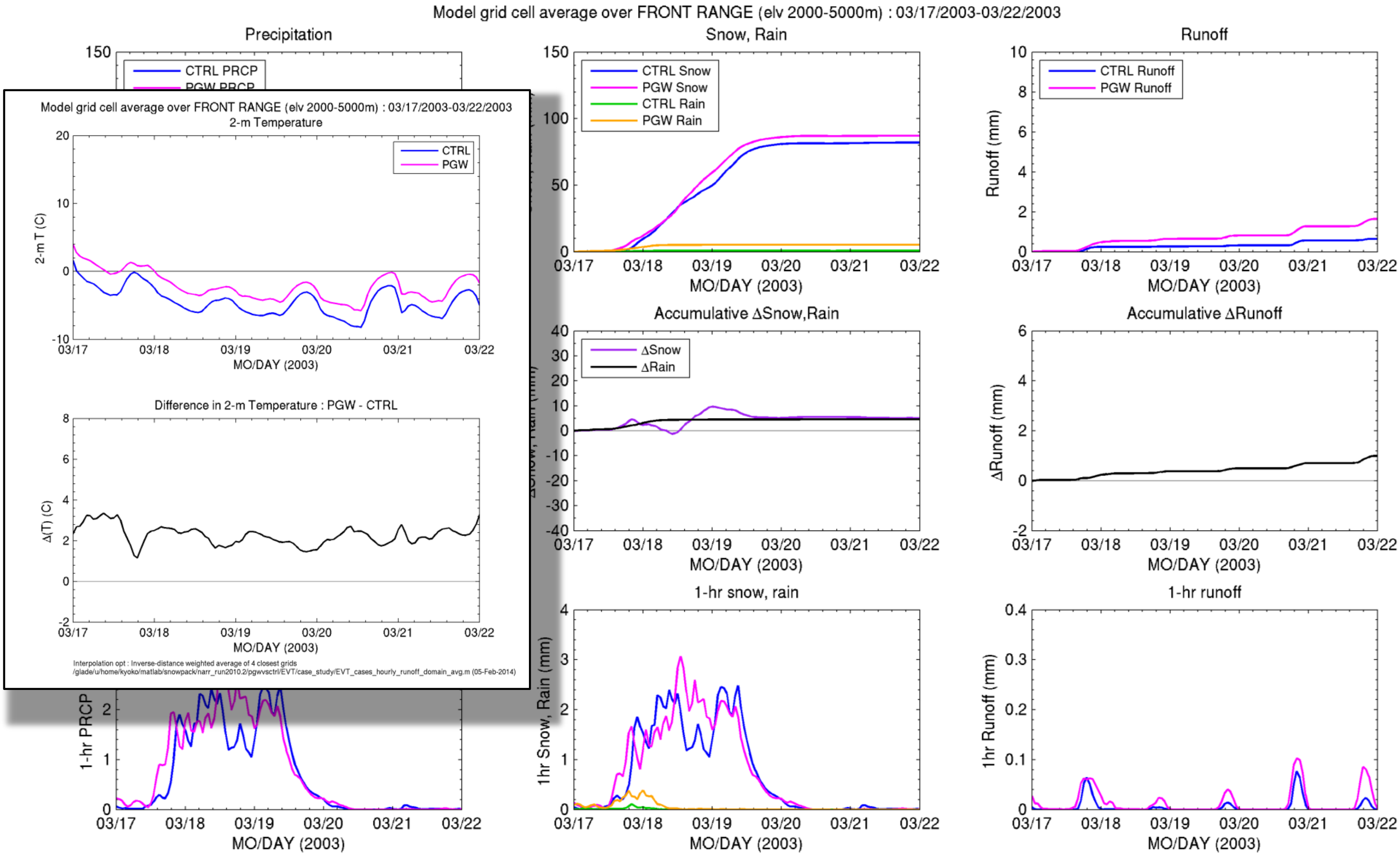
Average over FR region : elevation < 2000m



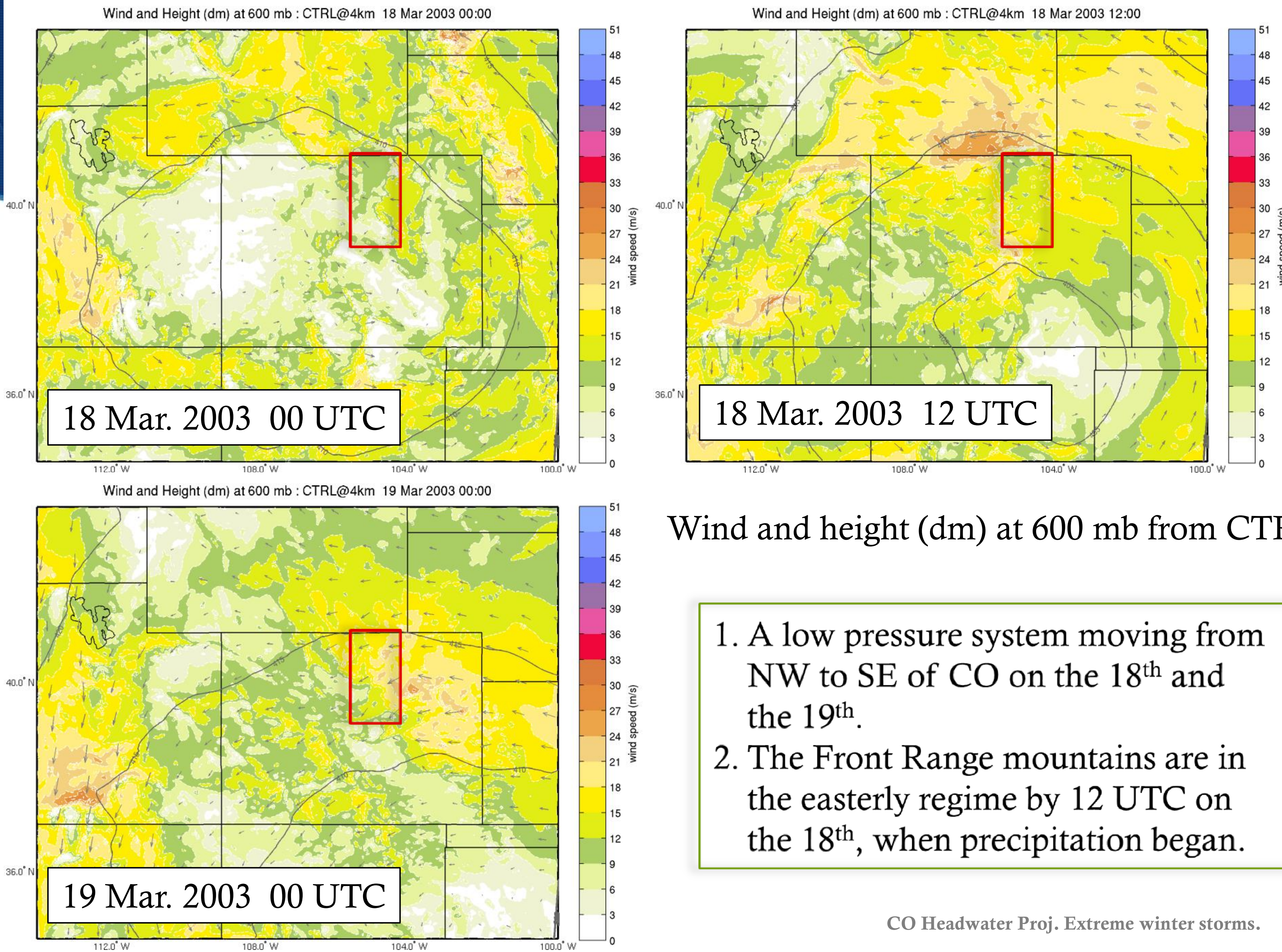
Average over FR region : elevation < 2000m



Average over FR region : elevation > 2000m

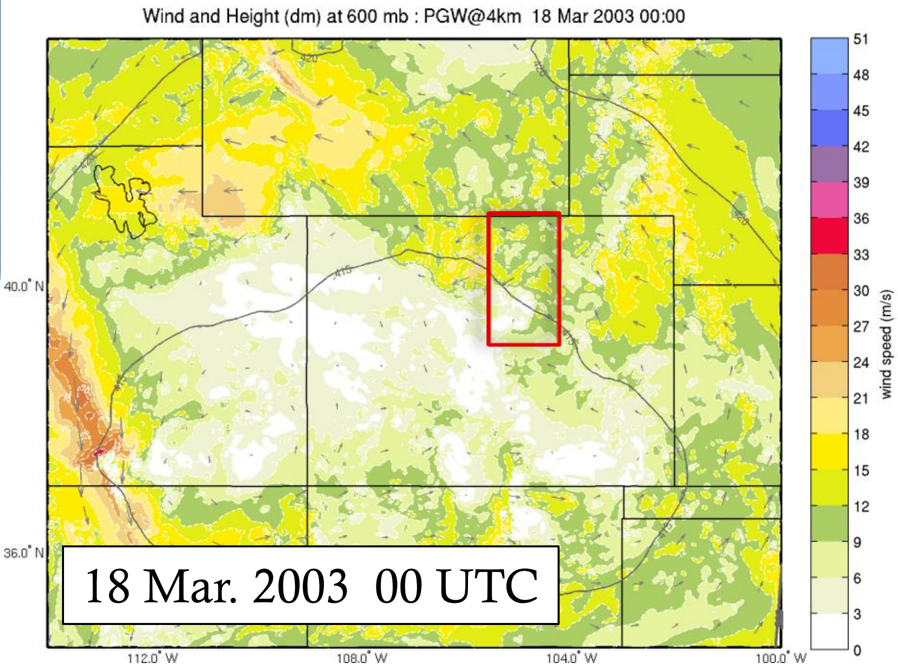


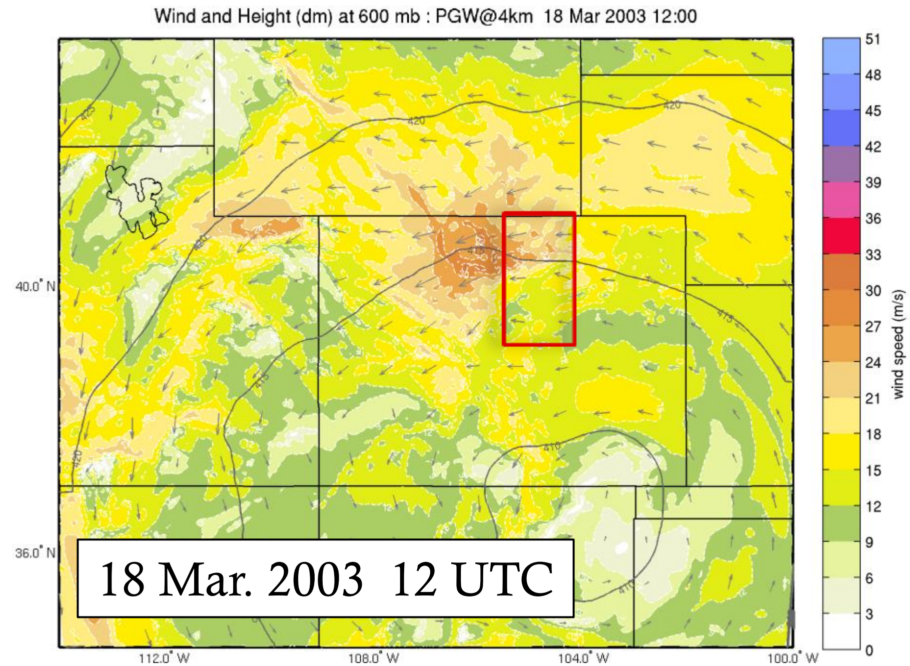
Key contributing factors to the increase in precipitation

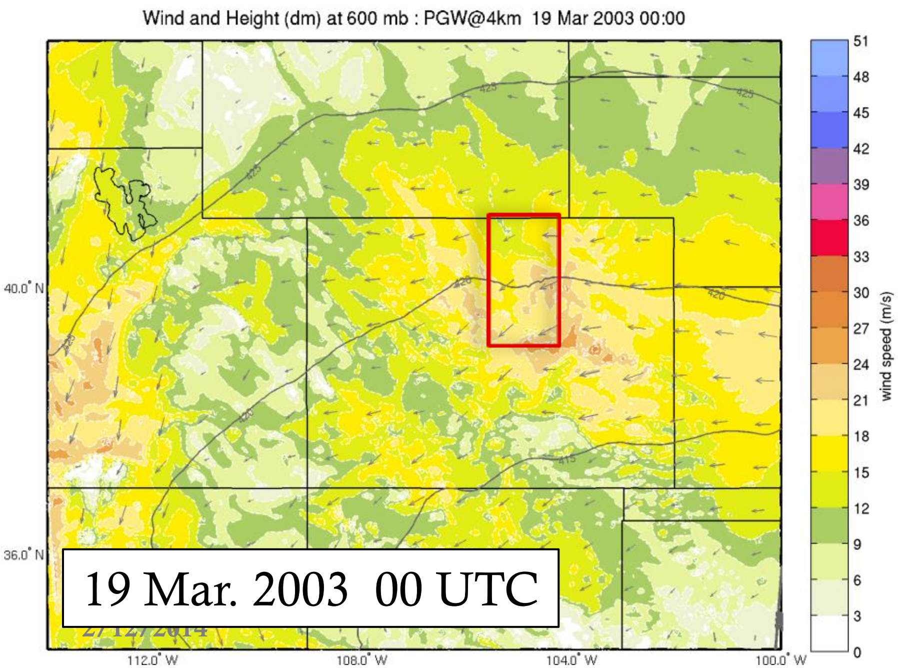


Wind and height (dm) at 600 mb from CTRL

1. A low pressure system moving from NW to SE of CO on the 18th and the 19th.
2. The Front Range mountains are in the easterly regime by 12 UTC on the 18th, when precipitation began.

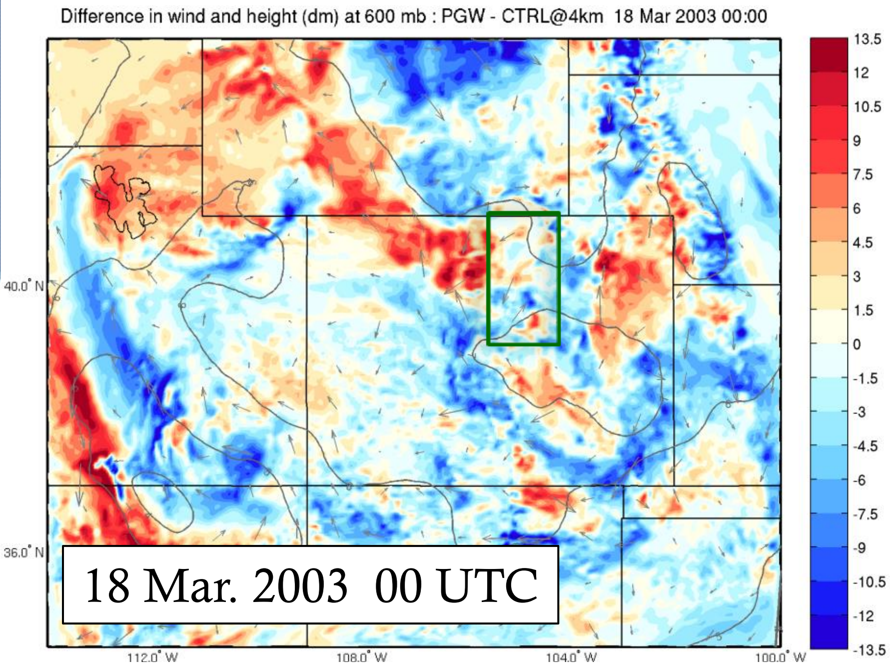


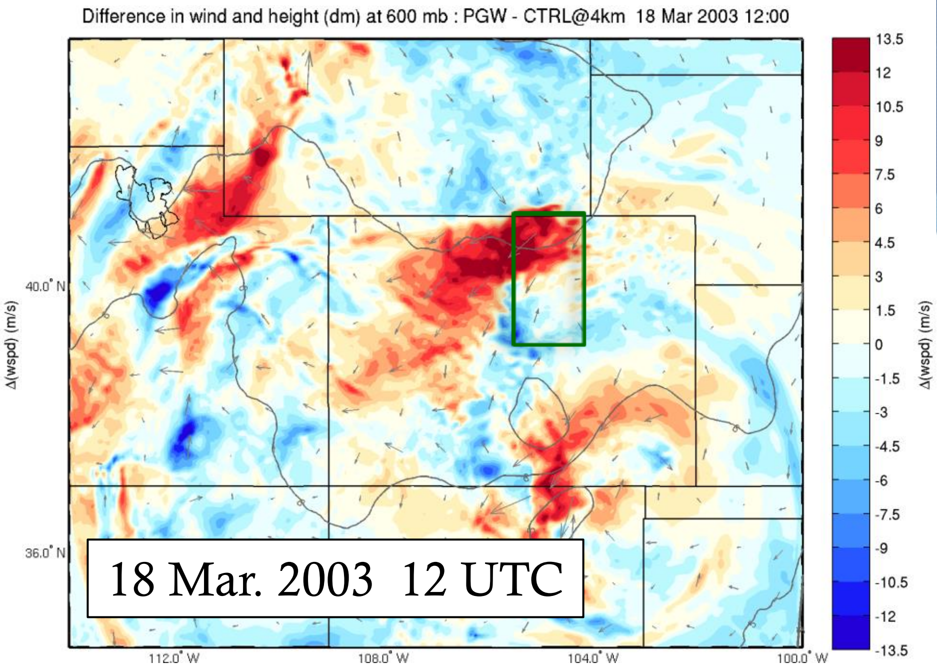


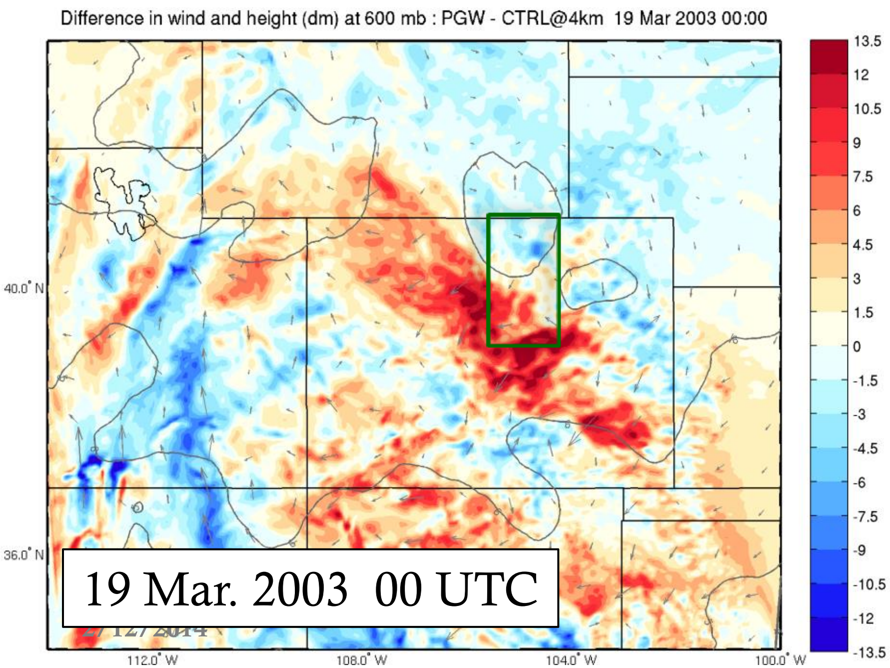


Wind and height (dm) at 600 mb from PGW

1. Stronger winds into the FR region in PGW.





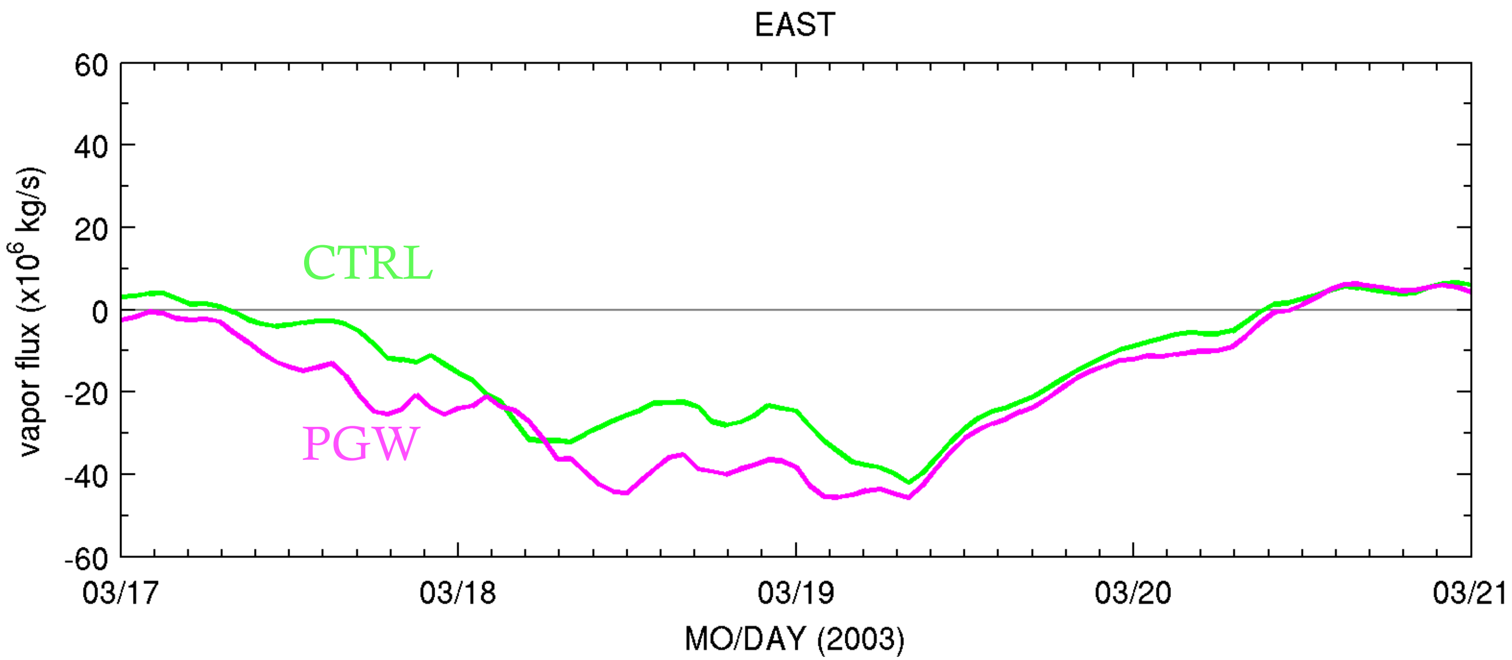


2/12/2014

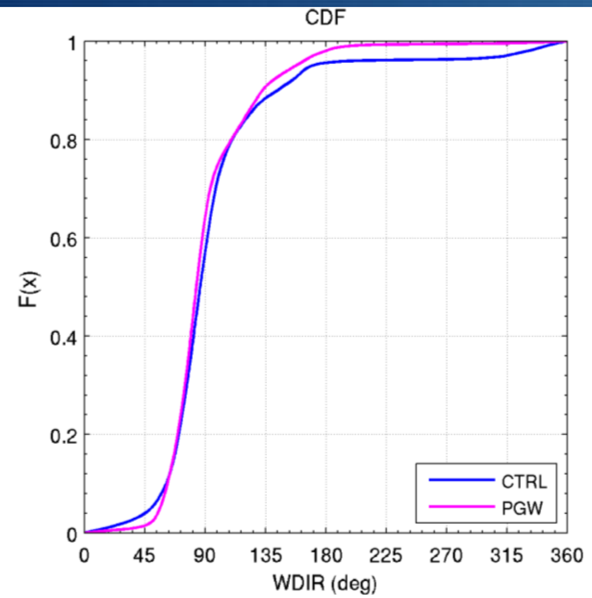
Change in wind speed and height (dm) at 600 mb

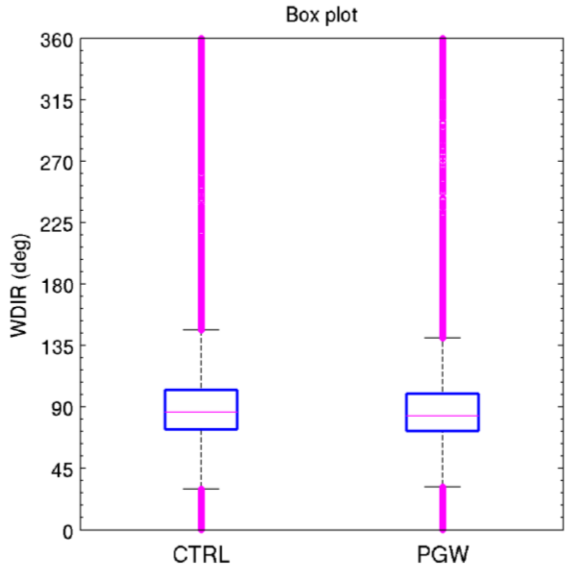
1. Stronger winds into the Front Range "box" in PGW, which helps to increase vapor flux.
2. The vectors are the difference vector (PGW-CTRL). As indicated in the previous slides, there is no significant difference in the wind direction over the Front Range region after the onset of precipitation.

Vapor Flux



1. Vapor flux from the eastern boundary of the Front Range box. The larger negative values means more vapor flux from the eastern boundary.
2. More vapor flux into the box in the PGW simulation, due to stronger winds and higher mixing ratio.
3. This leads to higher condensate supply rate in the PGW simulation.



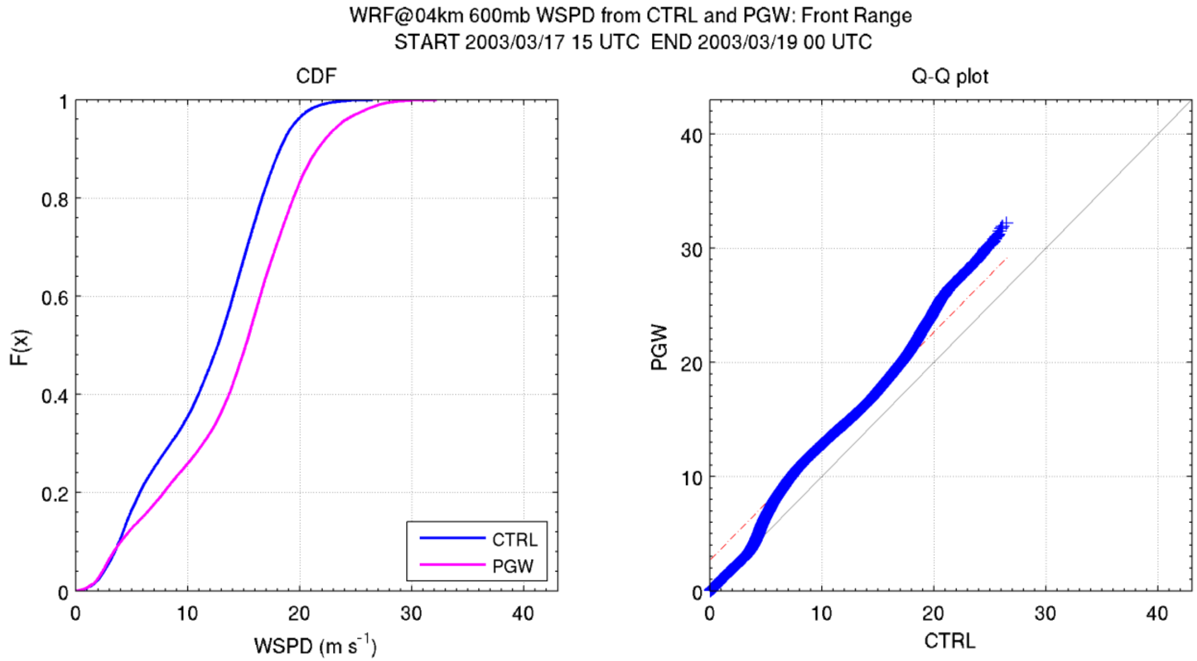


/glade/home/kyoko/matlab/snowpack/narr_run2010.2/pgwvsctrl/EVT/case_study/cdf_w.m (14-A

CDF and box plots of **WIND DIRECTION** in the Front Range box. All grid cell values between the indicated START and END time at 600 mb

**600 mb ~ 4000 m MSL

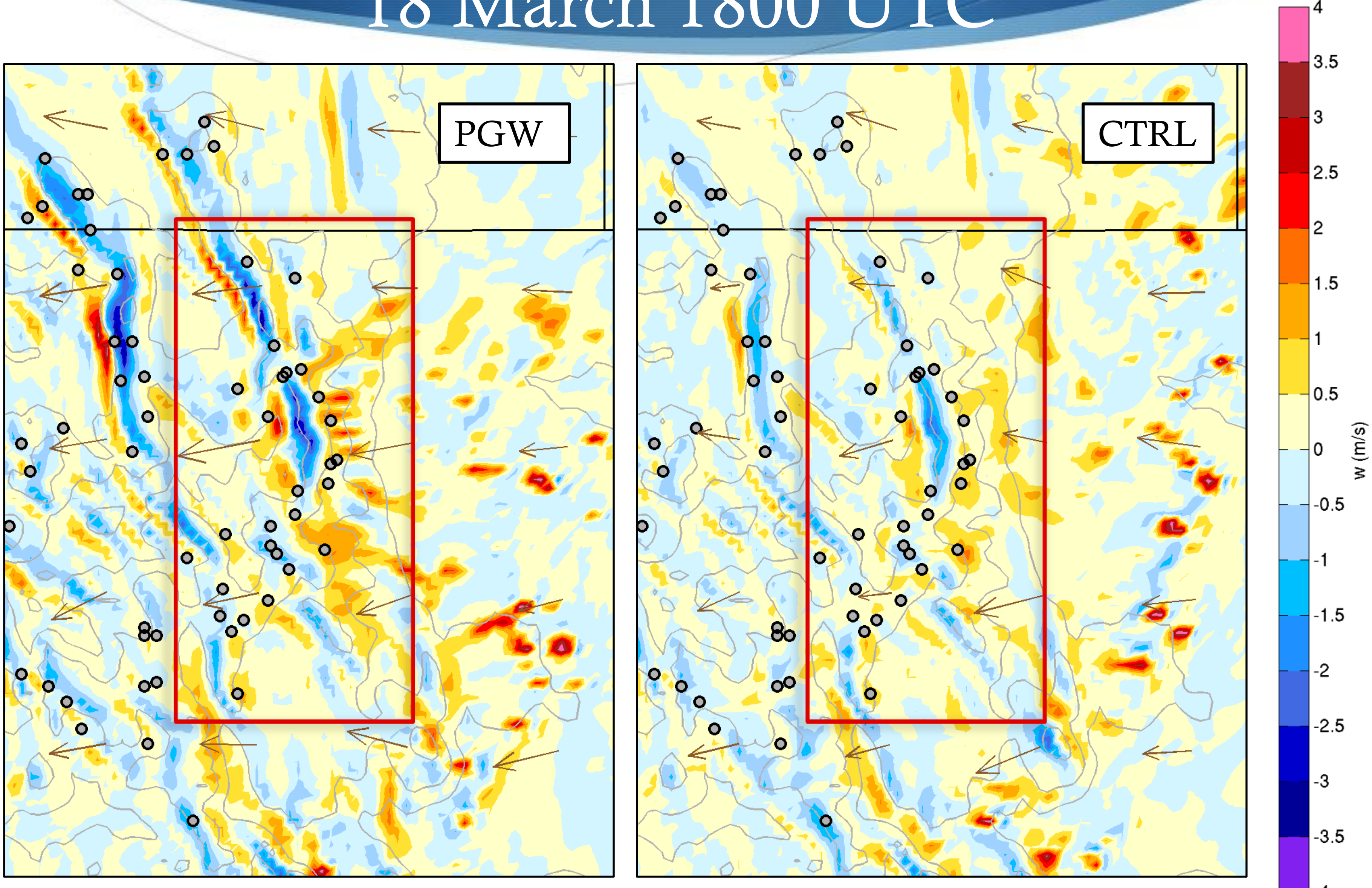
1. No significant difference in wind directions in the two simulations

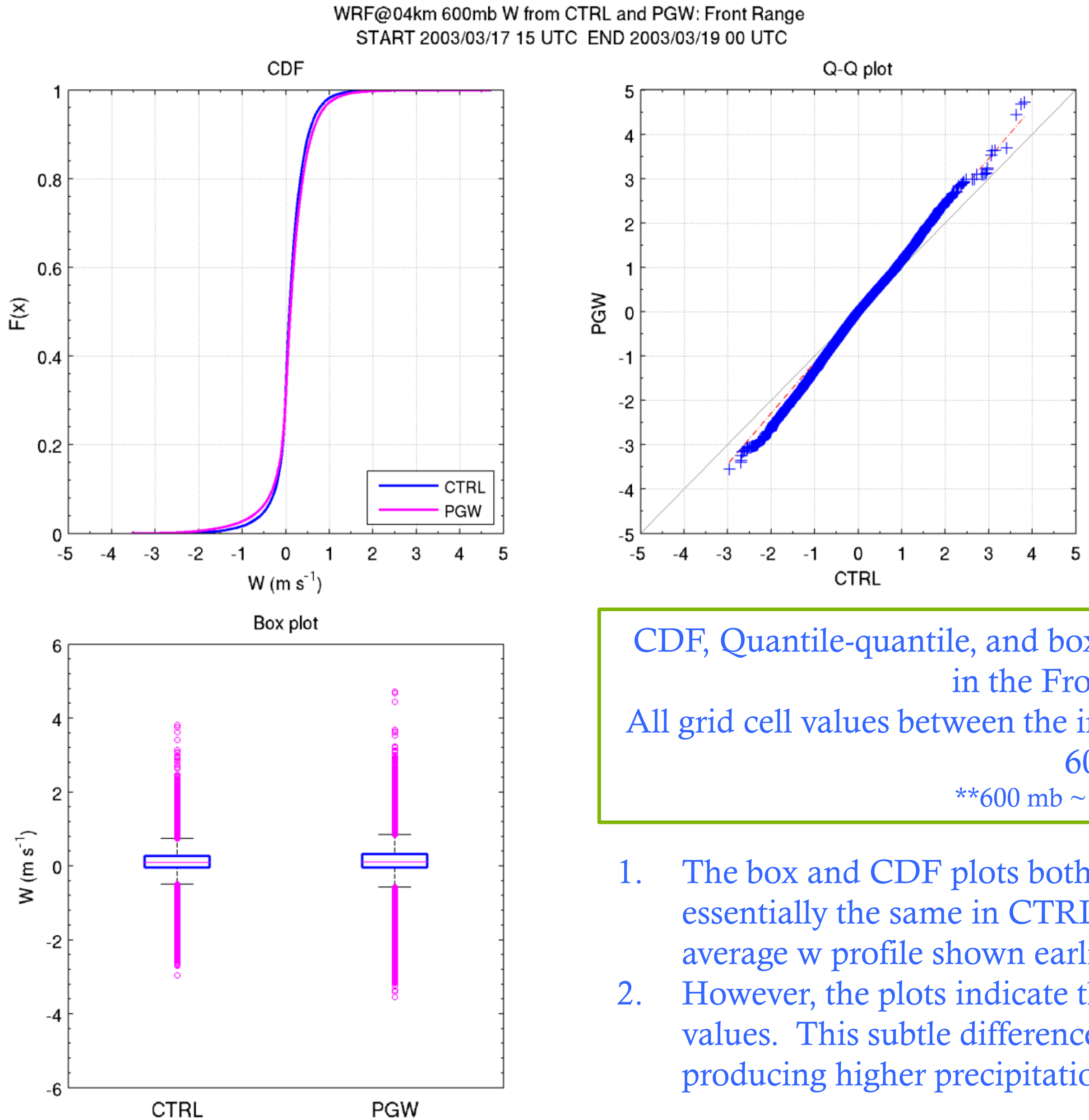


CDF, Quantile-quantile, and box plots of **WIND SPEED** in the Front Range box.
All grid cell values between the indicated START and END time at 600 mb
**600 mb ~ 4000 m MSL

1. Stronger winds in PGW → higher vapor flux into the Front Range "box"

W and horizontal wind vectors at 600mb: 18 March 1800 UTC



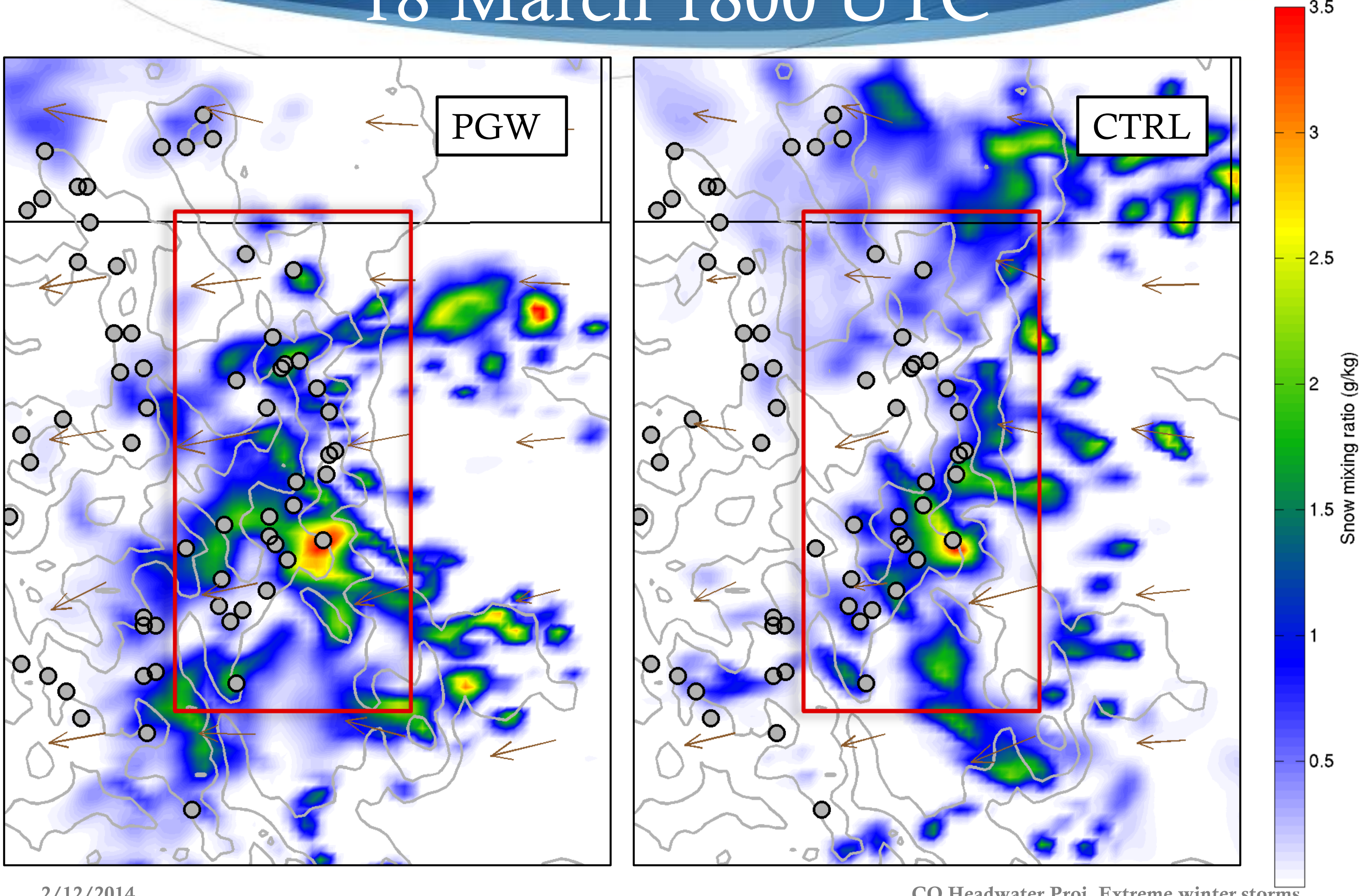


/glade/home/kyoko/matlab/snowpack/narr_run2010.2/pgwvsctrl/EVT/case_study/cdf_w.m (14-Aug-2012)

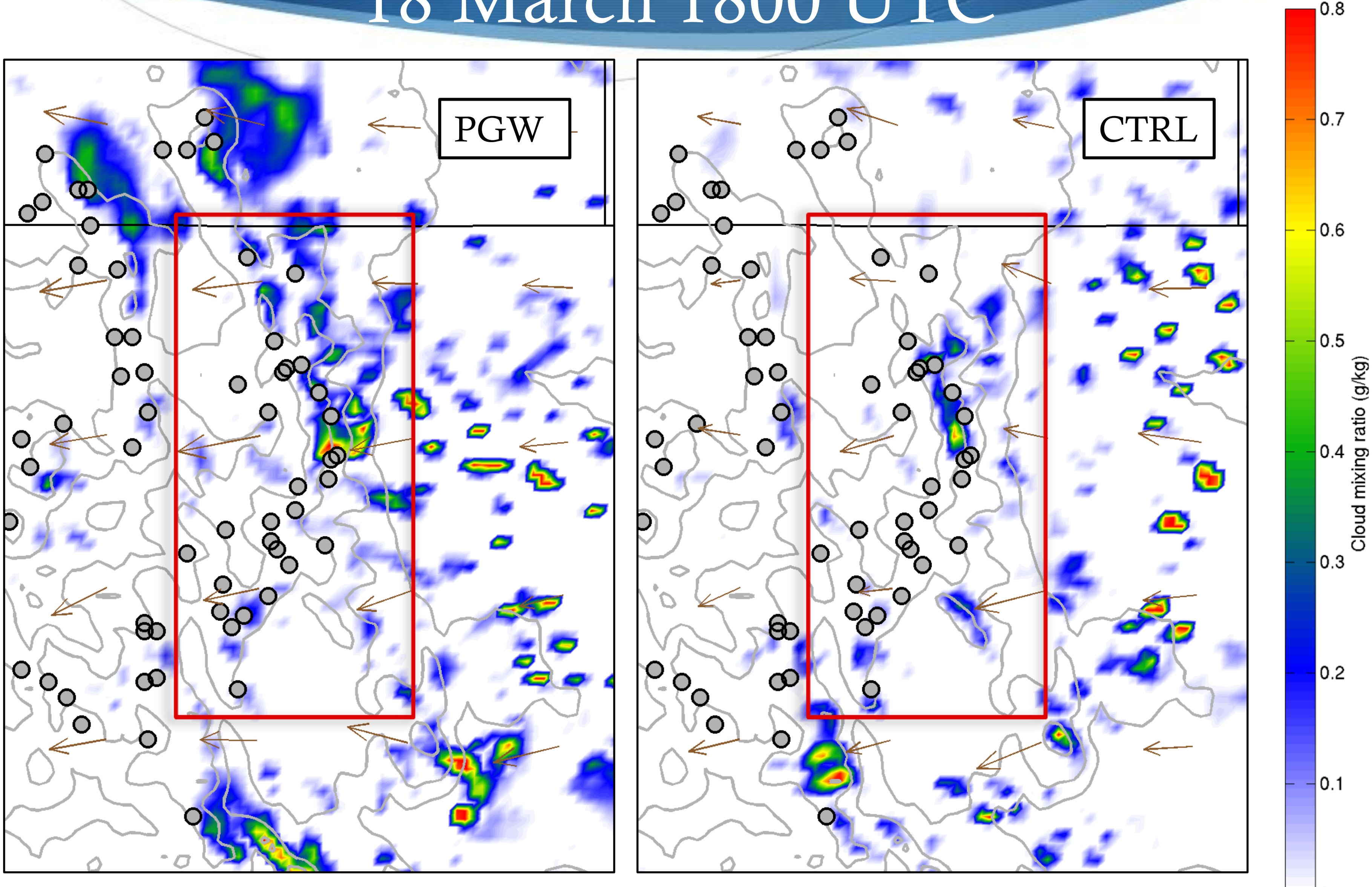
CDF, Quantile-quantile, and box plots of **VERTICAL VELOCITY** in the Front Range box.
All grid cell values between the indicated START and END time at 600 mb.
**600 mb ~ 4000 m msl

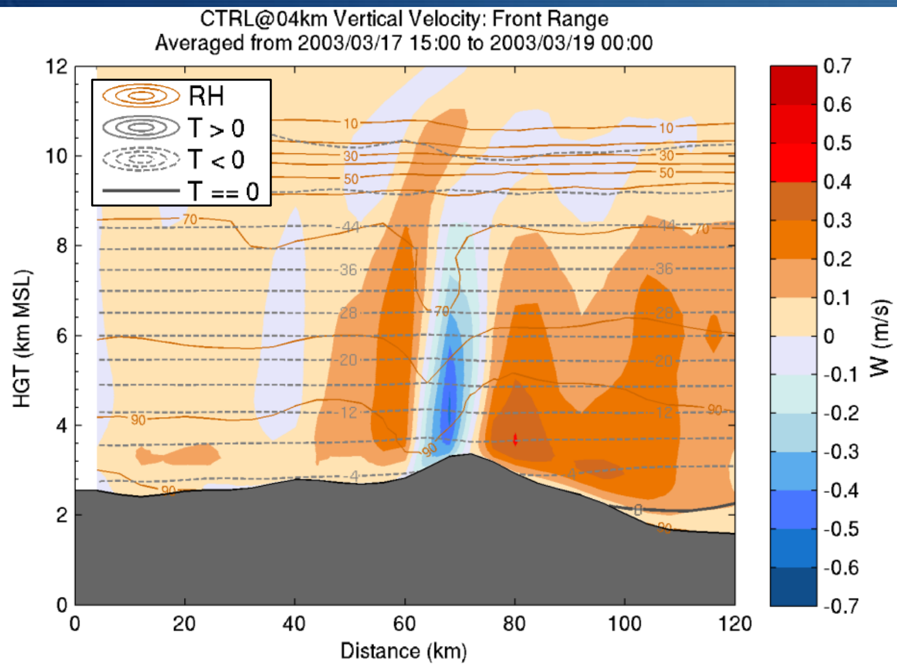
1. The box and CDF plots both show that the mean w is essentially the same in CTRL and PGW consistent with the average w profile shown earlier.
2. However, the plots indicate that PGW produced higher tail values. This subtle difference may be important for producing higher precipitation rates in PGW.

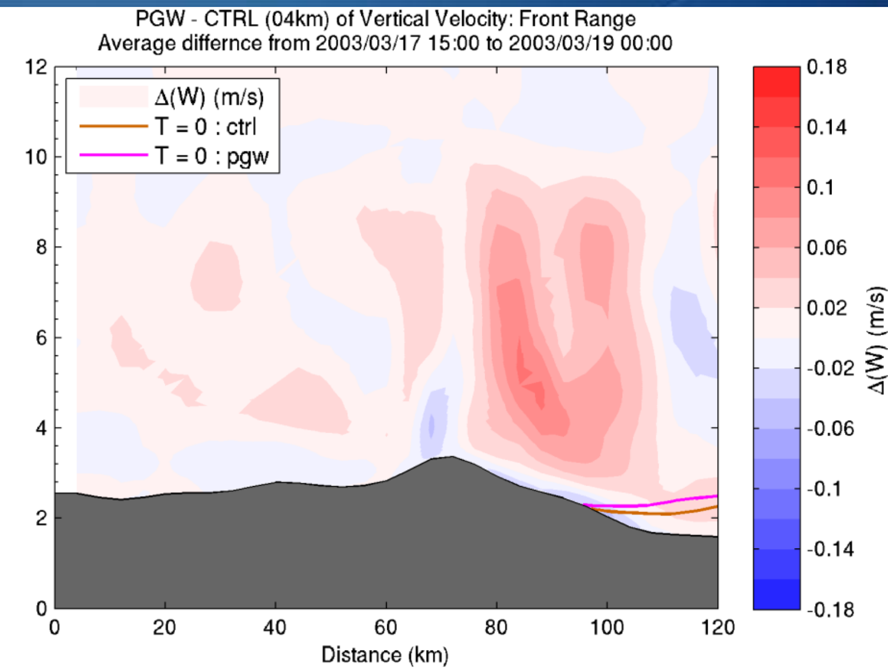
Snow mixing ratio at 600mb: 18 March 1800 UTC

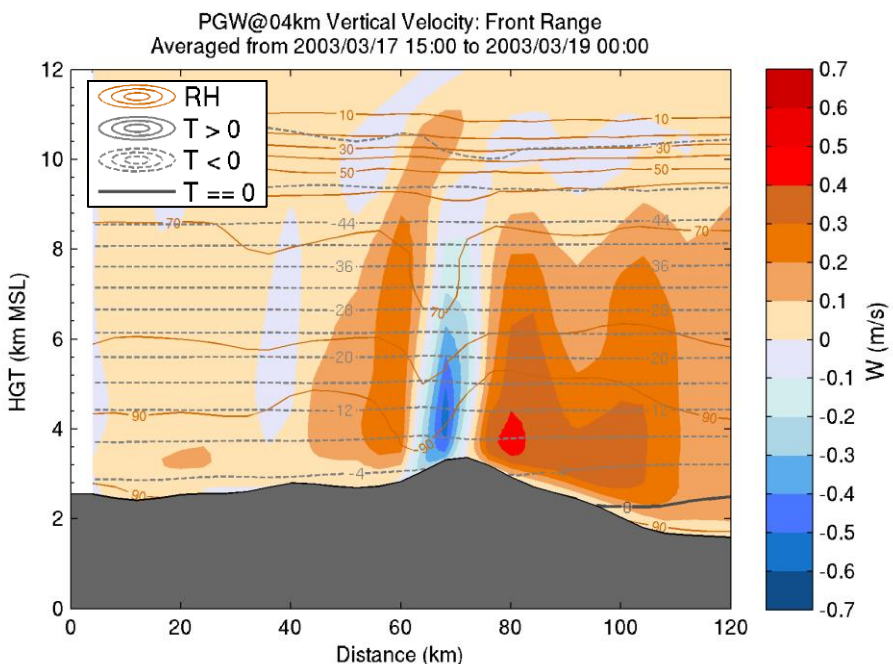


Cloud water mixing ratio at 600mb: 18 March 1800 UTC



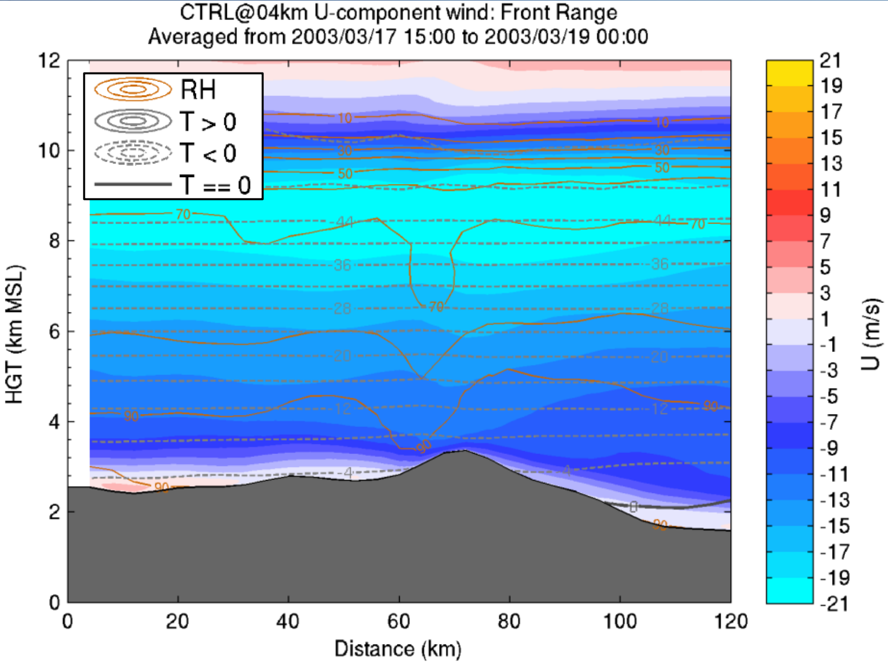


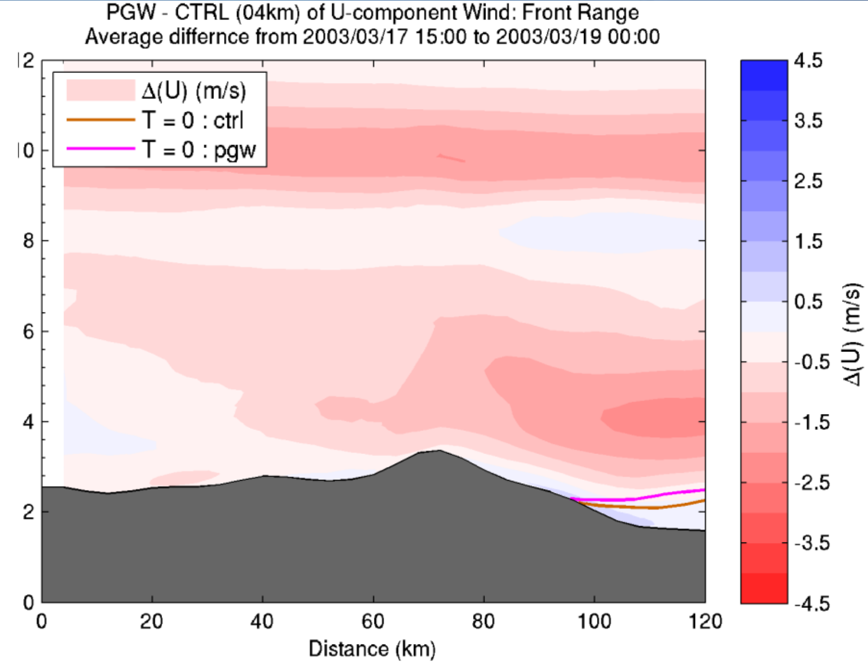


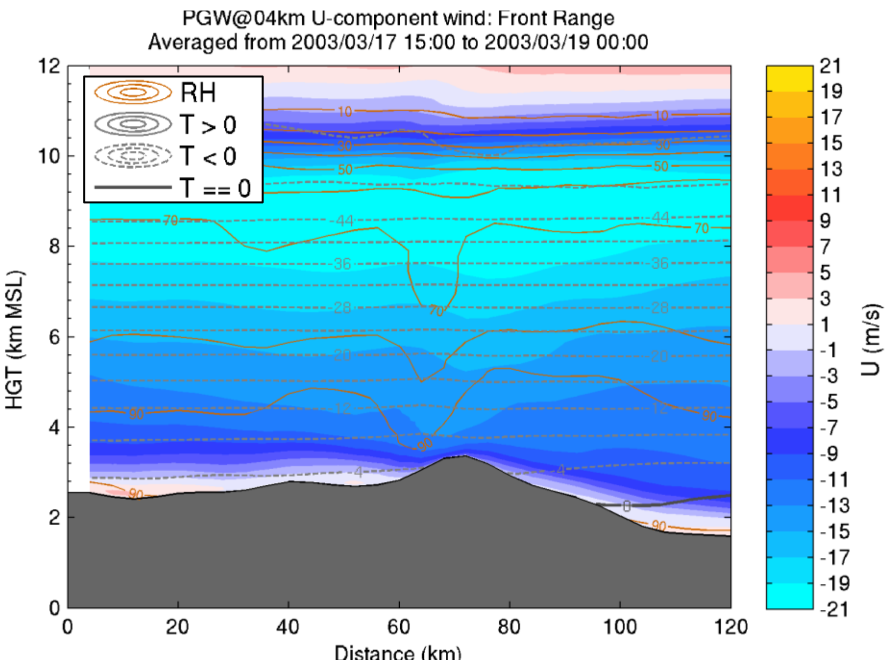


W
[Averaged between the indicated START and END time]

1. Stronger vertical motion at the mountain ridge (80 – 100km along the x-axis)





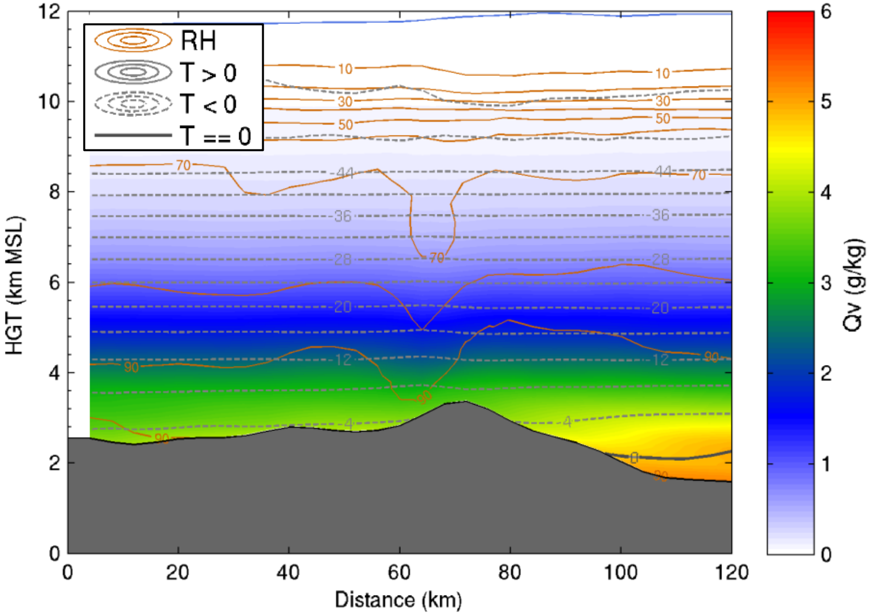


U-component wind speed

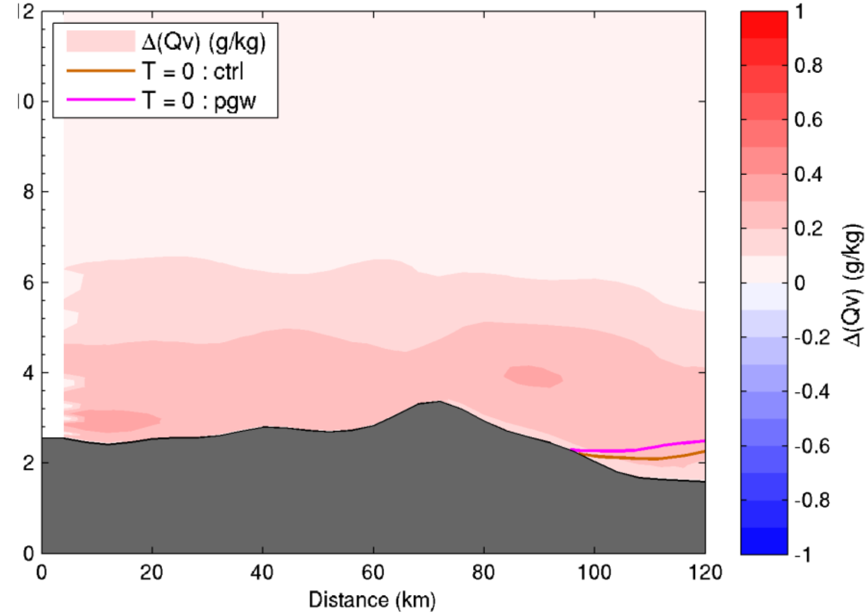
[Averaged between the indicated START and END time]

1. Stronger easterly upslope wind in PGW

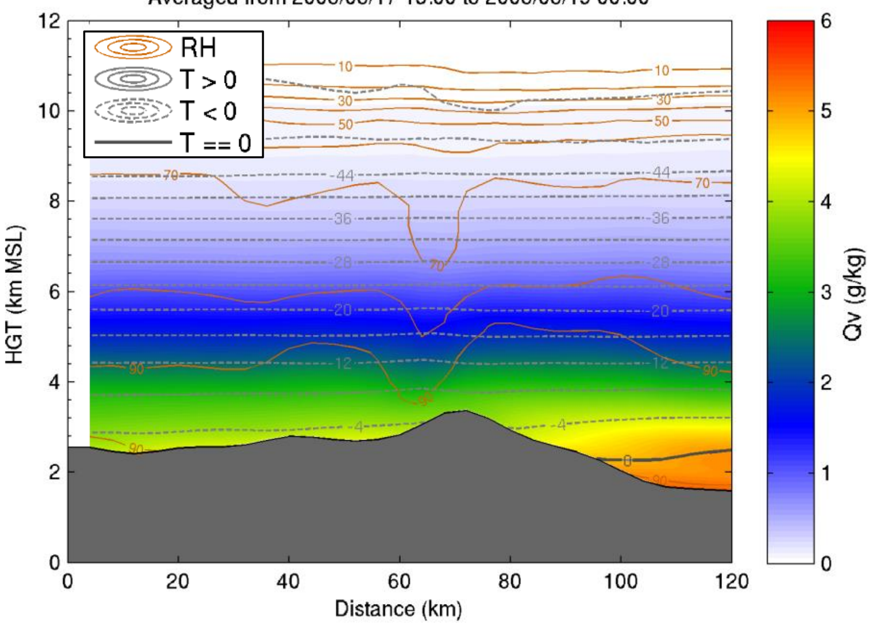
CTRL@04km Vapor Mixing Ratio: Front Range
Averaged from 2003/03/17 15:00 to 2003/03/19 00:00



PGW - CTRL (04km) of Vapor Mixing Ratio: Front Range
Average differnce from 2003/03/17 15:00 to 2003/03/19 00:00

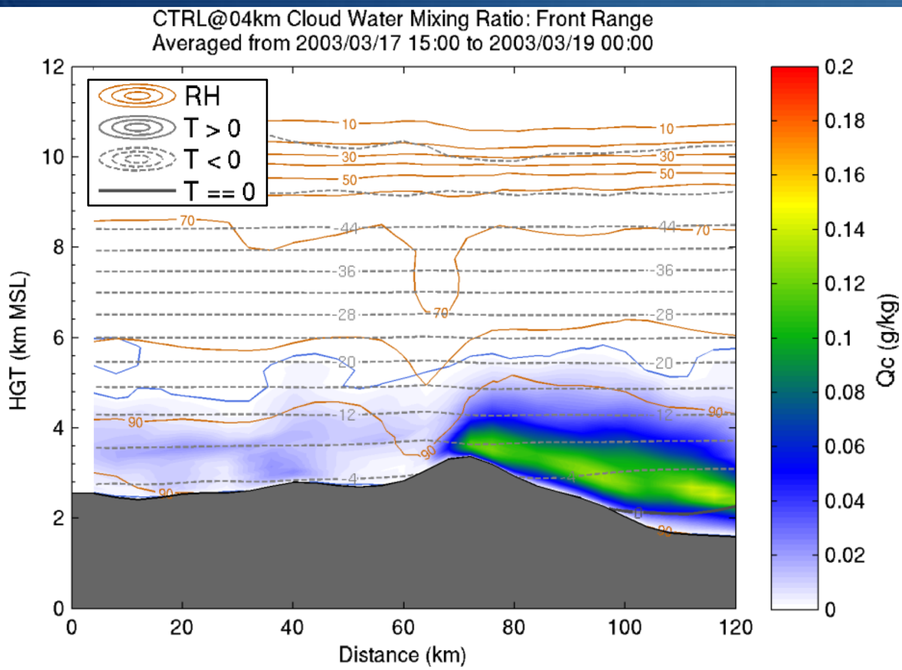


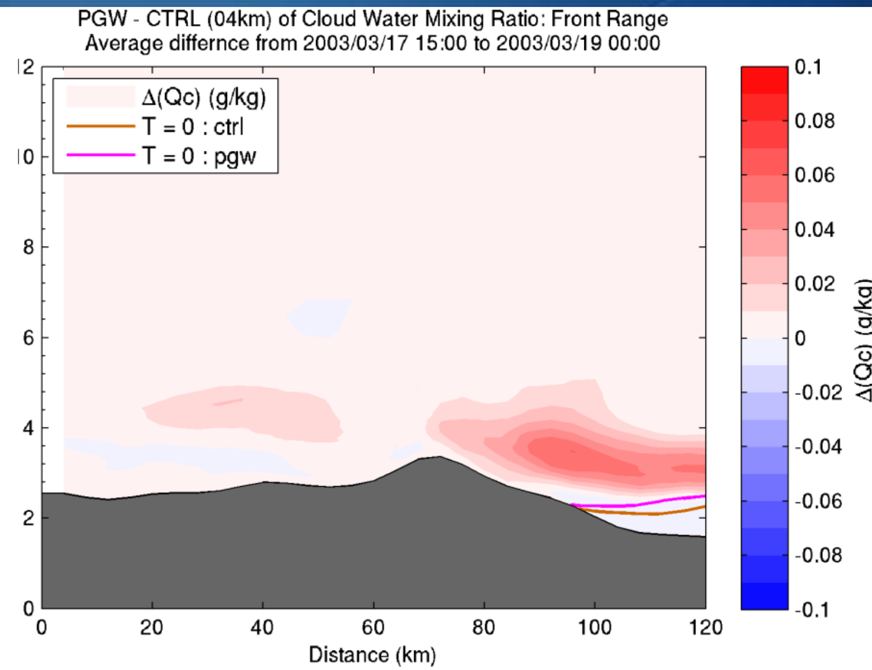
PGW@04km Vapor Mixing Ratio: Front Range
Averaged from 2003/03/17 15:00 to 2003/03/19 00:00

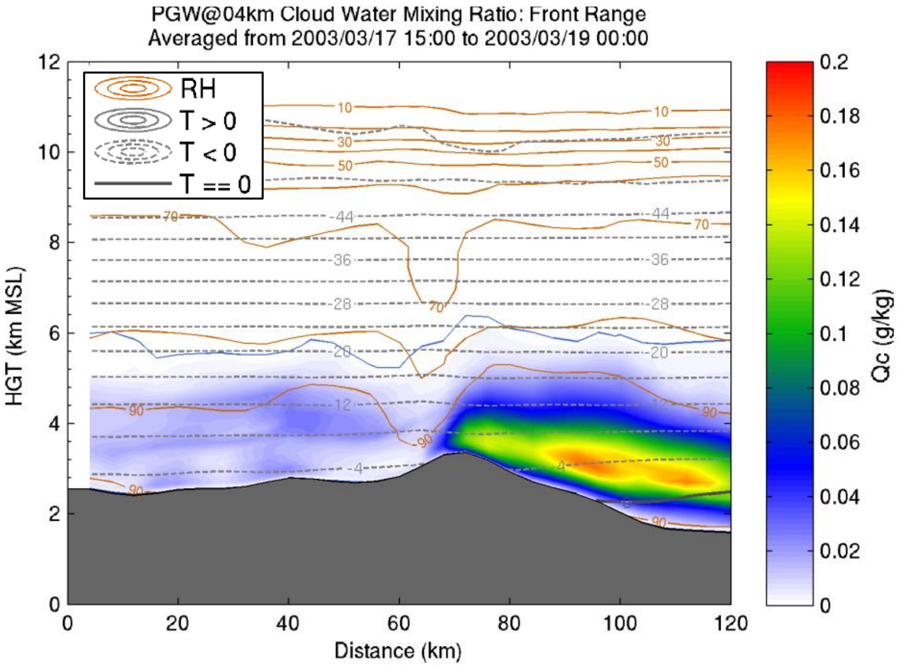


Vapor Mixing Ratio
[Averaged between the indicated START and END time]

1. Higher Qv throughout the vertical layer, as expected.
2. Note that the average difference in the 0C height for this case was ~150–200m.



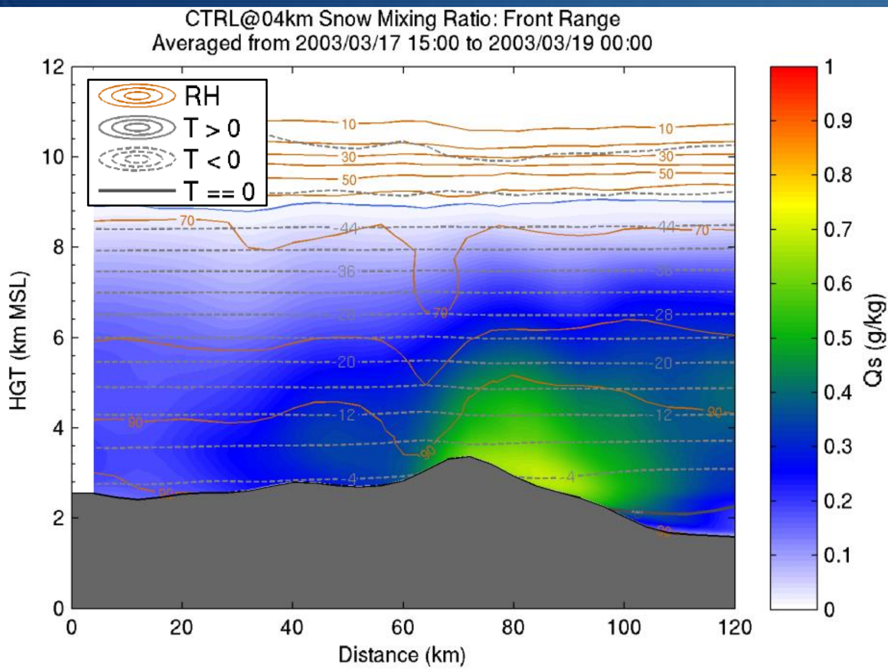


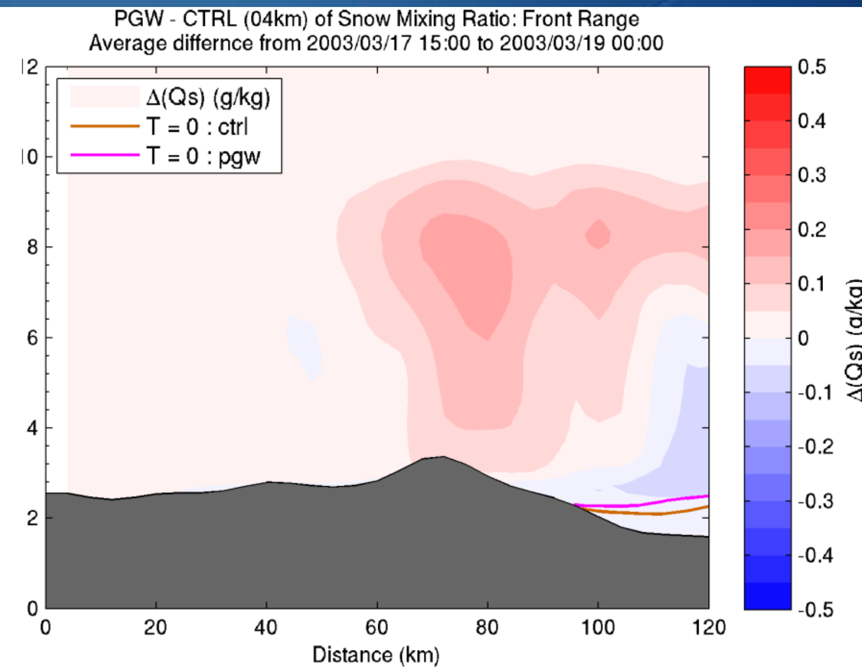


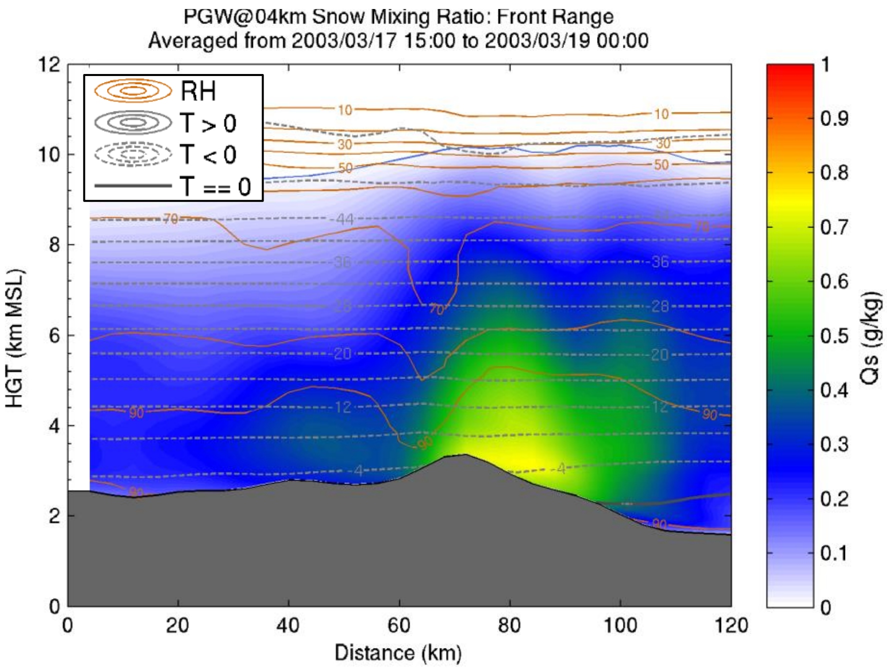
Cloud Water Mixing Ratio

[Averaged between the indicated START and END time]

1. More cloud water along the eastern mountain slopes due to more vapor flux and higher condensate supply rate.

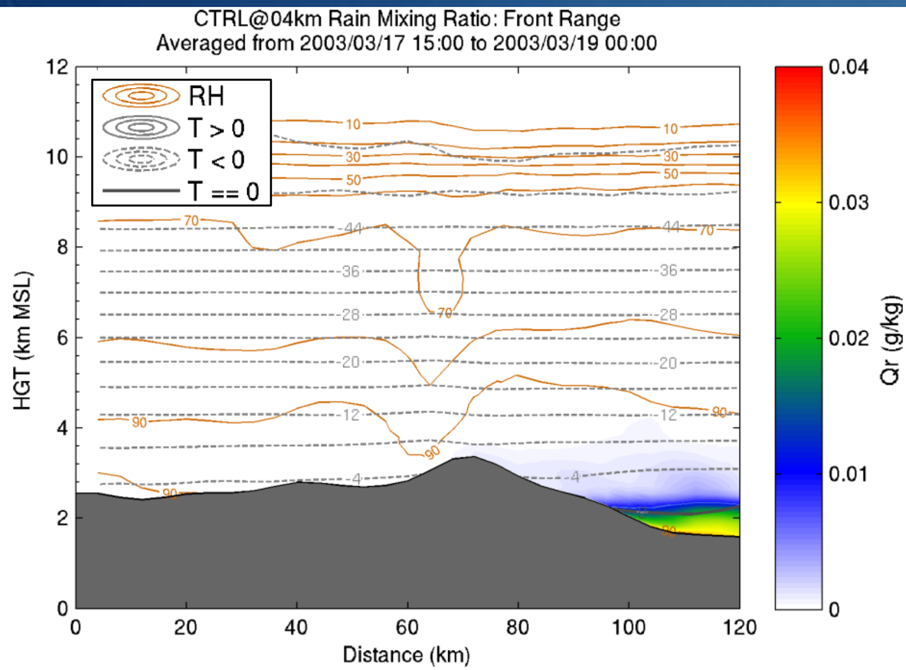


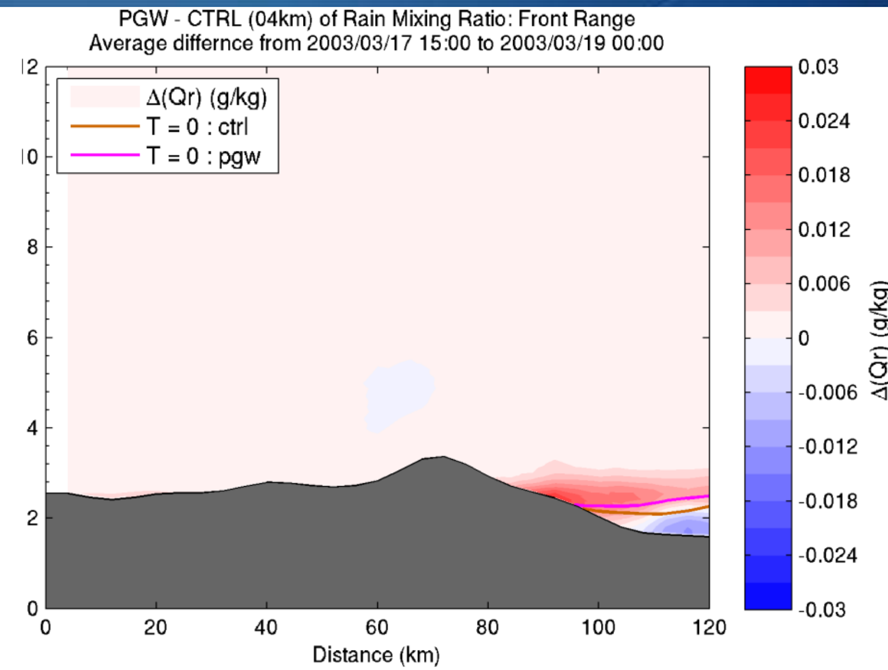


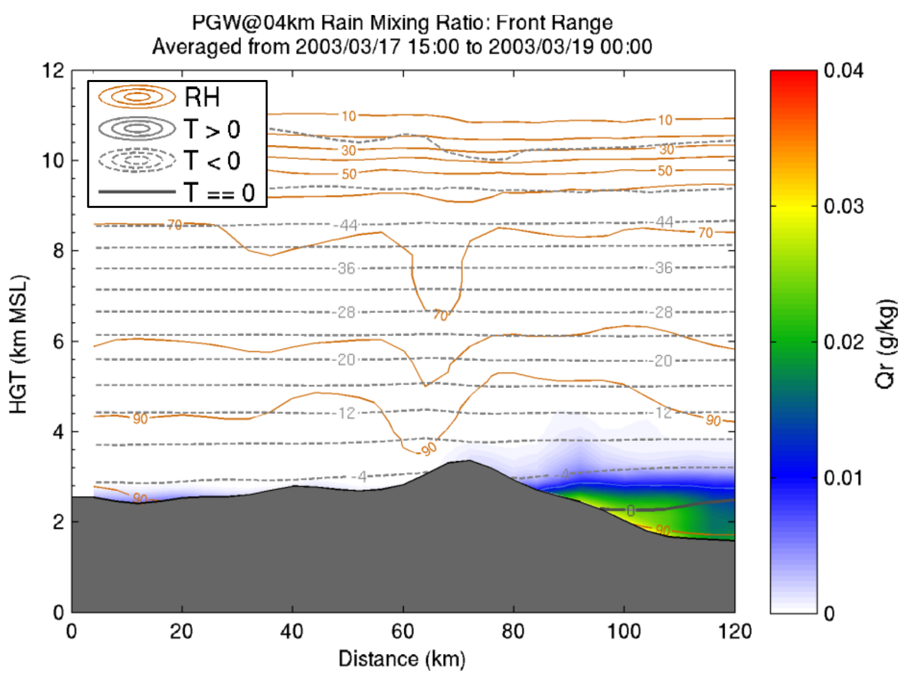


Snow Mixing Ratio
[Averaged between the indicated START and END time]

1. Deeper snow layer associated with a deeper cloud layer in PGW.
2. An increase in Qs associated with an increase in condensate supply in PGW.

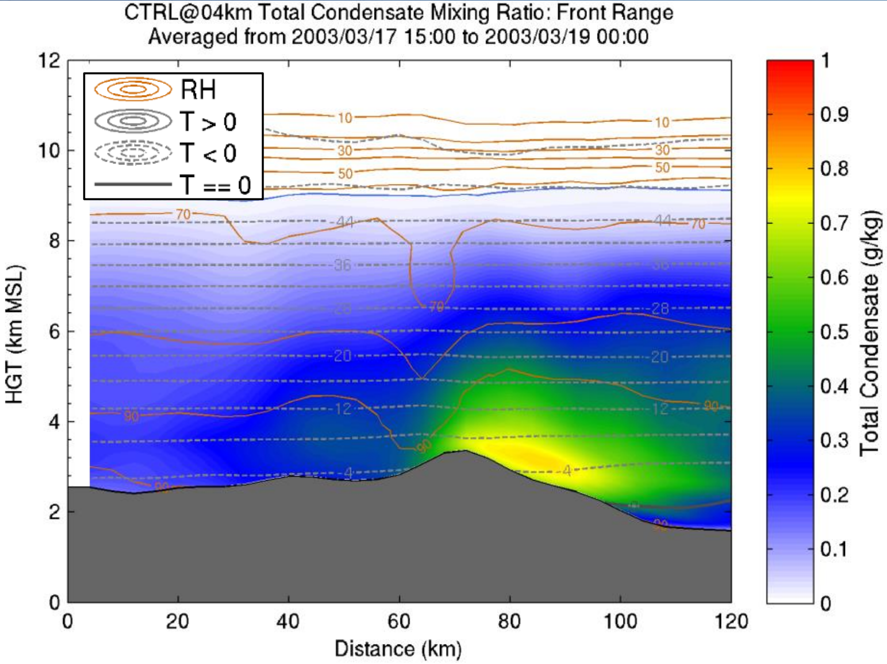


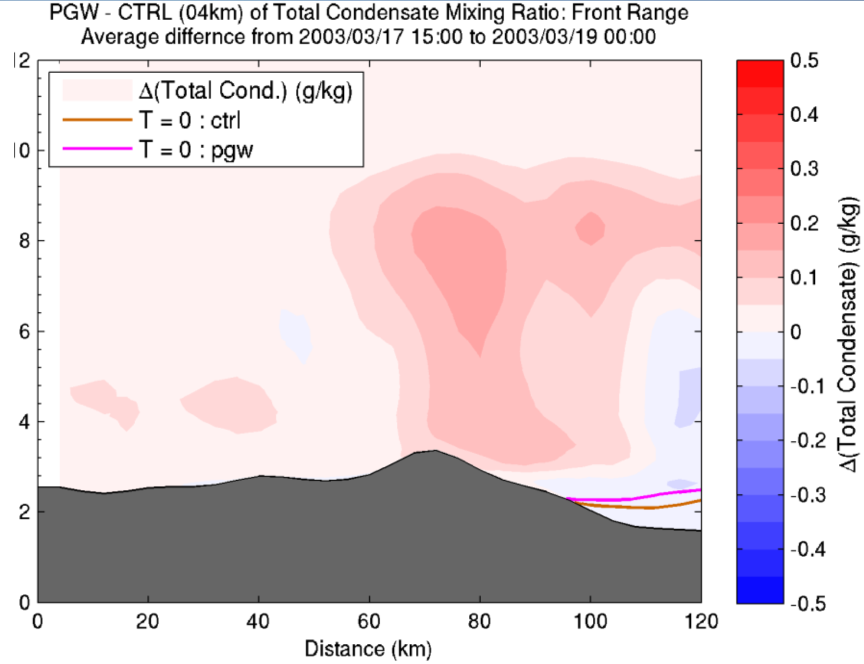


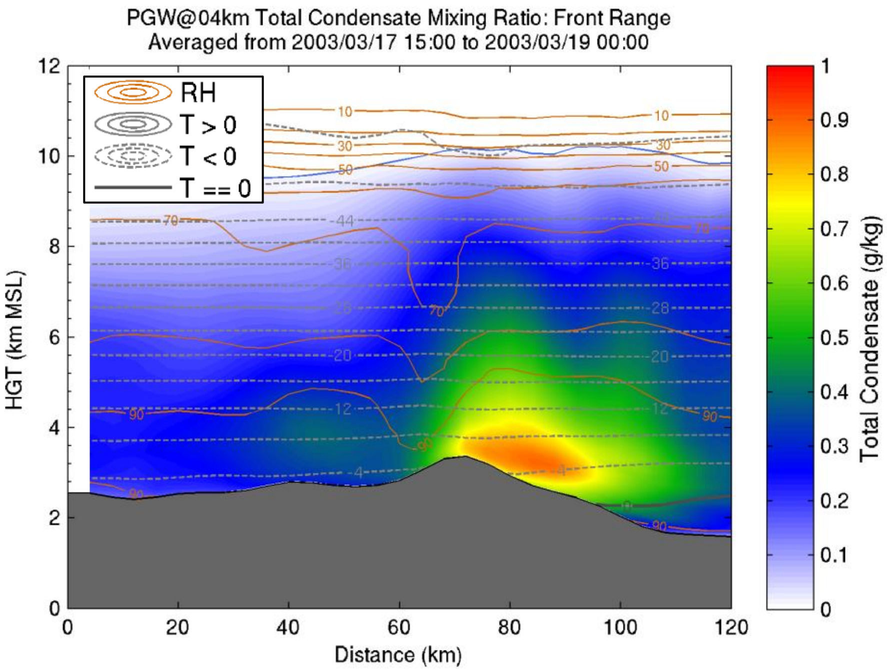


Rain Mixing Ratio
[Averaged between the indicated START and END time]

1. More rain at low elevations in PGW because of the change in the 0ºC height and increase in Qc.
2. Note that the max Qr is along the eastern mountain slopes in PGW (accretional growth is active in CTRL but condensational growth is active in PGW??)



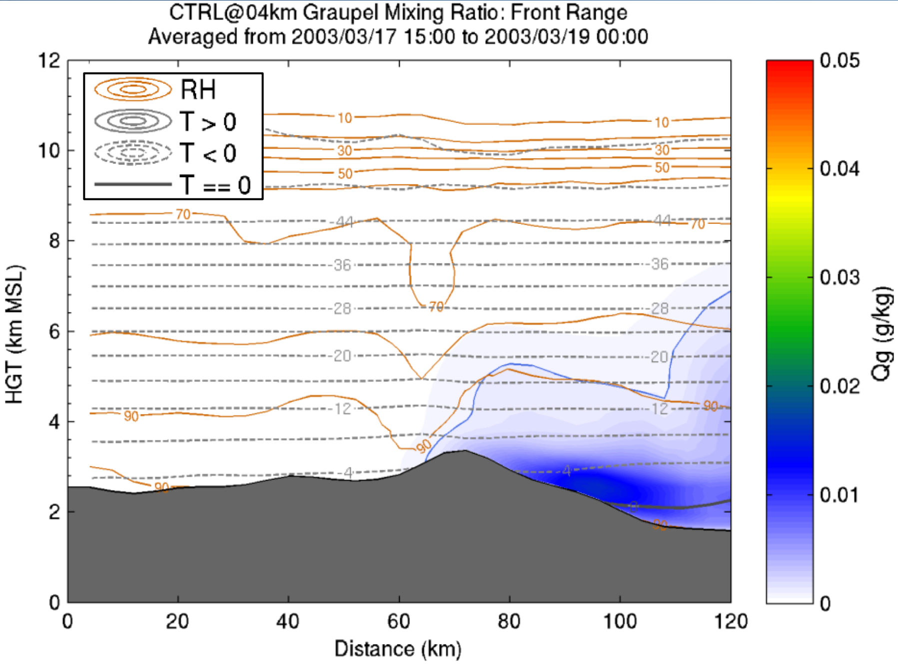


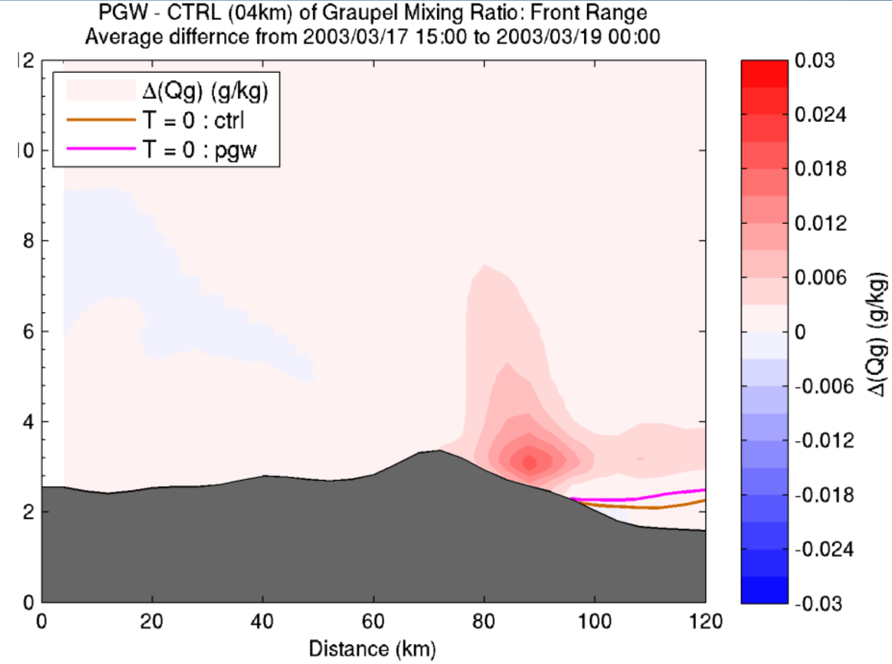


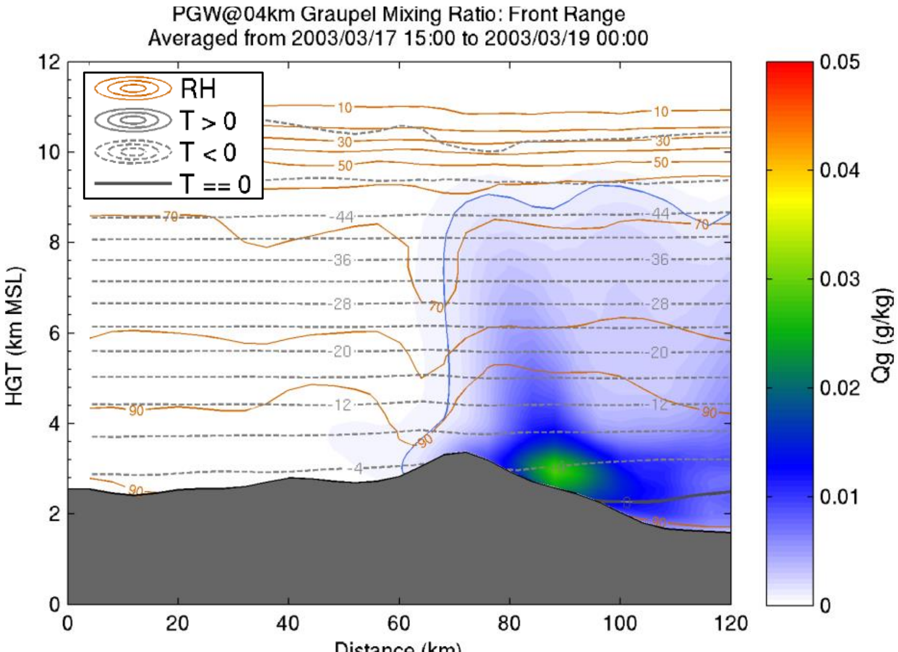
Total Condensate Mixing Ratio

[Averaged between the indicated START and END time]

1. Higher condensate mixing ratio at the mountain ridge in PGW.
2. The higher amount of Qtot comes from increases in Qs (primary) and Qg+Qi (secondary).







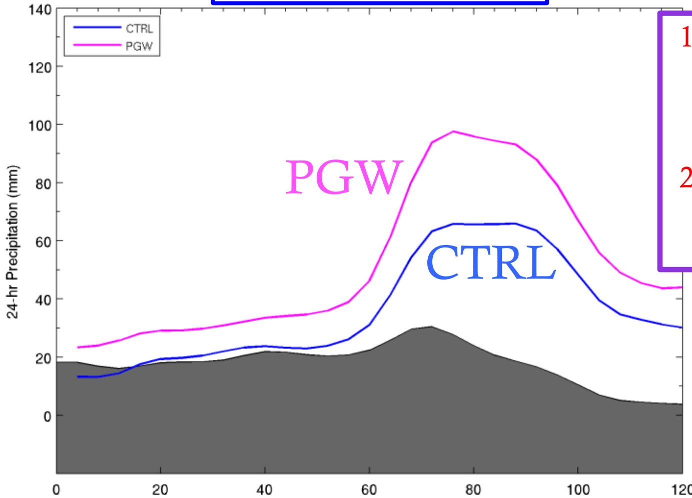
Graupel Mixing Ratio

[Averaged between the indicated START and END time]

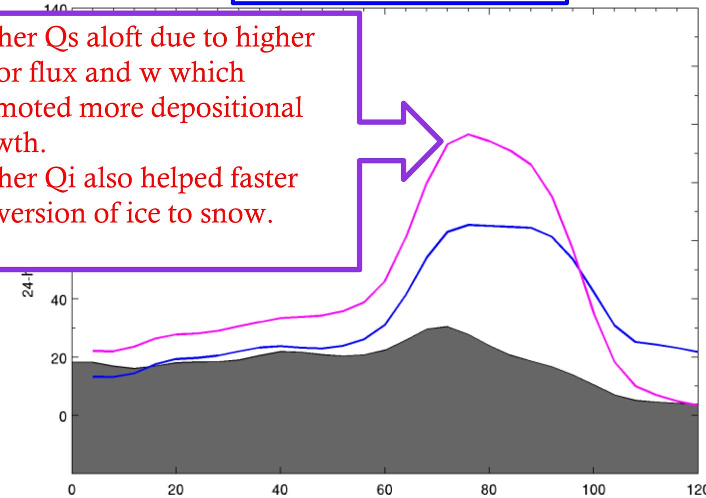
1. More graupel mixing ratio throughout the cloud layer in PGW
2. Higher W at this mountain ridge promoted Qg to increase.

18-19 March accumulation of precipitation, snow, rain, and graupel

Precipitation

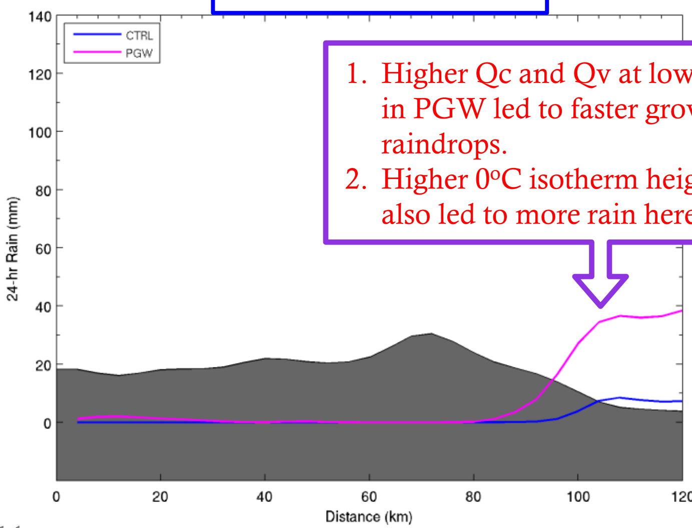


Snow



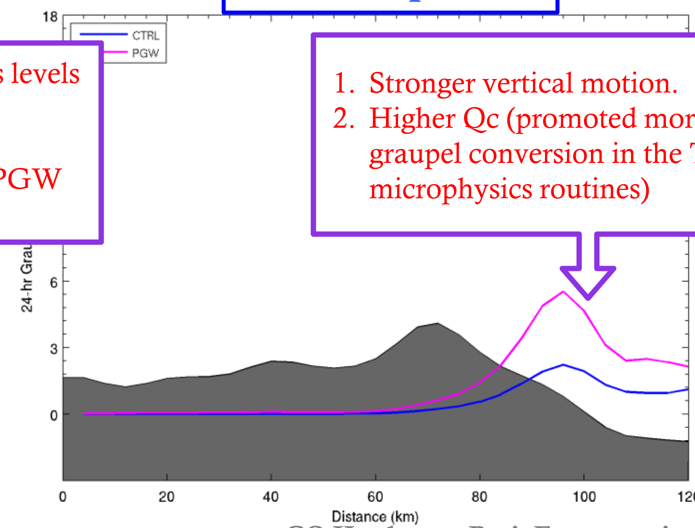
1. Higher Qs aloft due to higher vapor flux and w which promoted more depositional growth.
2. Higher Qi also helped faster conversion of ice to snow.

Rain



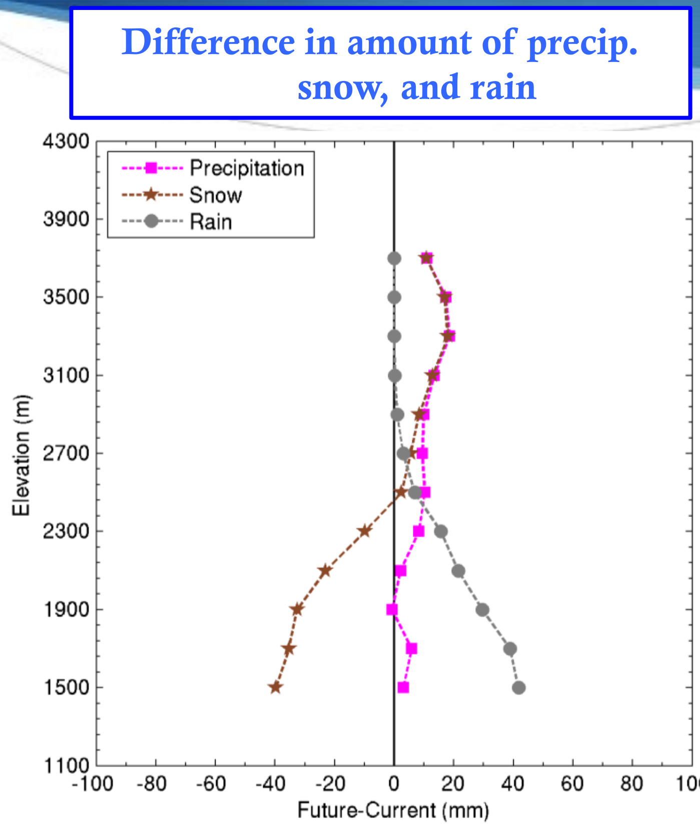
1. Higher Qc and Qv at low atmos levels in PGW led to faster growth of raindrops.
2. Higher 0°C isotherm height in PGW also led to more rain here.

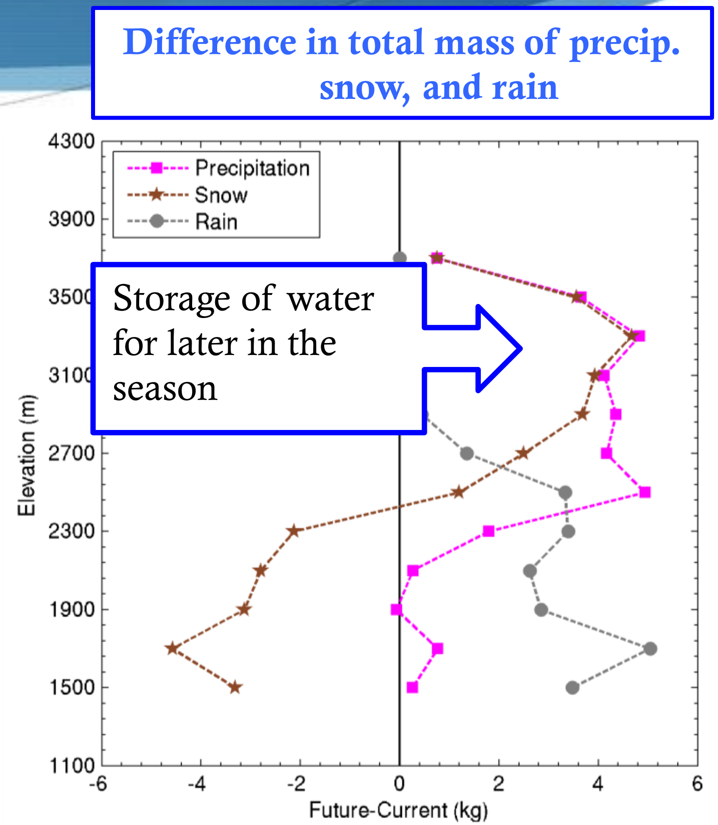
Graupel



1. Stronger vertical motion.
2. Higher Qc (promoted more snow-to-graupel conversion in the Thompson microphysics routines)

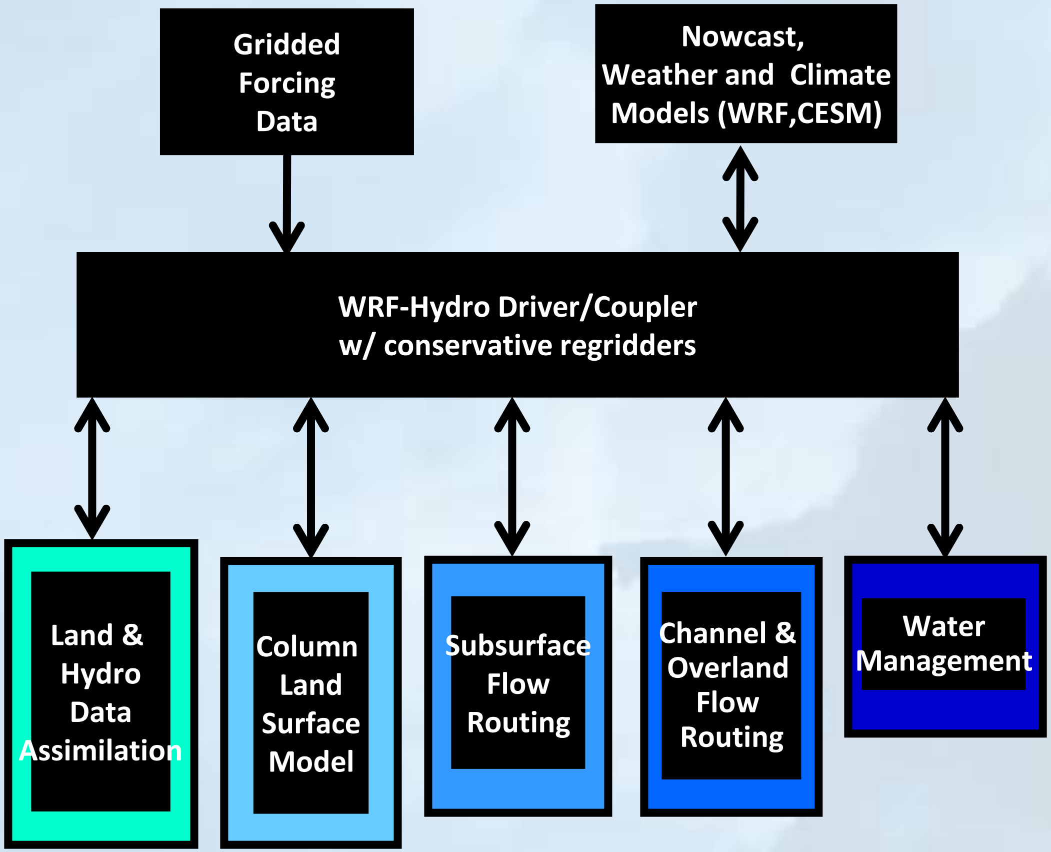
Change in total amount of water resources in various elevation bands





* Amount accumulated from 17 March 00 UTC to 21 March 00 UTC.

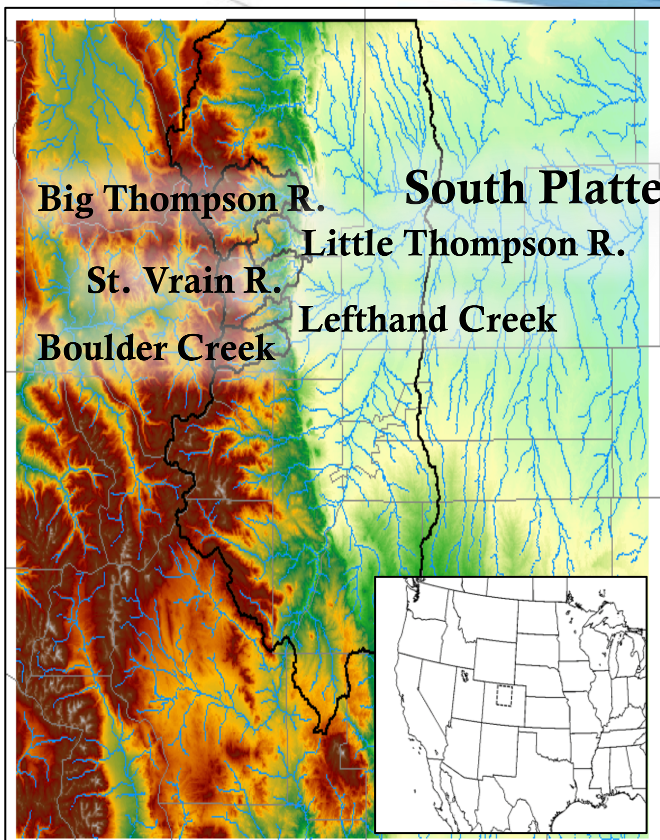
WRF-Hydro

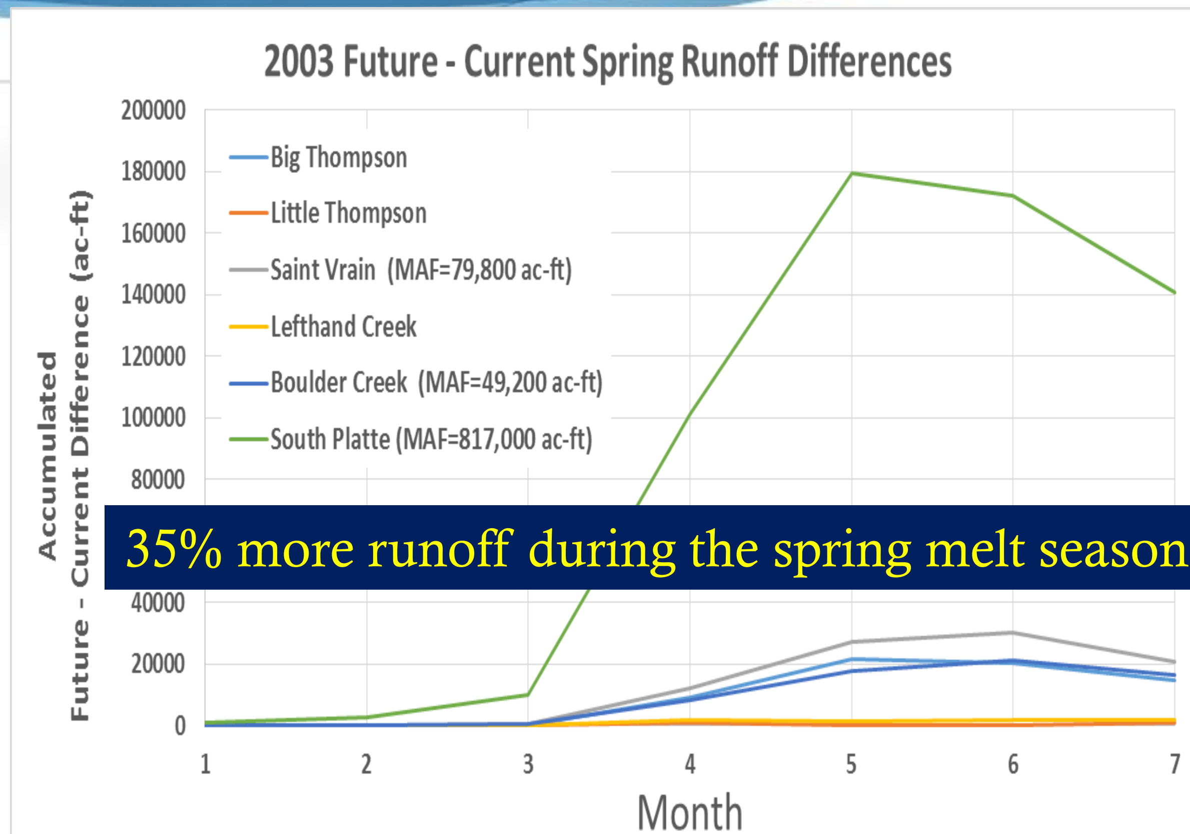


http://www.ral.ucar.edu/projects/wrf_hydro/

Event Impact on Key Water Resource Basins:

WRF-Hydro simulated changes in monthly streamflow volume





35% more runoff during the spring melt season!

Summary

- WRF simulated the March 2003 snow storm well in terms of precipitation amount as compared to observations.
- At SNOTEL sites (i.e., high elevations), this storm produced 35% more snow in PGW compared to CTRL.
- At lower elevations (<2000 m) rainfall increased because of the higher 0C level in PGW and the formation of rain by autoconversion. The immediate runoff increase in PGW was associated mainly to the change in precipitation type.
- There was a significant increase in water storage as snow at high elevation which significantly impacted runoff later in the season (35% more runoff, flooding likely!).
- An increase in precipitation amount in this event was related to:
  - Increased vapor flux
  - Increased extreme vertical motions
  - Much higher Qs and Qg aloft.
  - At low elevations (where there are no SNOTEL sites), Qr was also high.
  - The increase in precipitation for weaker events was only ~12% on average with no change in vertical velocity or horizontal wind speed, consistent with the 7%/C increase in mixing ratio and a 2 C increase in temperature.
- The current increase of 35% more precipitation occurs due to stronger storm dynamics leading to increased horizontal easterly flow into the Front Range, causing higher vertical motions, which in association with the higher moisture content leads to **a 3 times higher than Clasius-Claperyon equation increase in precipitation**.

Final Remark

- The March 18-20, 2003 blizzard case had a synoptic pattern similar to the Front Range and Alberta floods!
- Temperature lower, precipitation stored as snow instead of as rain.
- Current climate precipitation amount was 100 mm, less than observed in the two floods due to colder temperature and associate less moisture.
- Future precipitation levels predicted to increase by 35%, approaching flood levels of Alberta and Colorado Front Range.
- Warmer environment leads 35% more runoff over the spring melt season.