Dynamic and non-local responses to the SAF in the Colorado Rockies

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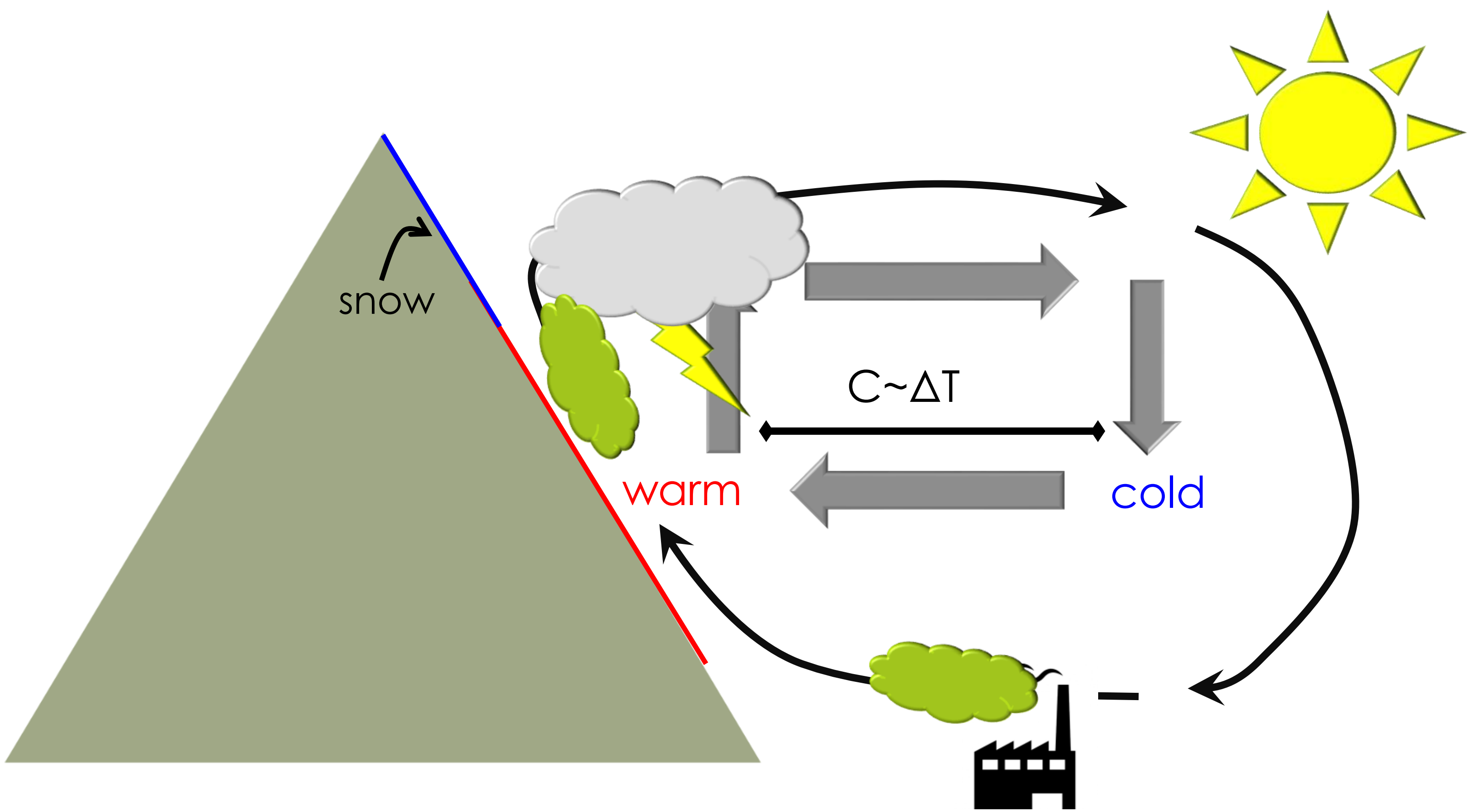
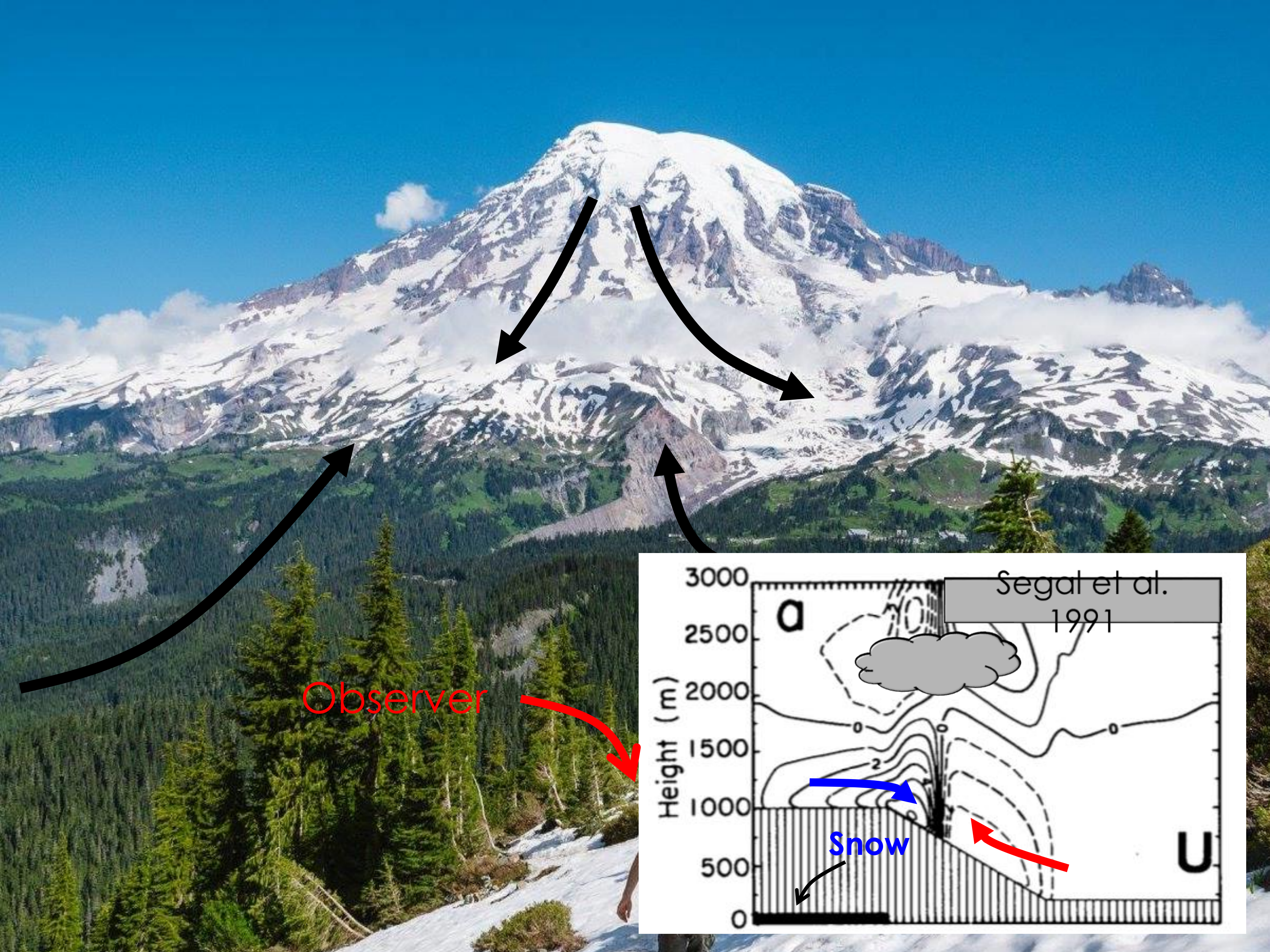
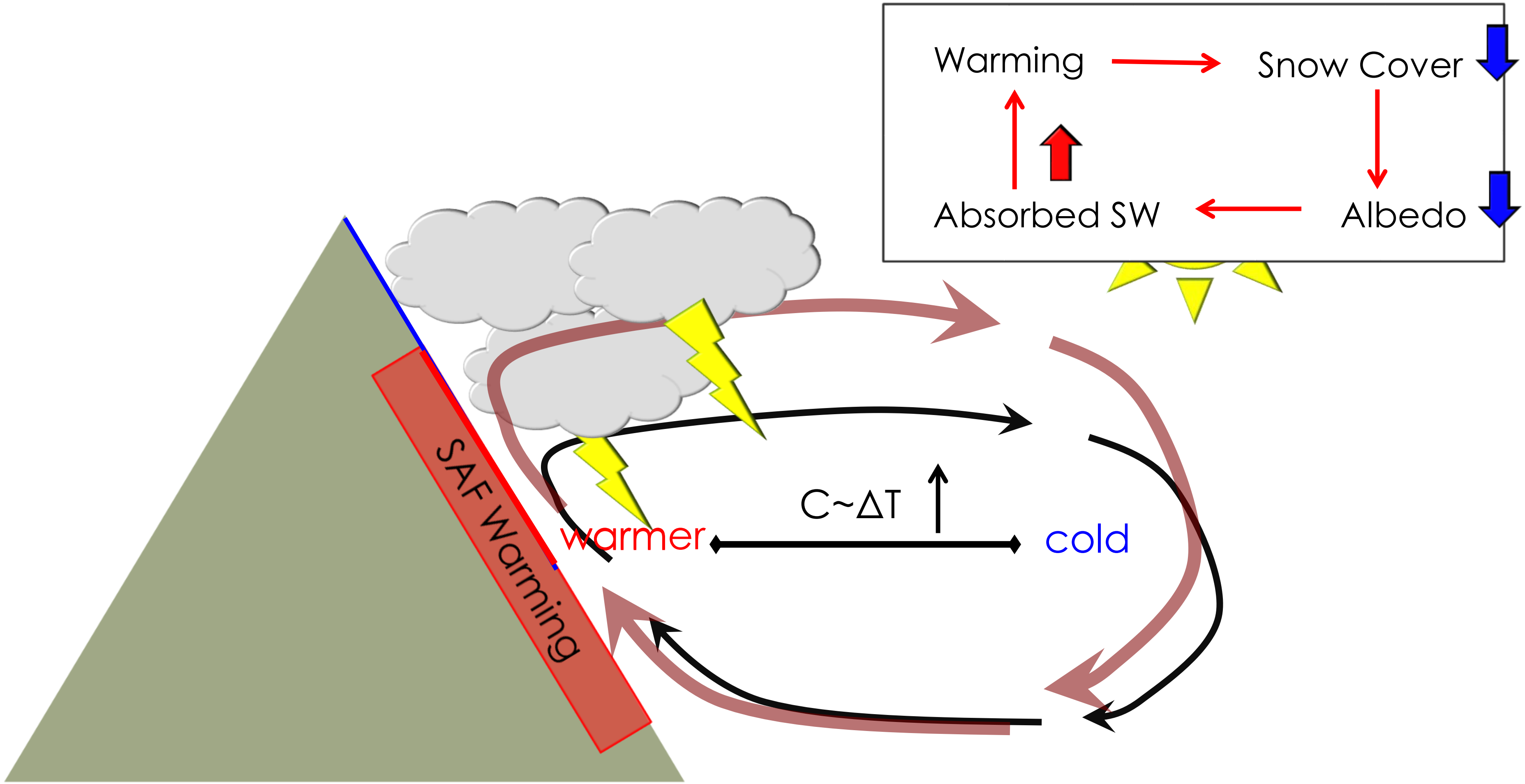
Mountain Breeze Circulations



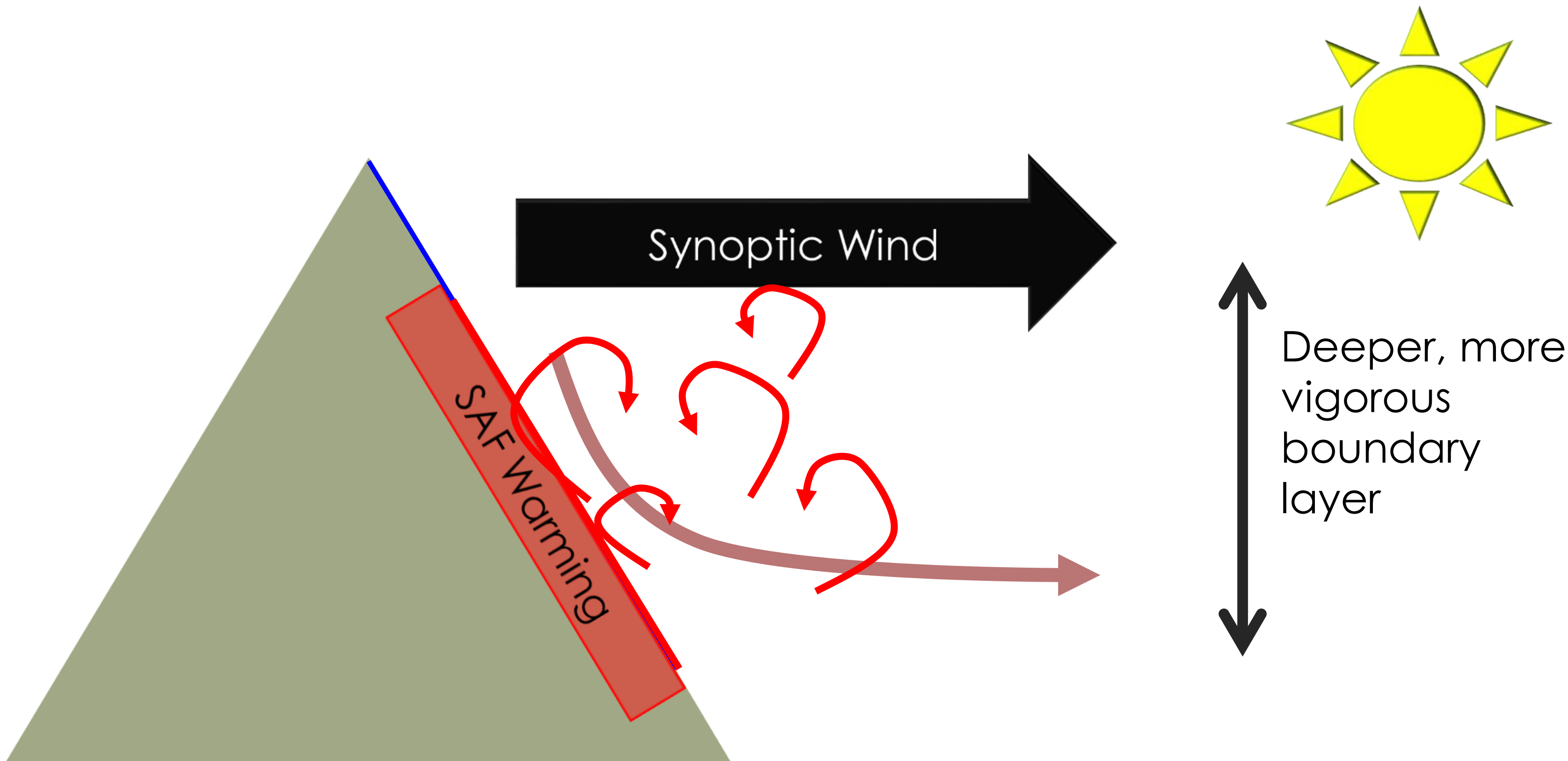


Observer
Segal et al.
1991
a
Height (m)
3000
2500
2000
1500
1000
500
0
Snow
U

Plausible Interactions: SAF changes ΔT

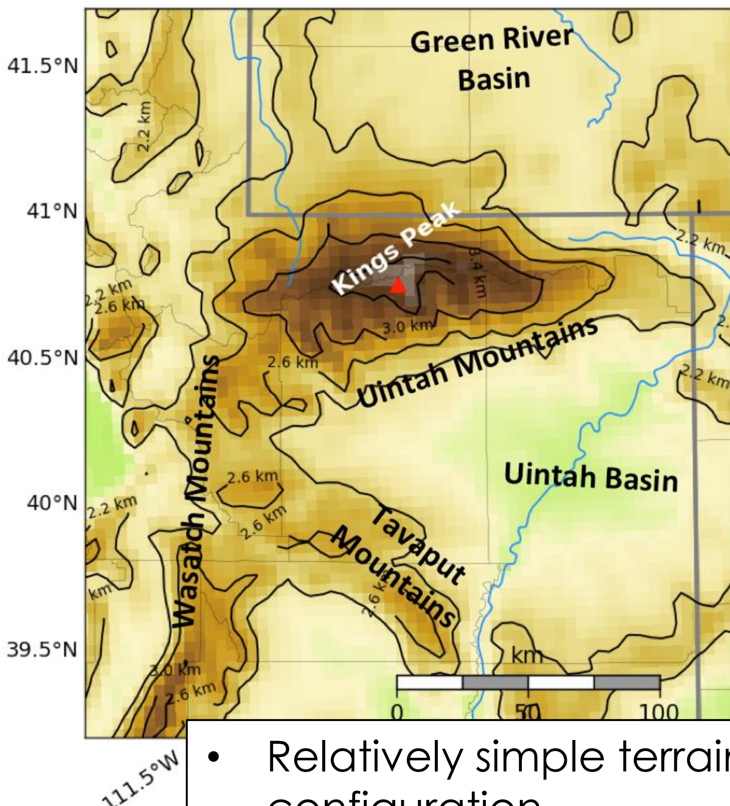


Plausible Interactions: SAF increases boundary layer mixing

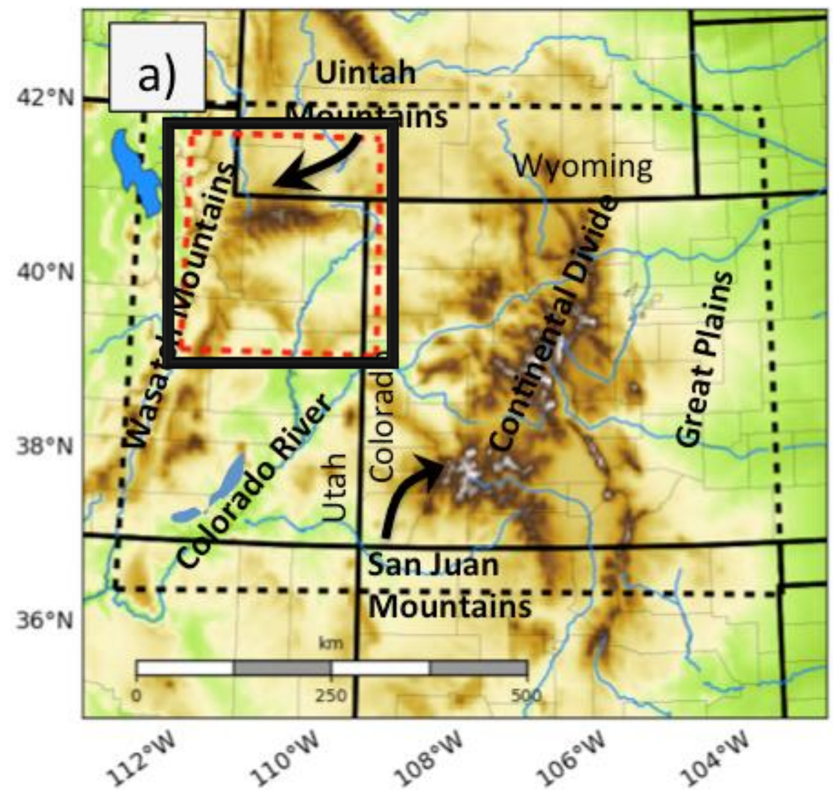


Banta and Cotton 1981 ; Neemann et al. 2015

4km Simulations



- Relatively simple terrain configuration
- Results easier to interpret

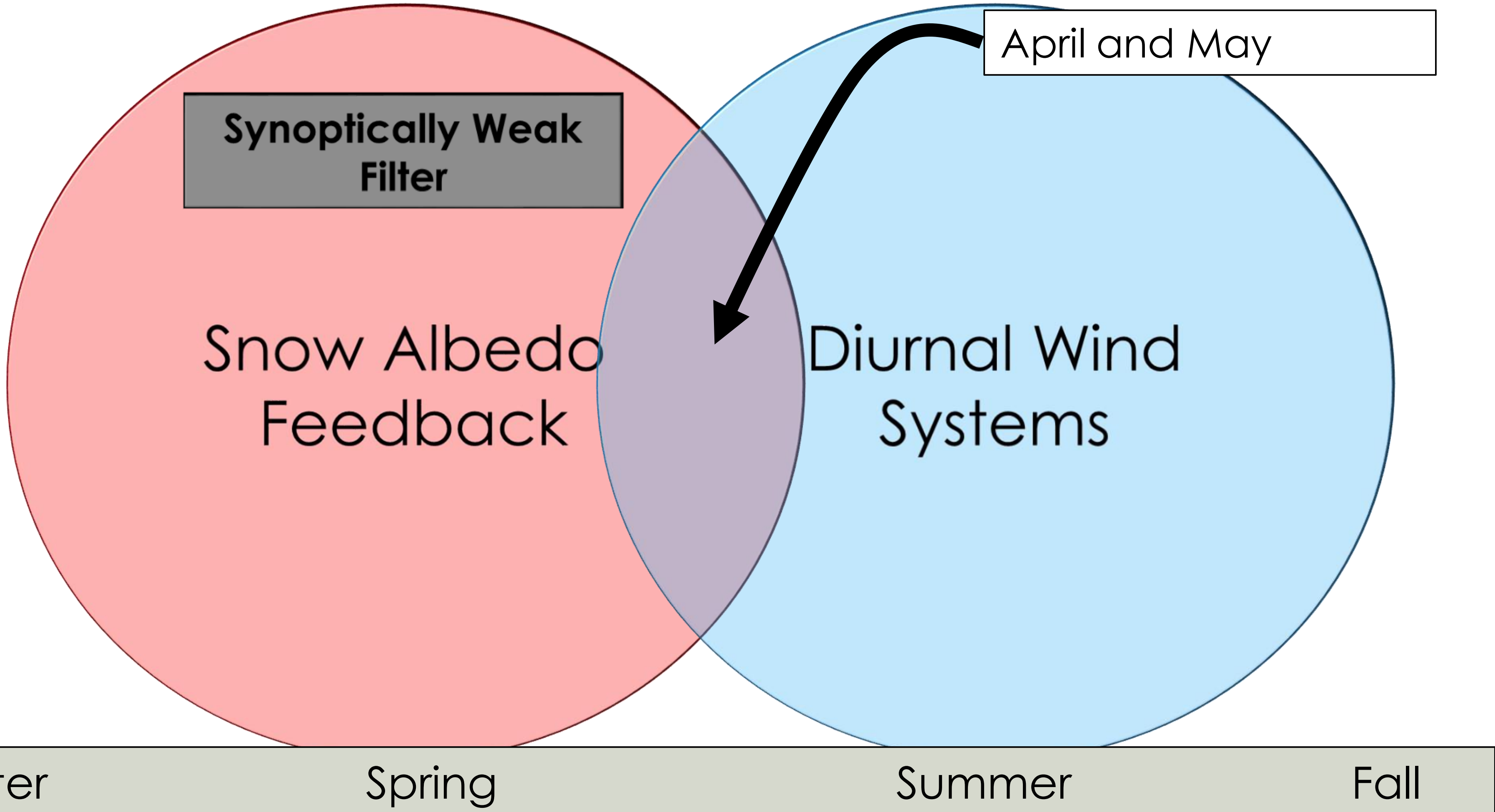


4km General Experimental Design

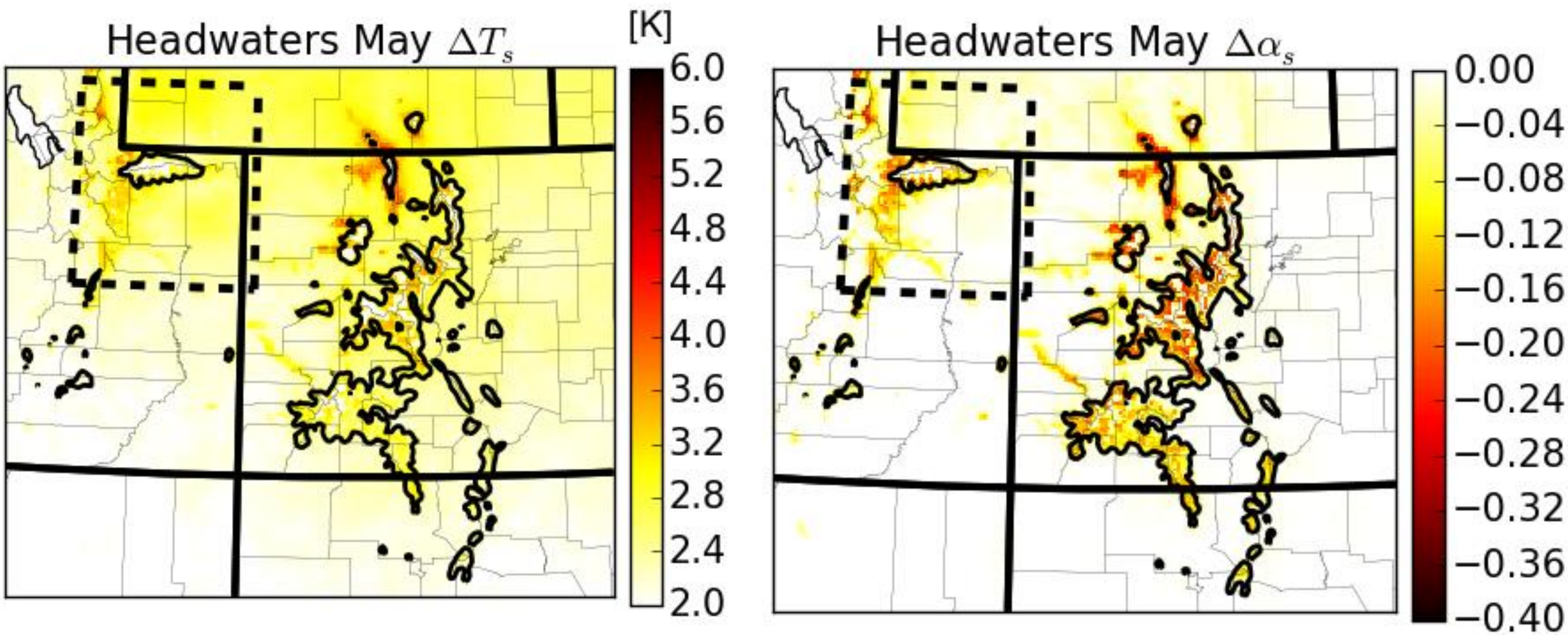
- High resolution regional climate model (RCM) simulations
  - **Headwaters simulations** (Rasmussen et al. 2014)
  - Limited area domain over Rockies
  - Weather Research and Forecast Model (WRF)
  - 4km horizontal resolution
  - NOAH LSM
    - Snow model adjustments (Barlage et al. 2010)
  - 8-year simulations: Oct 2000 – June 2008
    - Disregarded 1st year of output for spin up

- Pseudo Global Warming (PGW) Experiment
  - Add a large scale climate perturbation to the reanalysis forcing to simulate the mesoscale response to a large scale climate perturbation
  - Same "Weather" as control simulation → on warmer mean climate
  - SRES A2 2050 Forcing
    - CCSM Ensemble

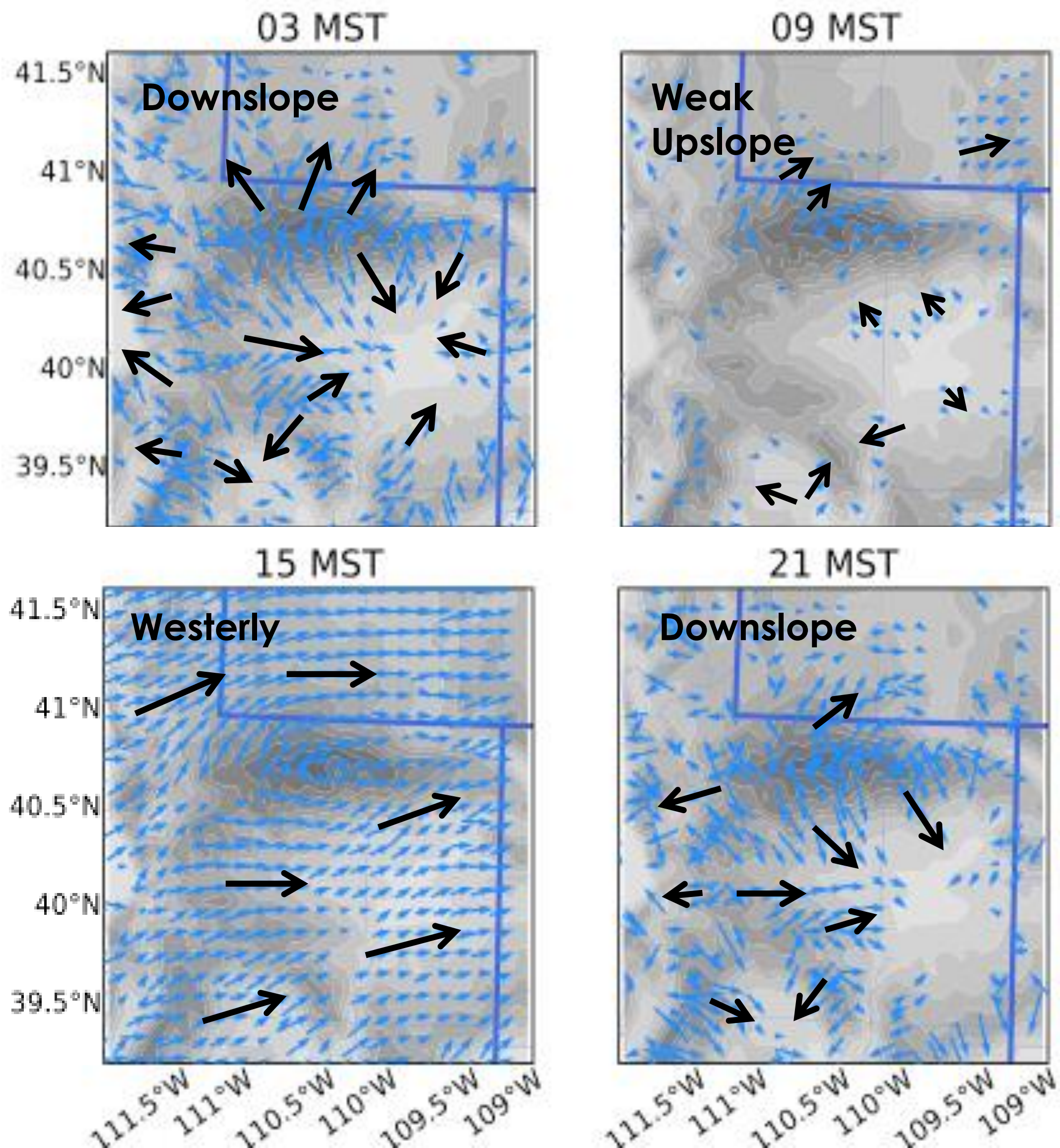
Filtering and Compositing: Spring Focus



Overview: Warming matches snow loss



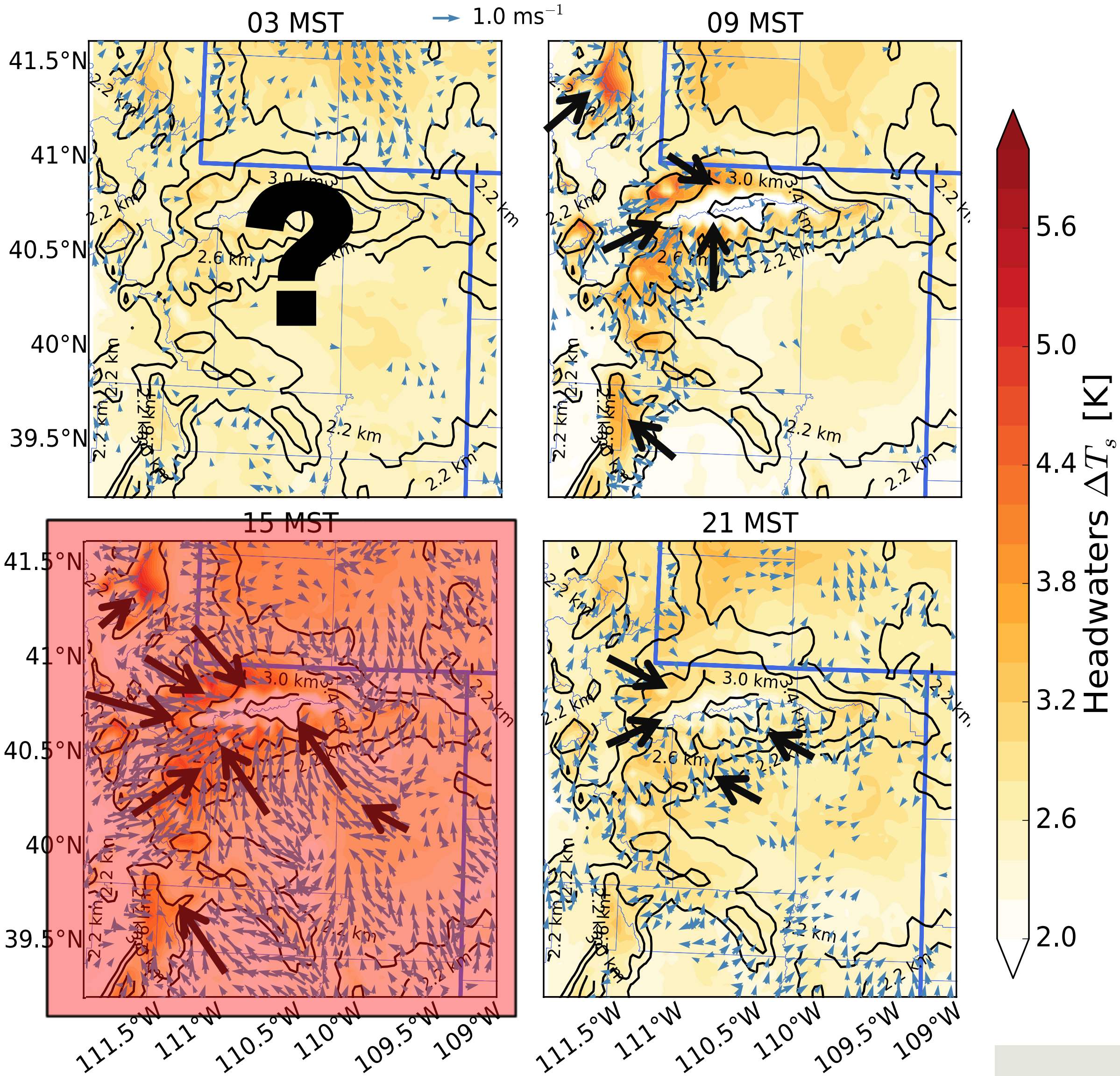
Headwaters May Control Circulations



Diurnal Cycle

- **Overnight**: downslope flow
- **Mid-morning**: weak upslope
- **Afternoon**: westerly (synoptic mixing)
- **Evening**: back to downslope

Headwaters PGW-Control



(PGW-control)

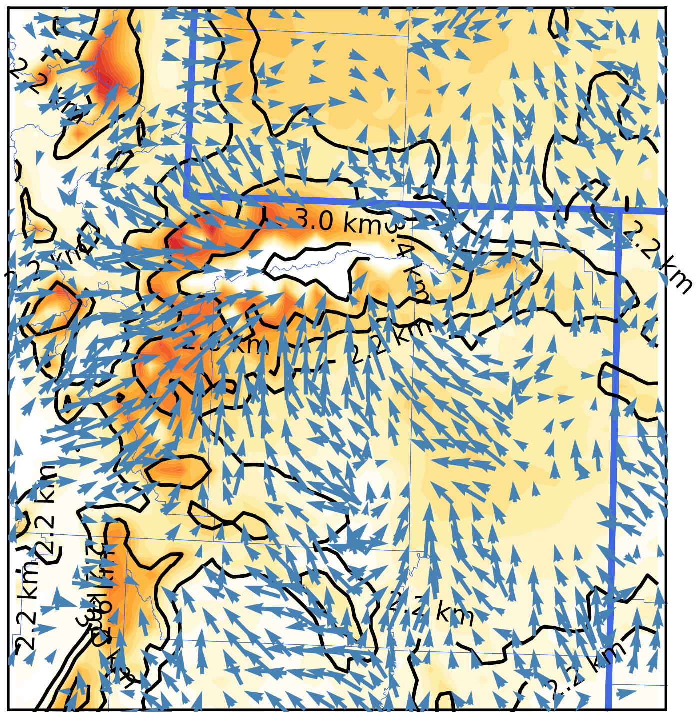
- **Overnight:** Weak response
- **Mid-morning:** Enhanced upslope ; oriented towards SAF warming
- **Afternoon:** Strongly enhanced upslope ; ΔT maximized.
- **Evening:** Response is weakening ; ΔT weakening

Key Points

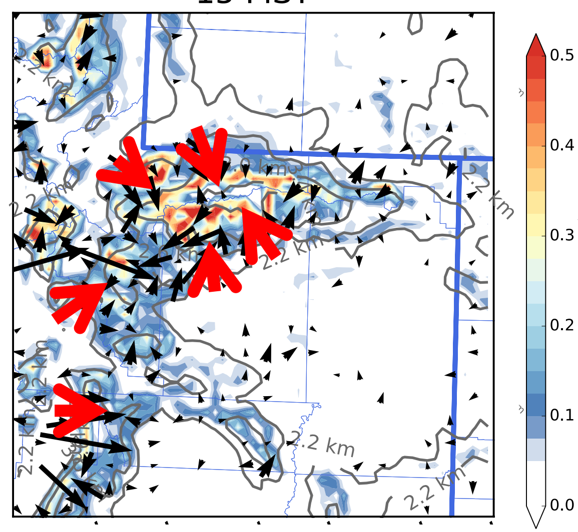
- Primarily a daytime response
- Oriented towards strongest warming
  - Thermal contrast
- ΔV ~ 1-1.5 ms^{-1}

Thermal Contrast vs. Enhanced Mixing: 15 MST

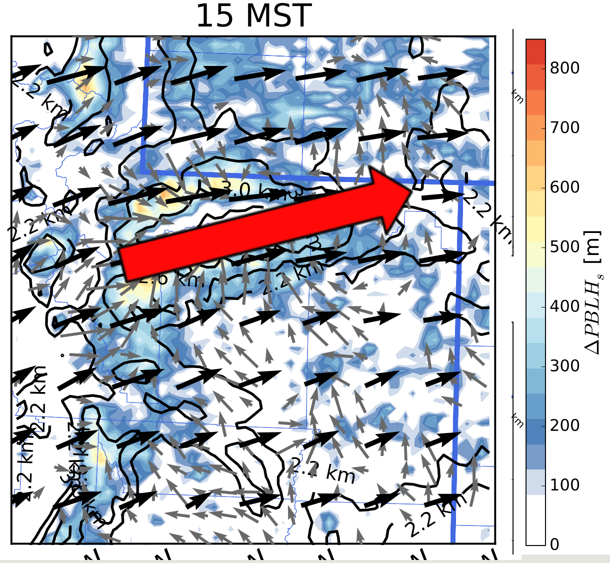
15 MST



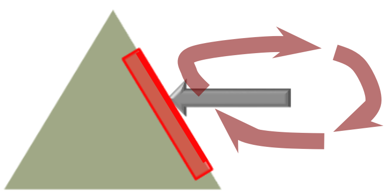
15 MST



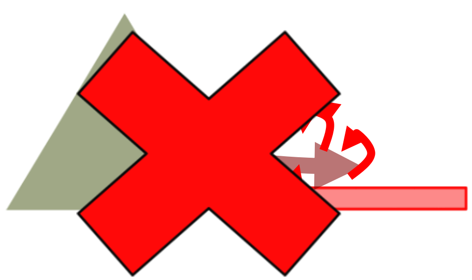
15 MST



ΔPGF: Thermal Contrast



ΔPBLH: Boundary Layer Mixing



Key Points

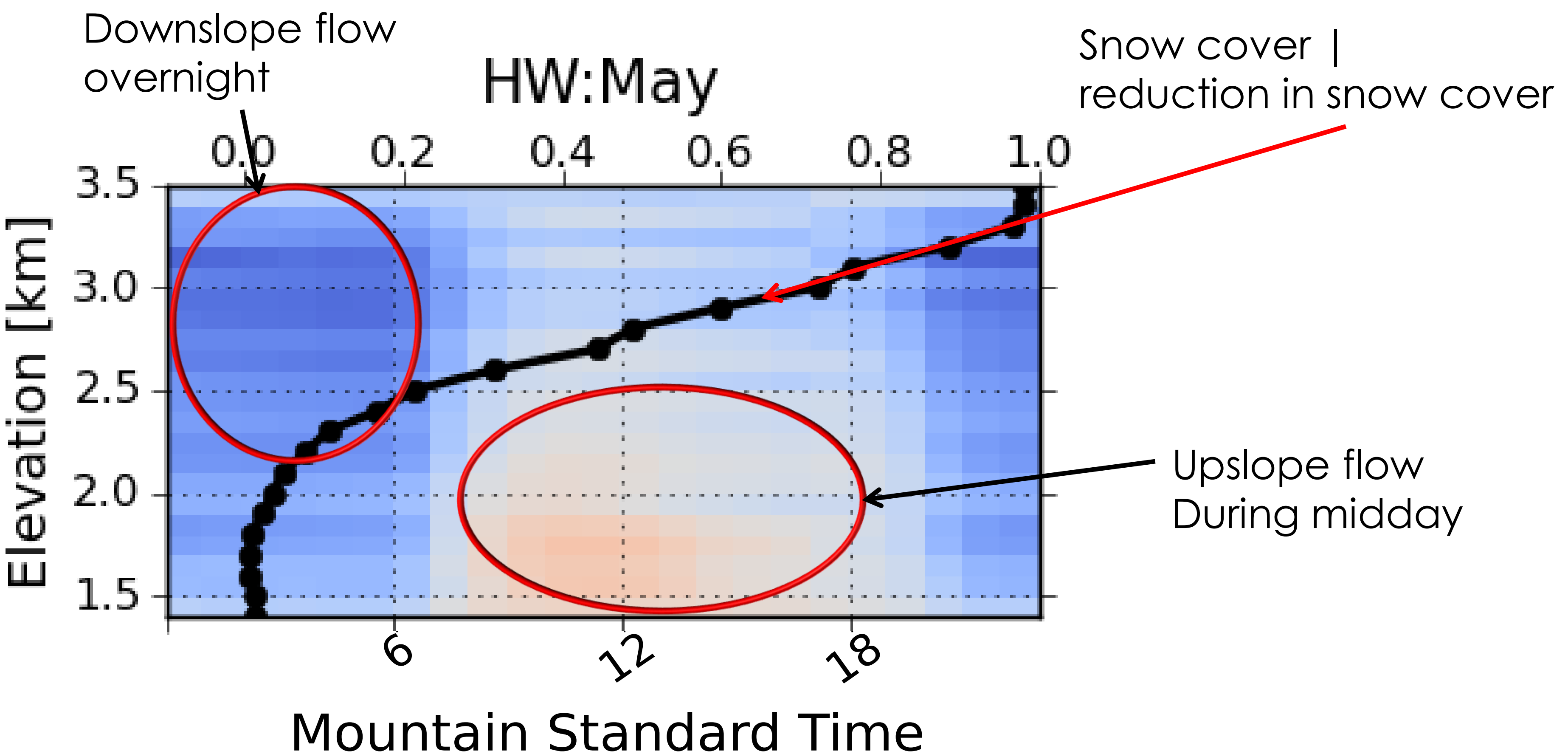
- ΔV well aligned with ΔPGF
  - ΔPGF correlated with increased thermal contrast
- PBLH↑ with SAF : ΔV does not reflect synoptic wind

Upslope Flow: Elevation vs. Time

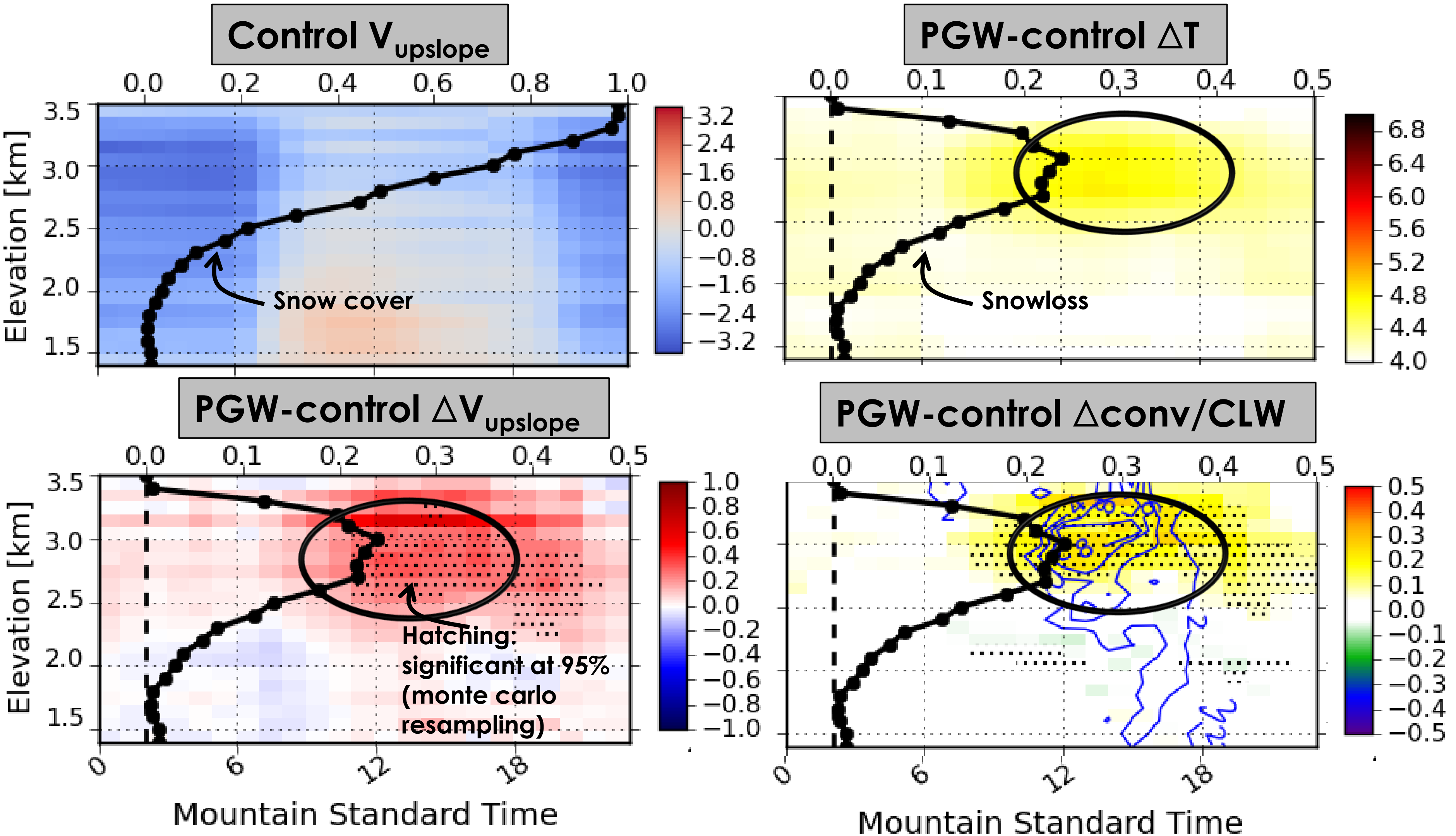
- Project wind vectors onto terrain gradient
  - Normalizes for differences in slope aspect and wind direction
- Bin data as a function of time and elevation
- Average over the Uintah Region
  - Upslope Flow
  - Warming
  - Convergence
  - Integrated cloud water

$$V_{upslope} = \frac{\vec{V}_{10m} \cdot \vec{\nabla} h}{|\vec{\nabla} h|}$$

Elevation vs. Time: $V_{upslope}$ Control

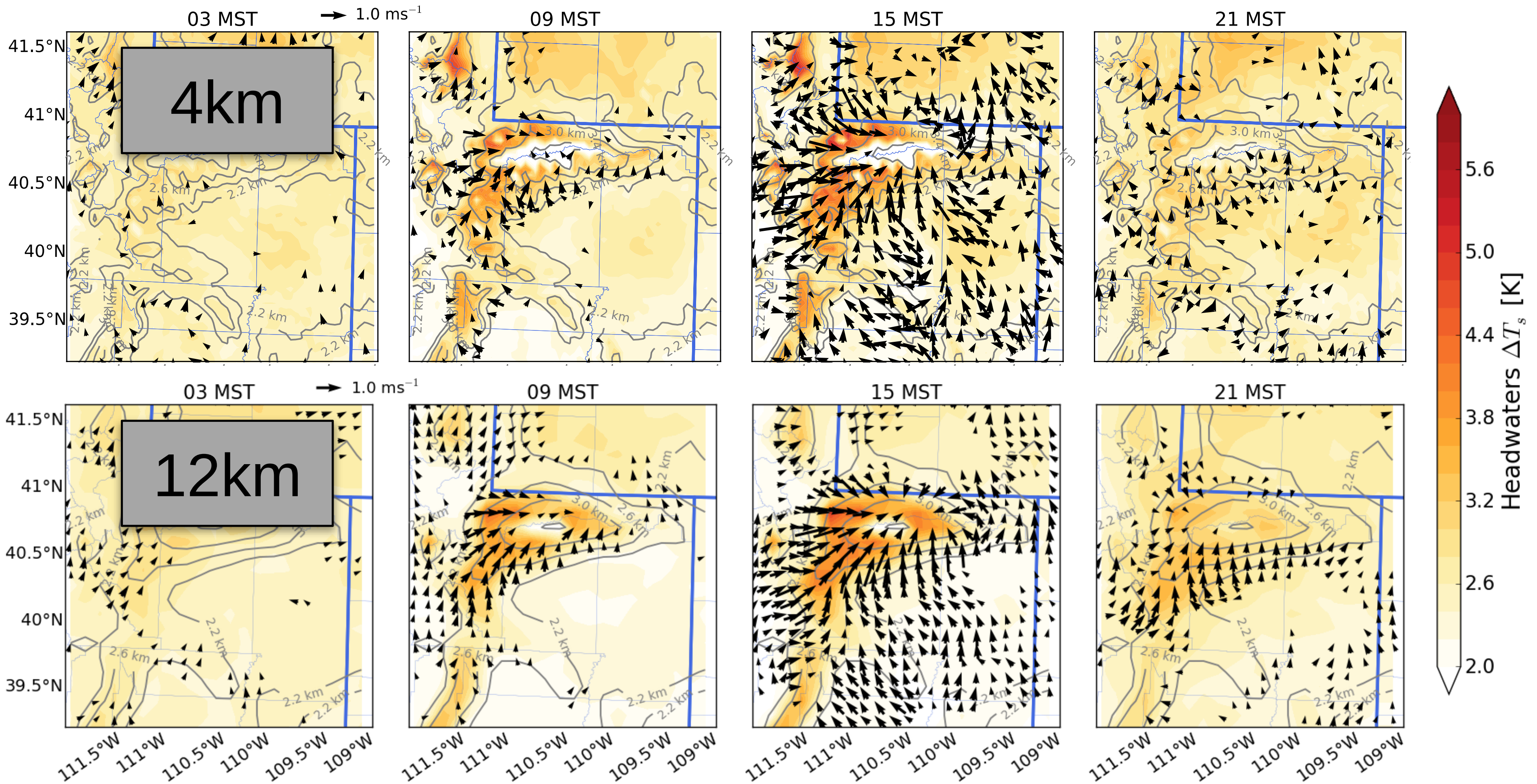


Elevation vs. Time: May (Headwaters)



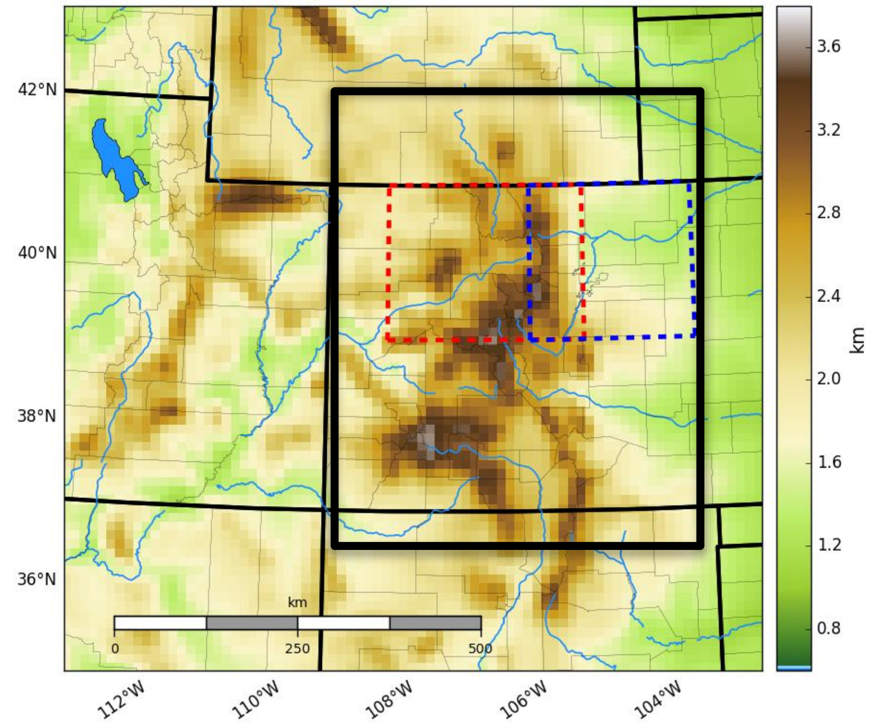
Mountain Breezes at 12km resolution

12km reproduces the broader features seen in the 4km simulations

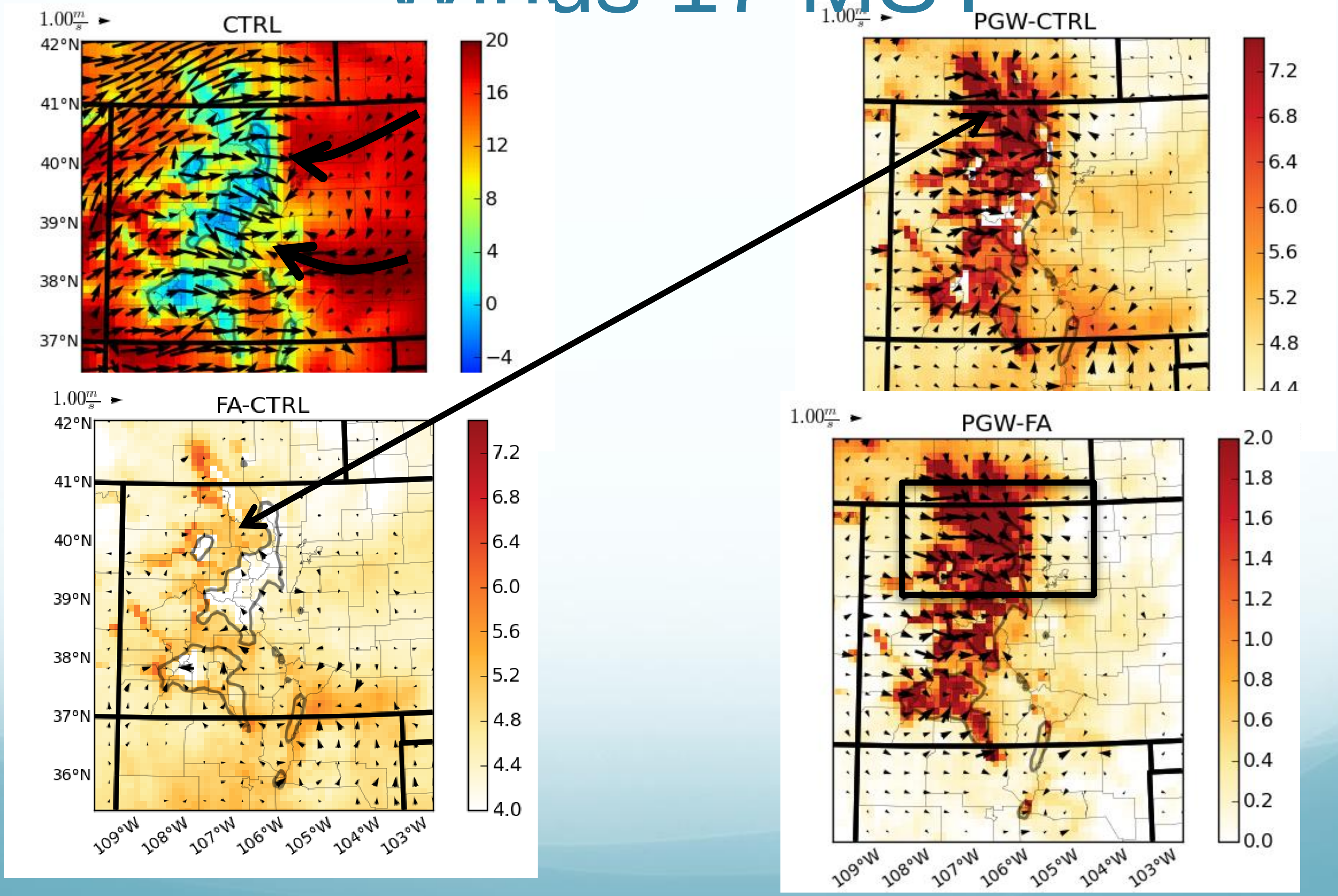


12km simulations

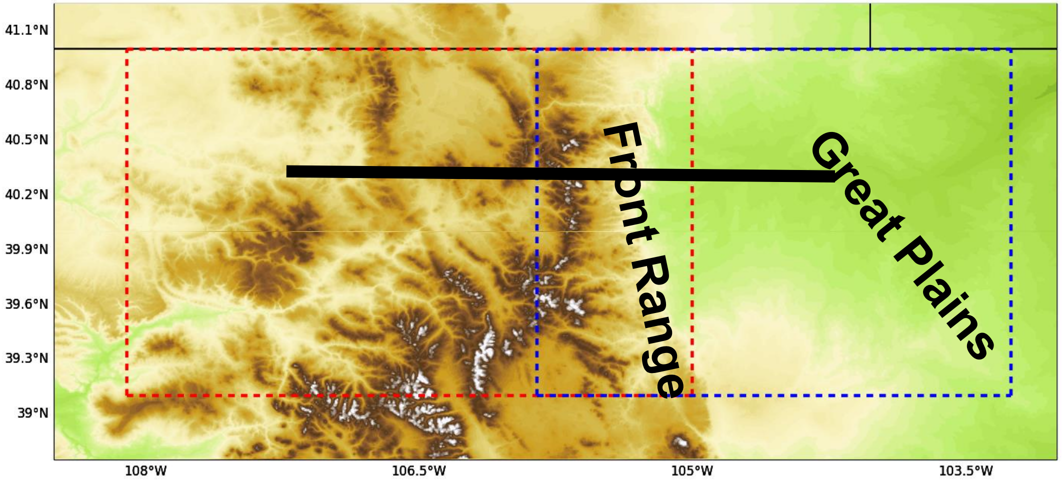
- **Same domain as Headwaters simulation**
- **Three simulations:**
  - Control , PGW, Fixed Albedo (FA)
- **NOAH LSM**
- CMIP5 ensemble RCP 8.5 Forcing
  - **Same forcing as CONUS Runs (Liu et al. 2016)**
- **Betts-Miller-Janjic convective parameterization**
- **Fixed Albedo experiment**
  - PGW boundary forcing
  - Albedo fixed to control simulation
  - Climate change experiment without the SAF
- **Analysis shifted to Colorado Rockies**
  - **April response**
  - **Same "synoptically weak filtering as control"**
  - **Preliminary: 2002-2006 mean**



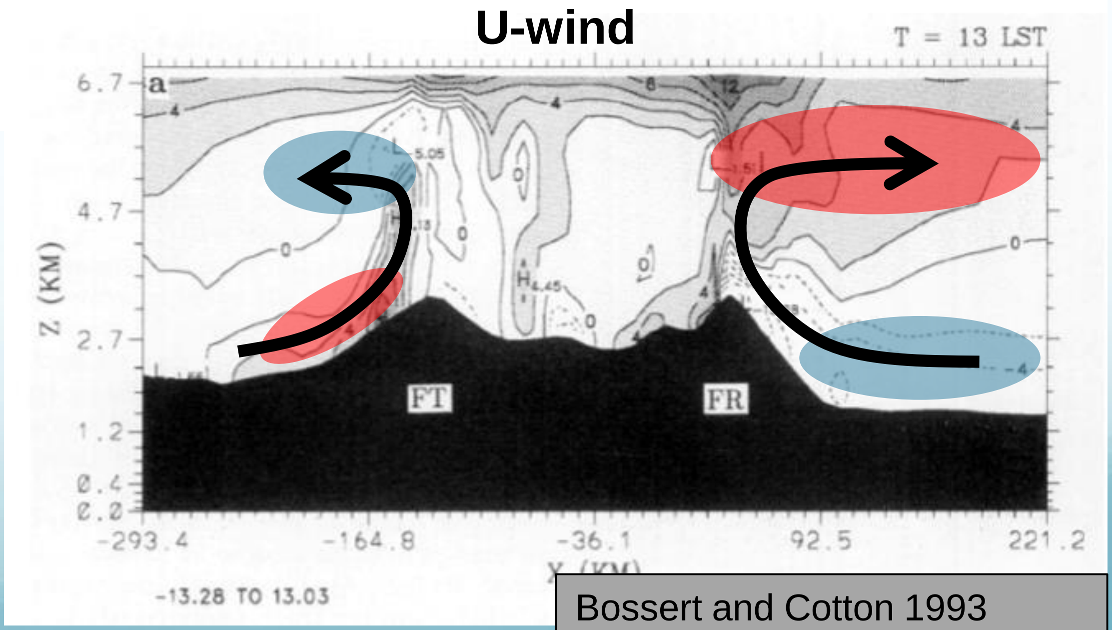
12km April warming and Winds 17 MST



Front Range Mountain Range Circulation



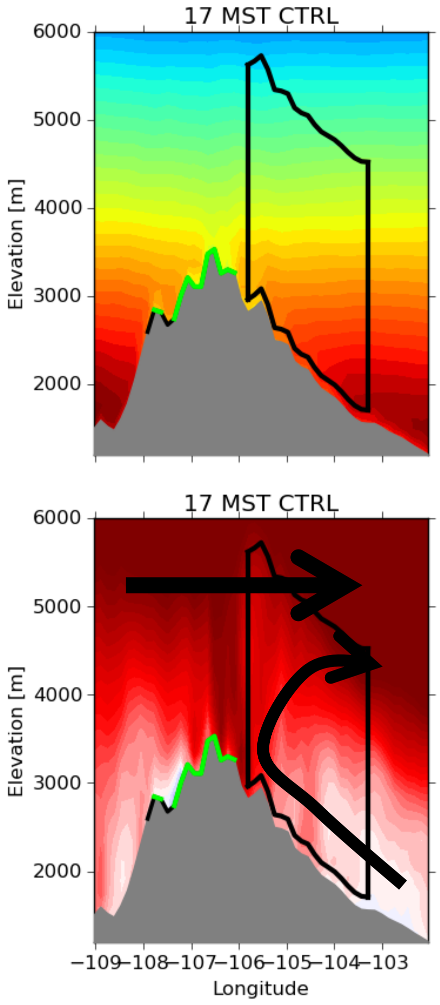
Blue: Easterly
Red: Westerly



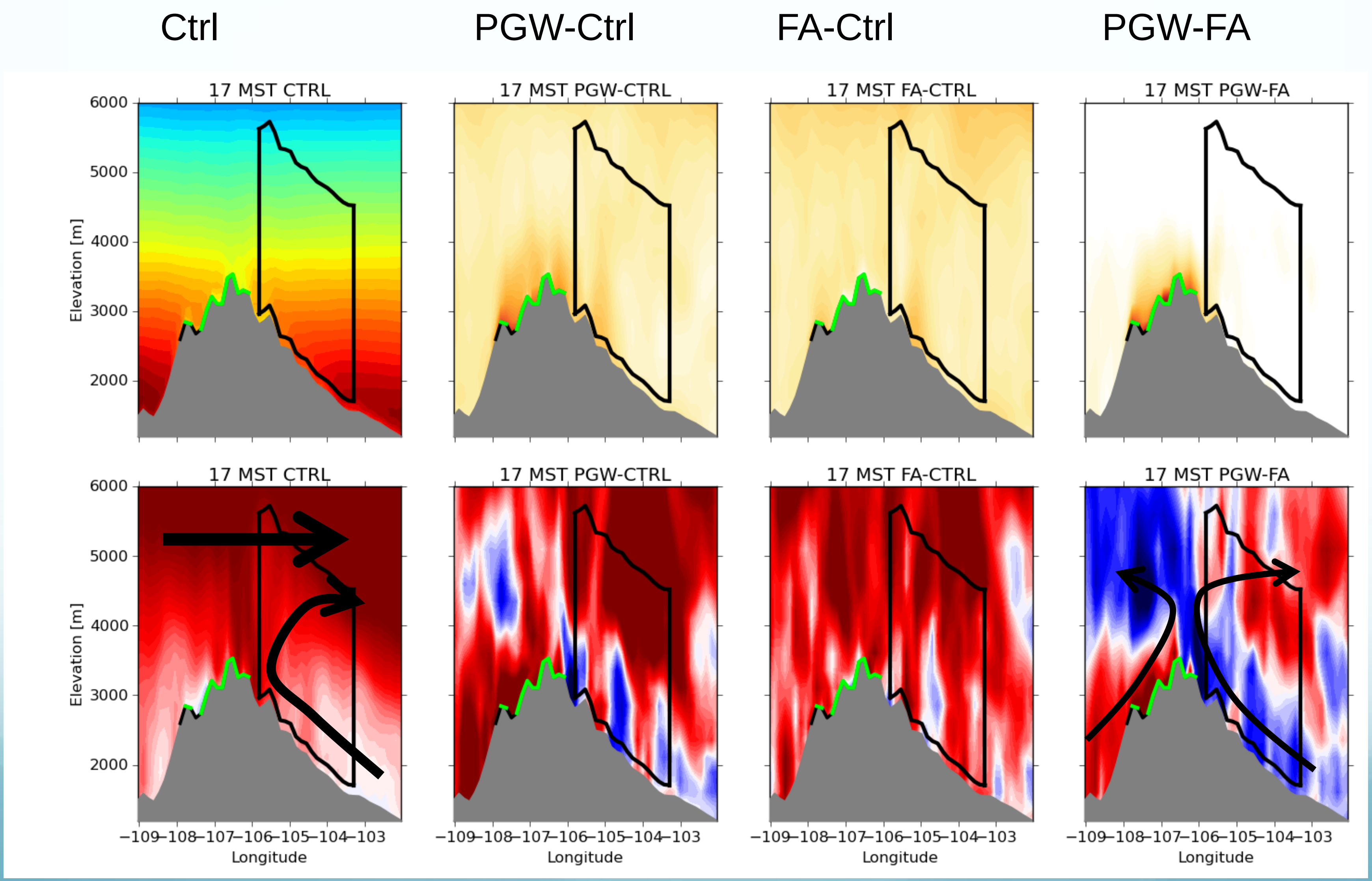
Bossert and Cotton 1993

April mean FRMC

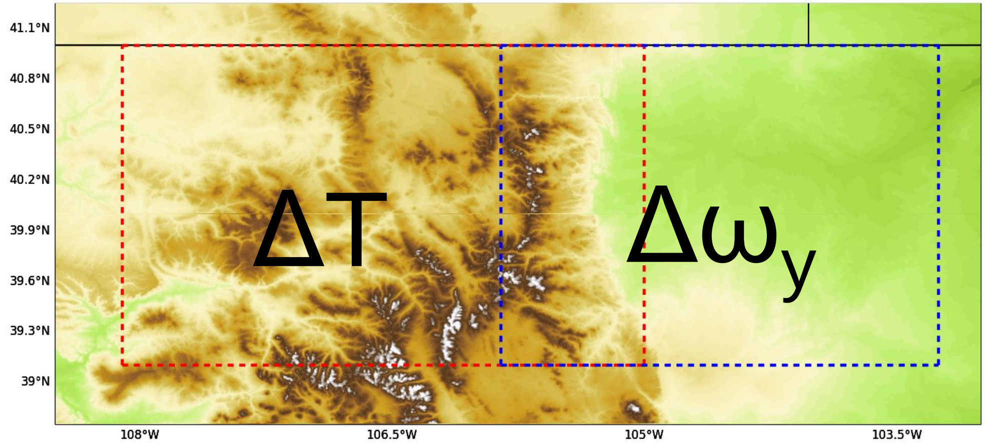
Ctrl PGW-Ctrl FA-Ctrl PGW-FA

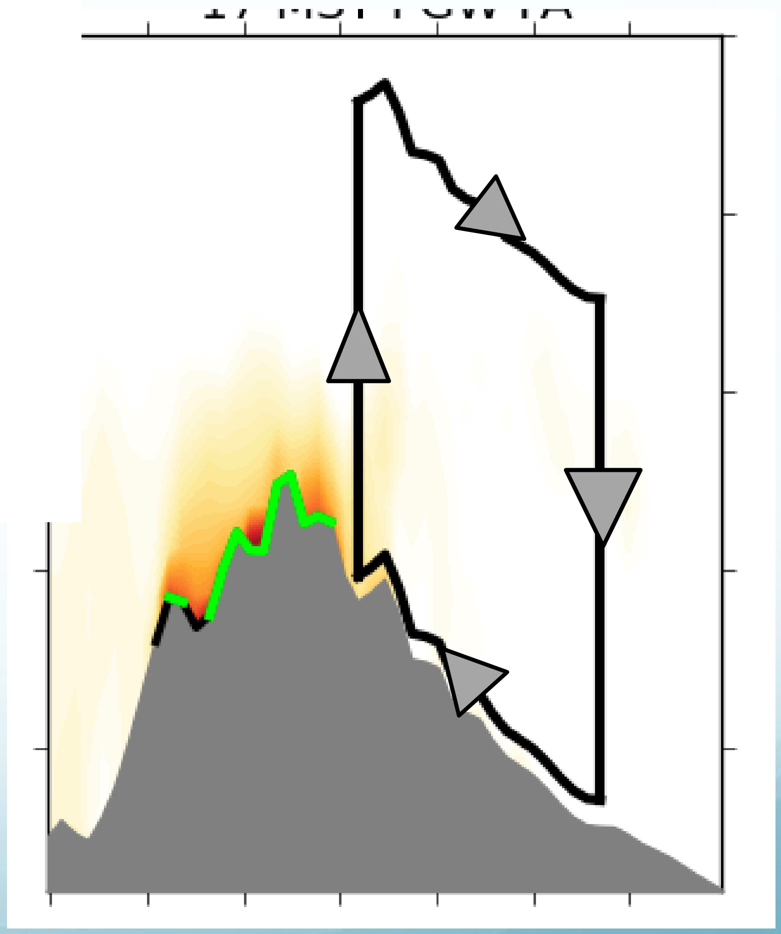


April mean FRMC



FRMC vs. ΔT

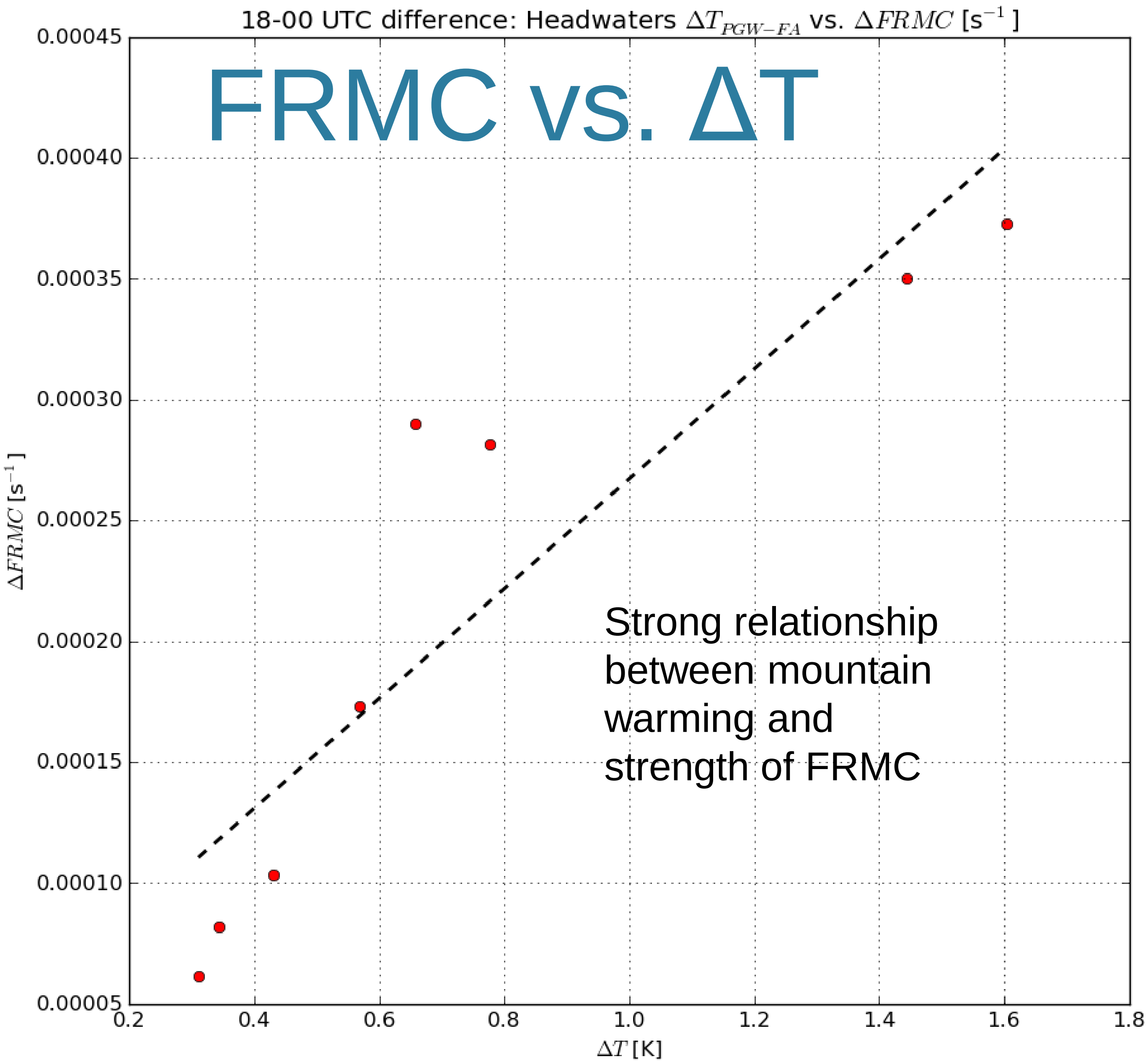




Stokes' Theorem: C = Average Vorticity

$$\frac{\partial u}{\partial z} - \frac{\partial w}{\partial x}$$

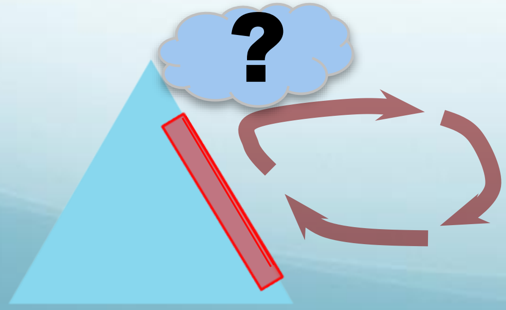
FRMC vs. ΔT



Strong relationship between mountain warming and strength of FRMC

Conclusions

- SAF increases regional variability of warming particularly during the daytime
- Changes in the thermal contrast (ΔT) between the mountains and lowlands increased the strength of daytime upslope flow and decreased the strength of overnight downslope flow
  - Increased convergence and cloudiness
  - Increased Boundary Layer mixing secondary to thermal contrast



Conclusions (2)

- 12km is sufficiently high resolution to simulate changes in diurnal circulations over broad regions.
- SAF is responsible for most mesoscale variability of warming
- Influences the large scale FRMC mountain plain circulation