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Addressing Snowmelt Biases over Glacier National Park in a Variable-Resolution Configuration of CESM

Kyle Nardi
Postdoc at NSF NCAR
LMWG Meeting
Tuesday, February 24, 2026

Thank you to my collaborators!

Christine Shields

Adam Herrington

Will Wieder

Andy Newman

Andy Wood

Alan Rhoades (LBNL)

Colin Zarzycki (PSU)

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November 2006 Flooding in Glacier NP

- Rain-on-snow flooding event: **November 6-8, 2006**
- Going-to-the-Sun Road and Many Glacier Hotel damaged
- More than $5 million (2006 dollars) in repair costs
- *"It's a big, big hole…It's significant because there's no material. Everything's gone."* – Ranger Matt Graves

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Why does this matter?

National Parks and public recreational lands are sources of:

- Health benefits (physical and mental) for visitors
- Economic benefit for communities surrounding parks
- Important natural resources to sustain life
- Preservation for a variety of cultural resources
- National pride and morale

We want to use Earth System Models to help local communities protect public lands from extreme weather

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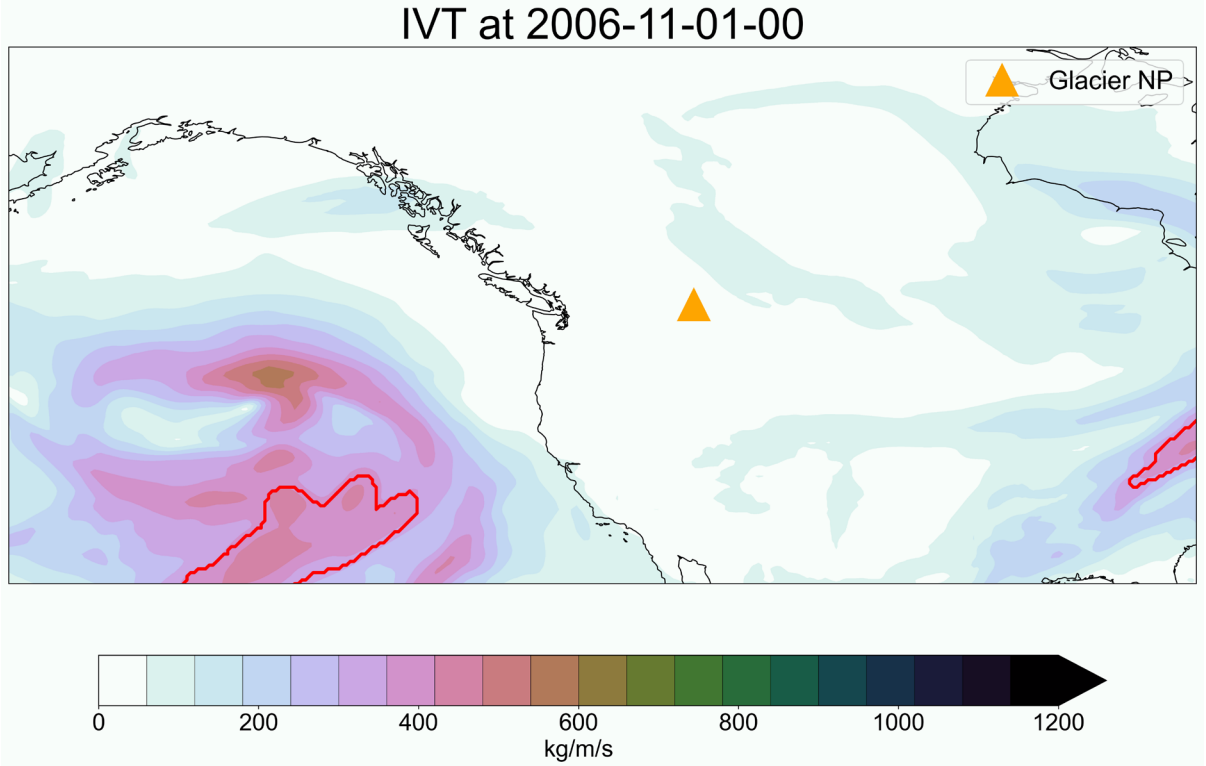
Ingredients for a Flooding Event

- A family of atmospheric rivers (ARs) with high water vapor transport

ARs typically bring:

a) Warm temperatures
b) Strong winds
c) Heavy precipitation

Red outline indicates the presence of a detected AR



Water Vapor Transport from ERA5

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Research Objectives

1. To determine how well an Earth System Model (CESM) can depict key physical processes (land, atmosphere, and river) driving the November 2006 rain-on-snow flooding in Glacier NP

2. Using an Earth System Model, can we determine how this same storm would impact Glacier NP, and nearby communities, under a range of plausible future scenarios?

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Variable-Resolution ESM Setup

Basic Details:

- Community Earth System Model version 3 (CESM3)
- “Hindcasts” initialized with ERA5 and NOAA SSTs
- 12-month land spin-up with ERA5 atmospheric forcing

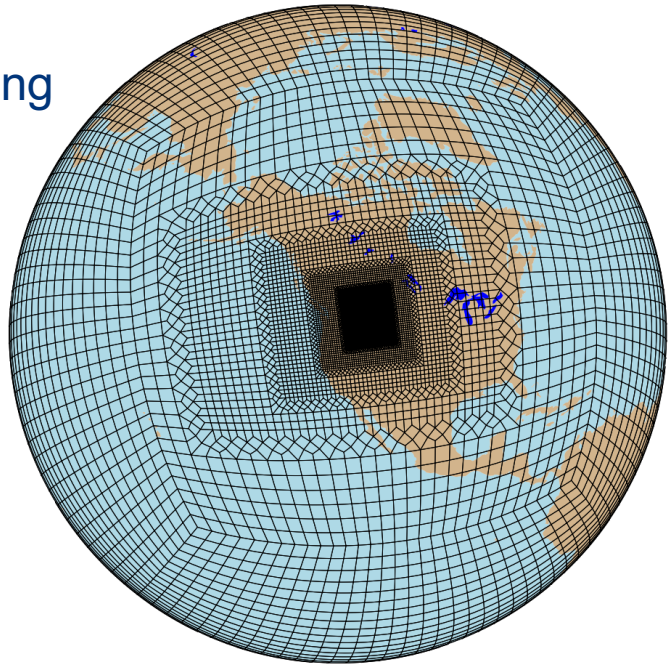
Grid:

- 58 vertical levels
- Variable-resolution SE grid
- 1 degree globally
- Refined to 1/16th of a degree over Glacier

Nudging:

- Vertical nudging of atmosphere above PBL
- Free troposphere nudged to ERA5

ne0np4.glacier.ne30x16_v3



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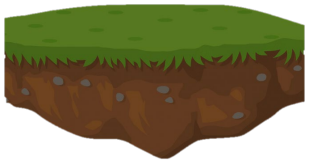
Hindcast Setup for Glacier Flooding Event

Land Spin-up:
00Z November 4, 2005

CESM3 Initialized:
00Z November 4, 2006

Event:
November
6-8, 2006



12 months

2-4 days

Land-only forced w/ ERA5

ERA5 and NOAA SSTs

Time

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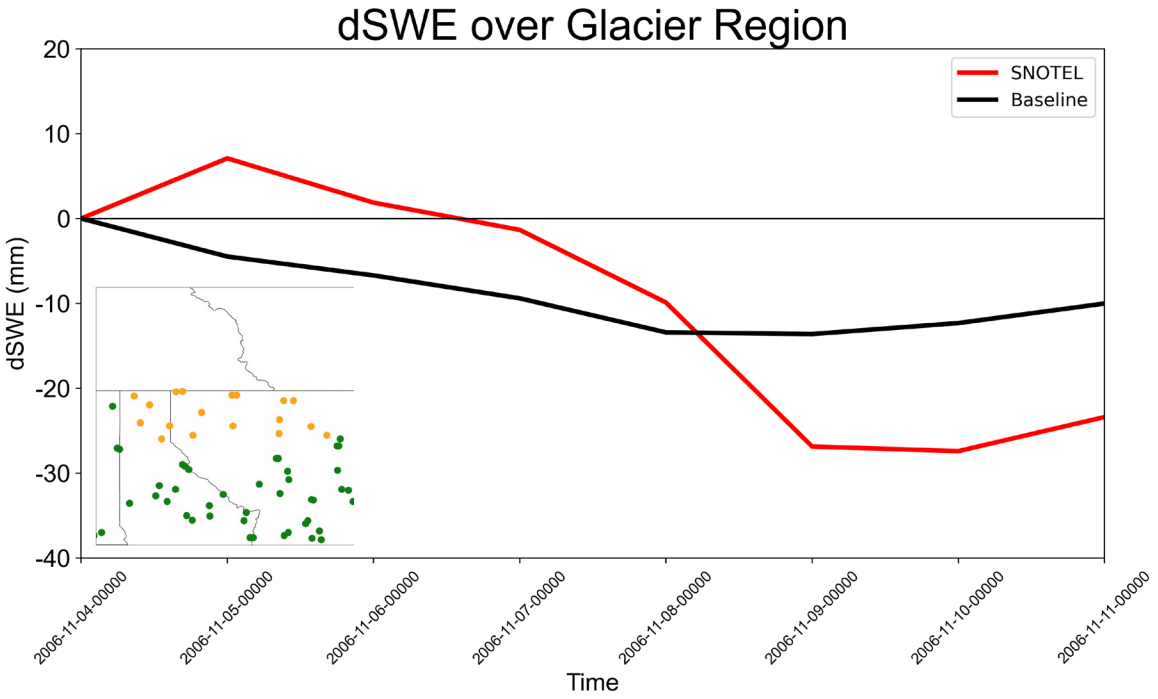
Modeled vs. Observed Impact on Snowpack

- Snow depth initializes too high at the start of the simulation **(currently working on this!)**
- When the rain-on-snow event occurs, **there isn't enough snowmelt** compared to SNOTEL observations



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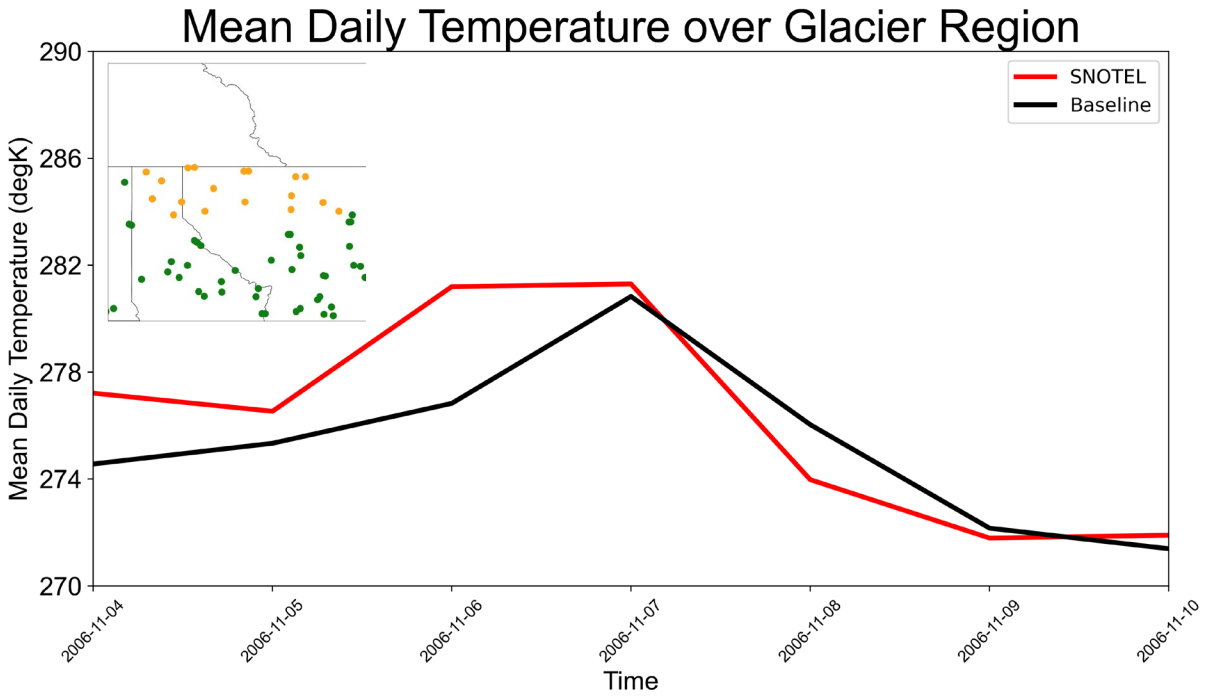
Modeled vs. Observed 2m Temperature

- 2m temperature in CAM is consistently too cold leading up to event
- We hypothesize that the cold near-surface air is **preventing sufficient snowmelt during the event**



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How can we address these biases?

Can the tuning of parameters in the atmosphere and land models improve modeled snowmelt?

As a proof-of-concept, we'll increase a turbulent mixing parameter (c_{k10}) to enhance momentum flux and vertical mixing in the atmosphere

Hypothesis: Enhanced vertical mixing will impact thermodynamic profiles in the boundary layer, thus affecting fluxes of heat into the snowpack

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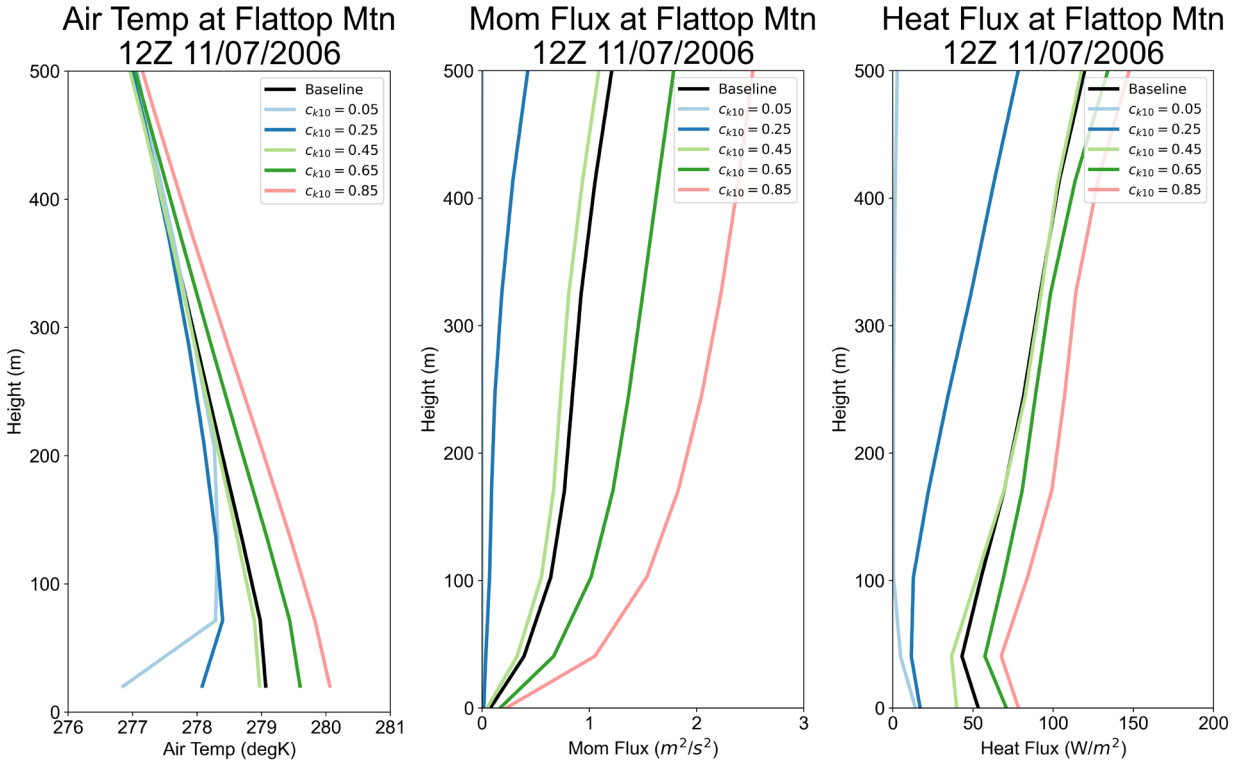
Influence of Mixing Parameter on Vertical Profiles

- **Increasing the mixing parameter effectively enhances momentum flux over Glacier NP (middle panel)**
- This results in more effective downward mixing of warmer air aloft, **thus potentially affecting heat flux into the snowpack**



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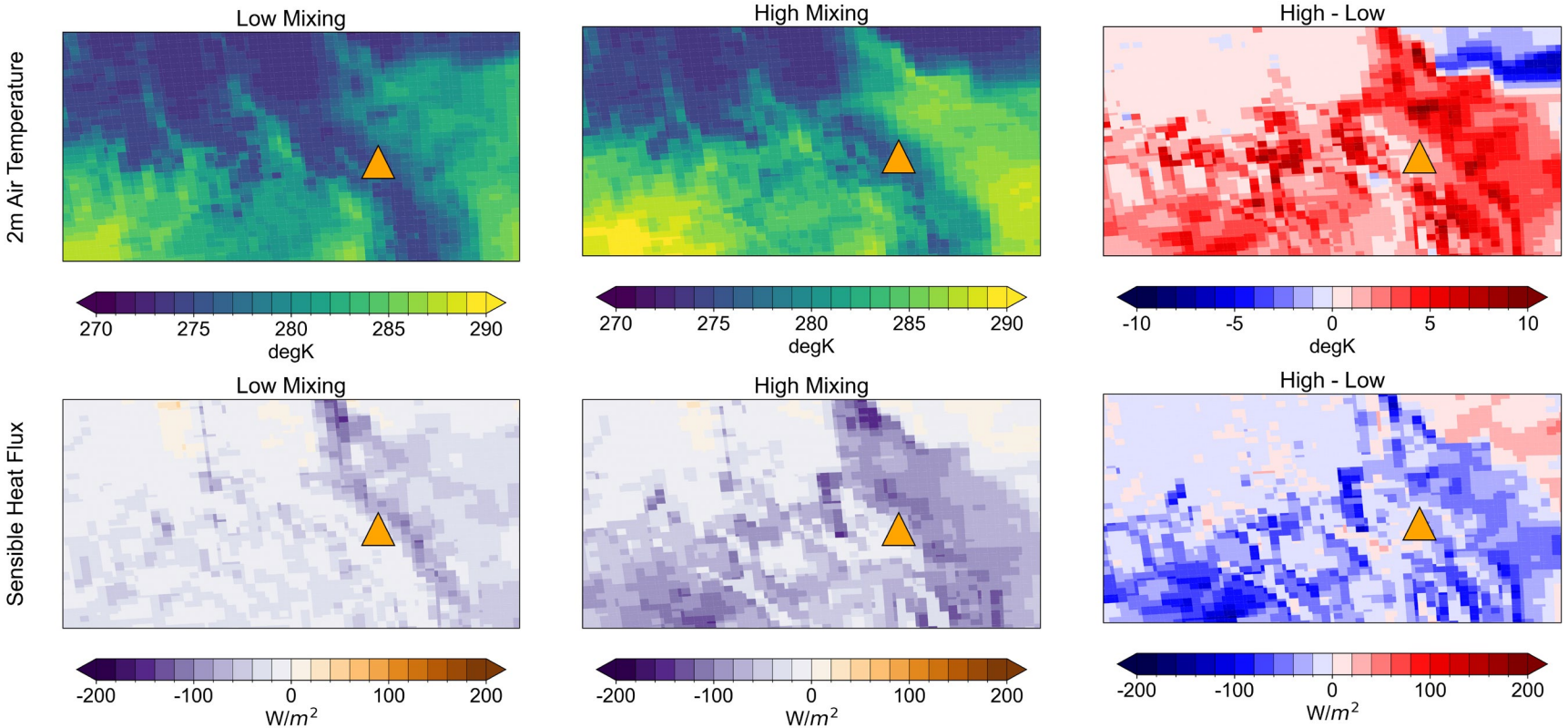
Impact of going from low to high turbulent mixing



Valid 12Z on November 7, 2006

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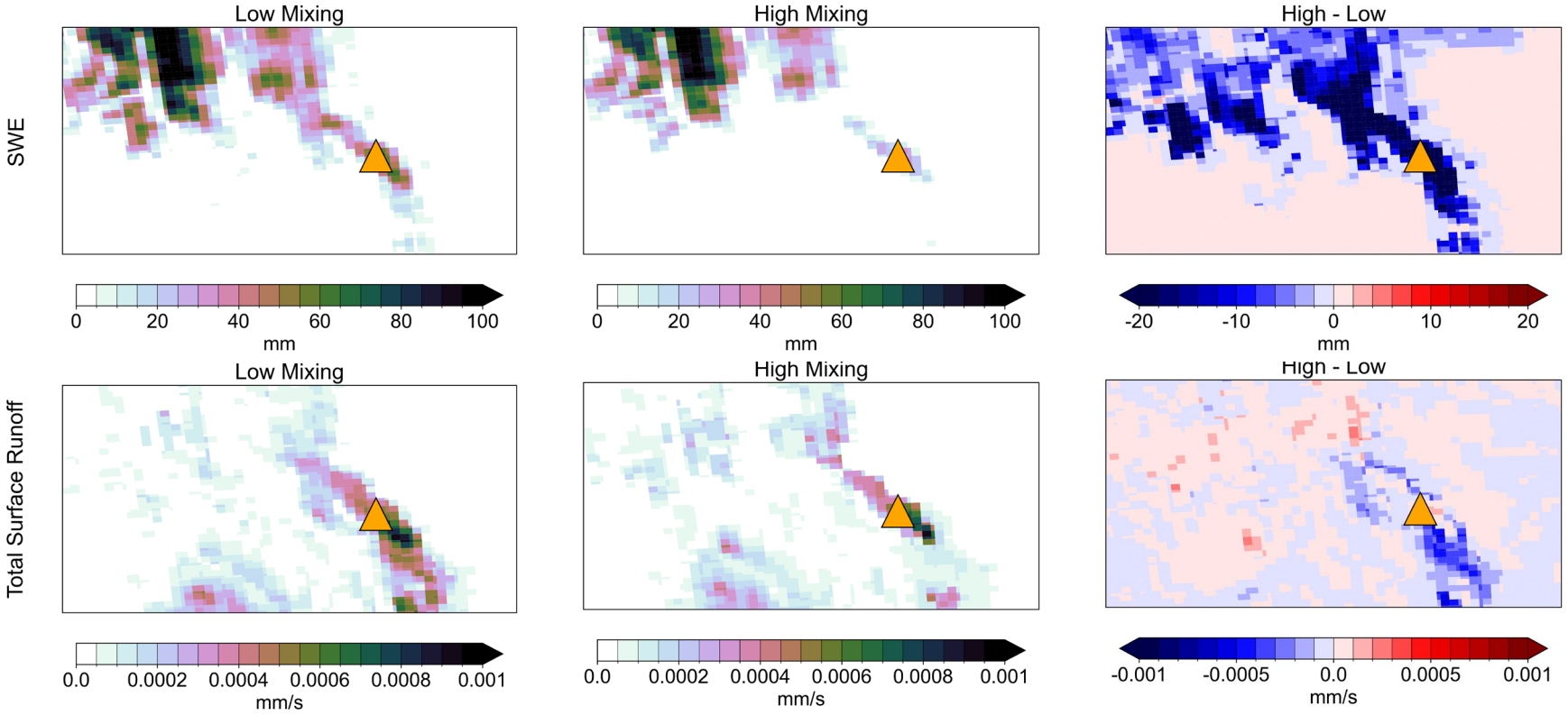
Impact of going from low to high turbulent mixing



Valid 12Z on November 7, 2006

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Where are we going with this work?

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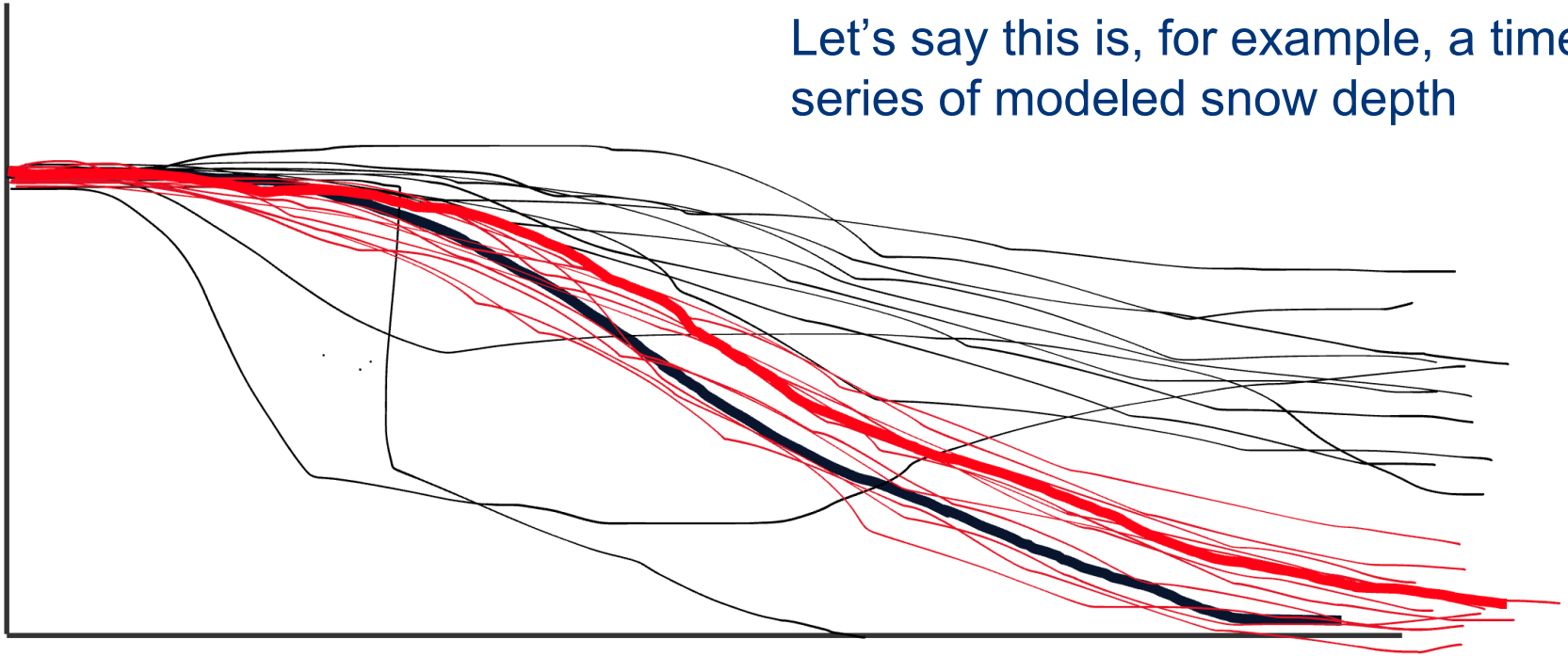
A Perturbed Parameter Ensemble in CAM…



Let’s say this is, for example, a time series of modeled snow depth

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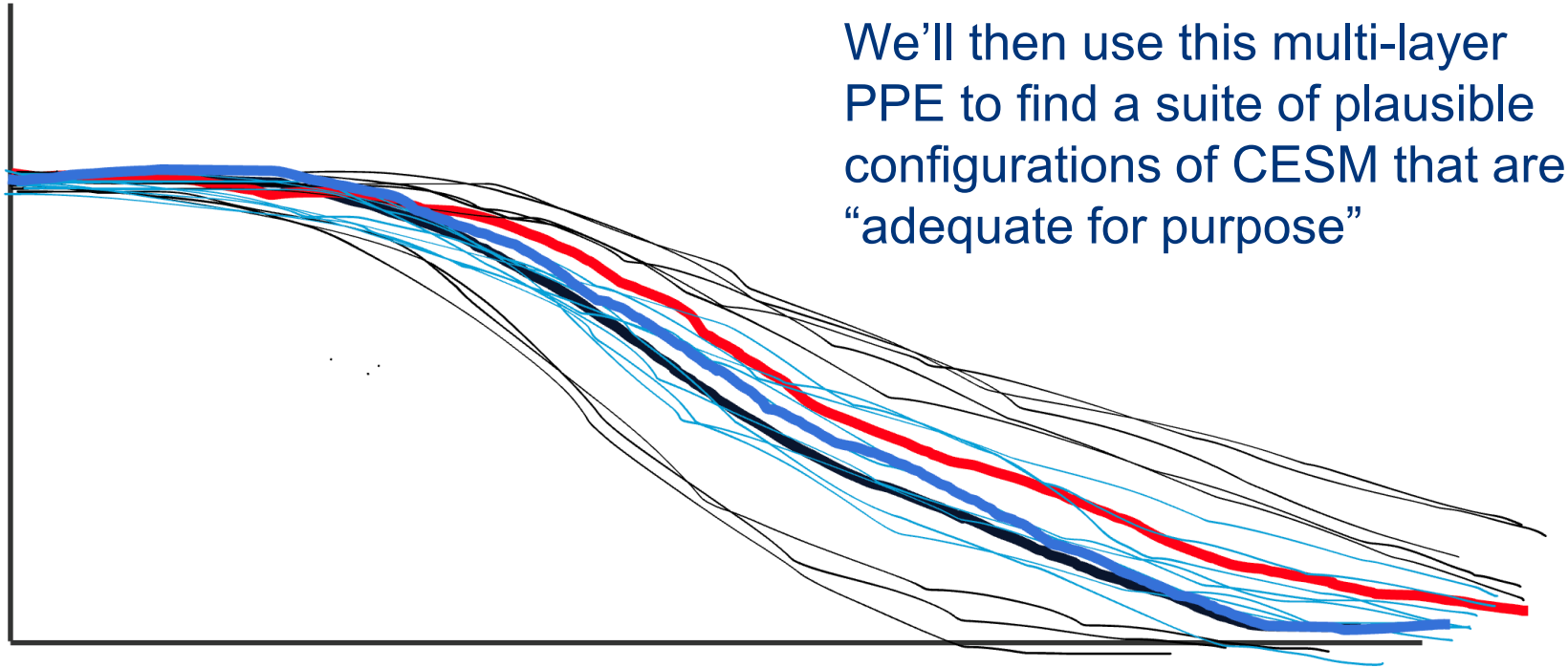
Informs a Perturbed Parameter Ensemble in CLM…



We'll then use this multi-layer PPE to find a suite of plausible configurations of CESM that are "adequate for purpose"

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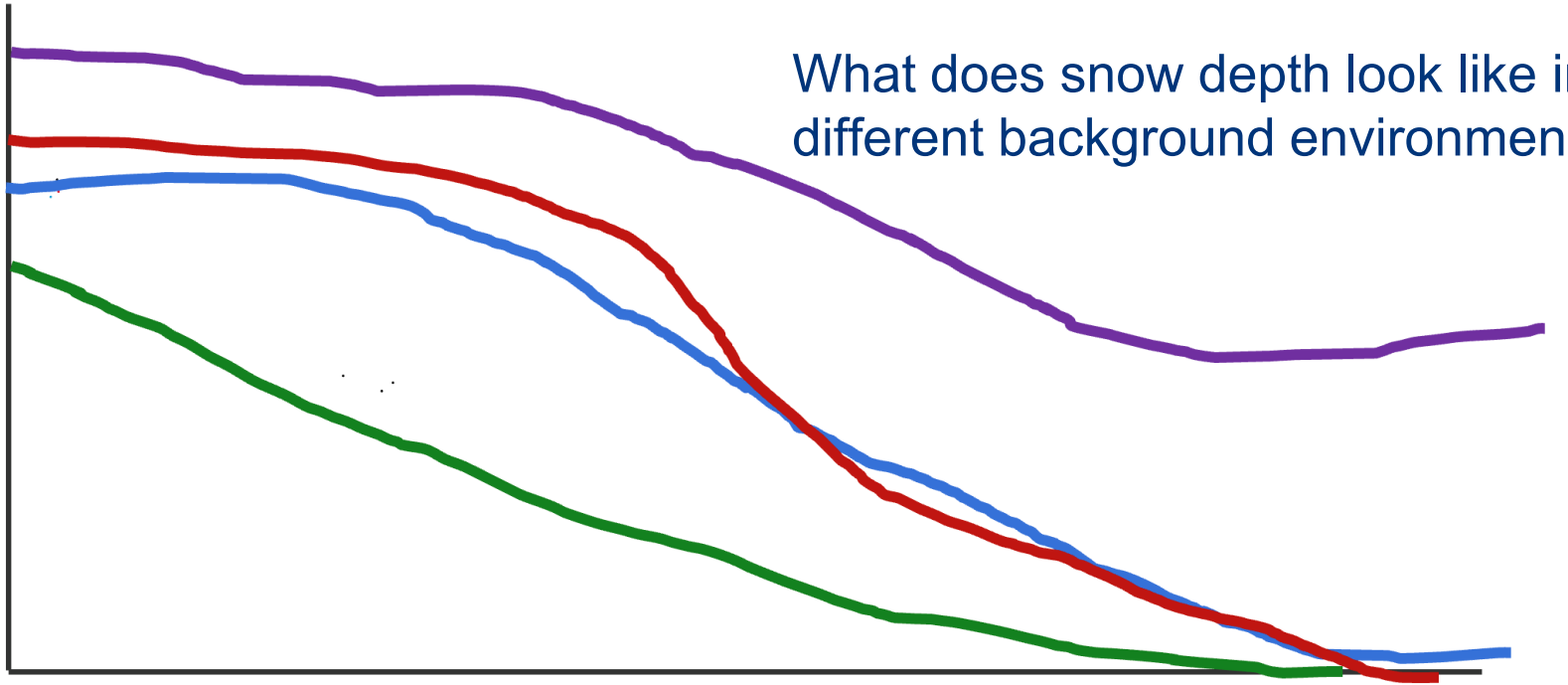
Launching counterfactual simulations



What does snow depth look like in a different background environment?

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First attempt at a CAM PPE

- 15 parameters across three CAM schemes
- Parameters have a demonstrated impact on precipitation, cloud fraction, and vertical mixing
- Latin Hypercube Sample with 150 simulations (will be adapted later)

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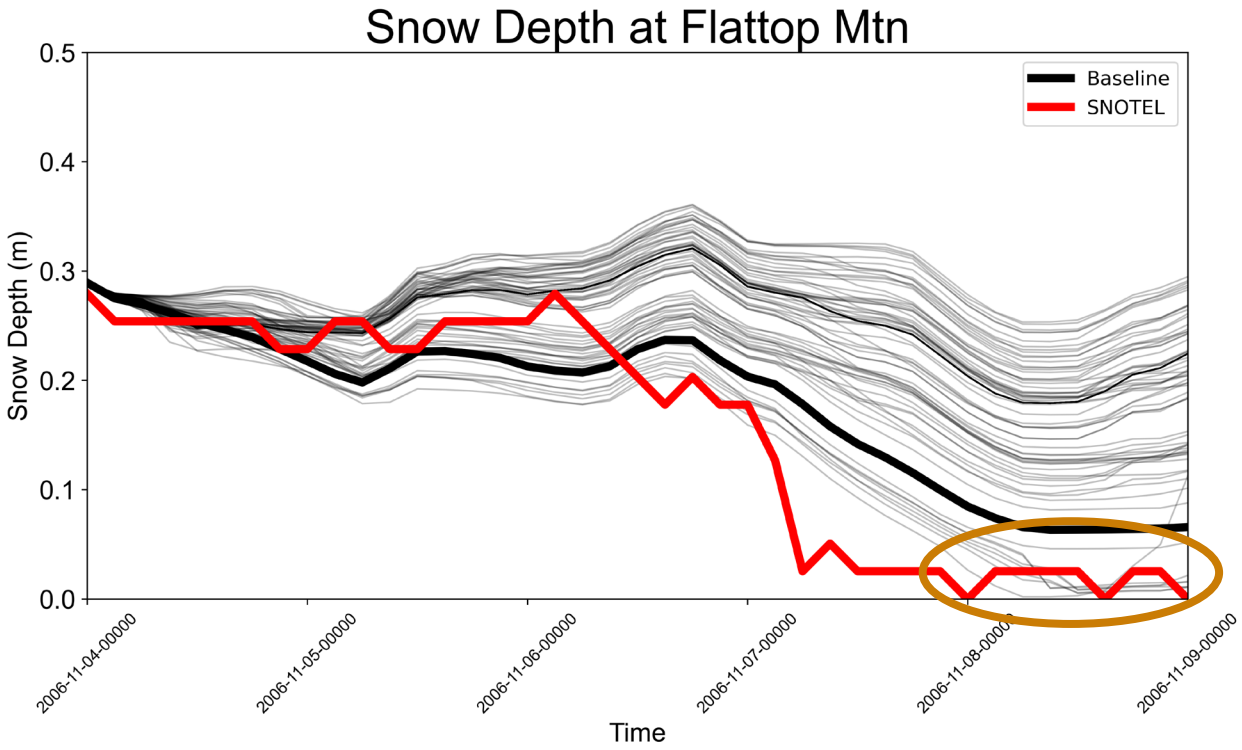
First attempt at a CAM PPE

- We get a range of different model outcomes
- There exists a cluster of configurations that appear to more effectively reduce snowpack
- **Can we use these more accurate configurations to launch a land PPE?**



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Thank you!

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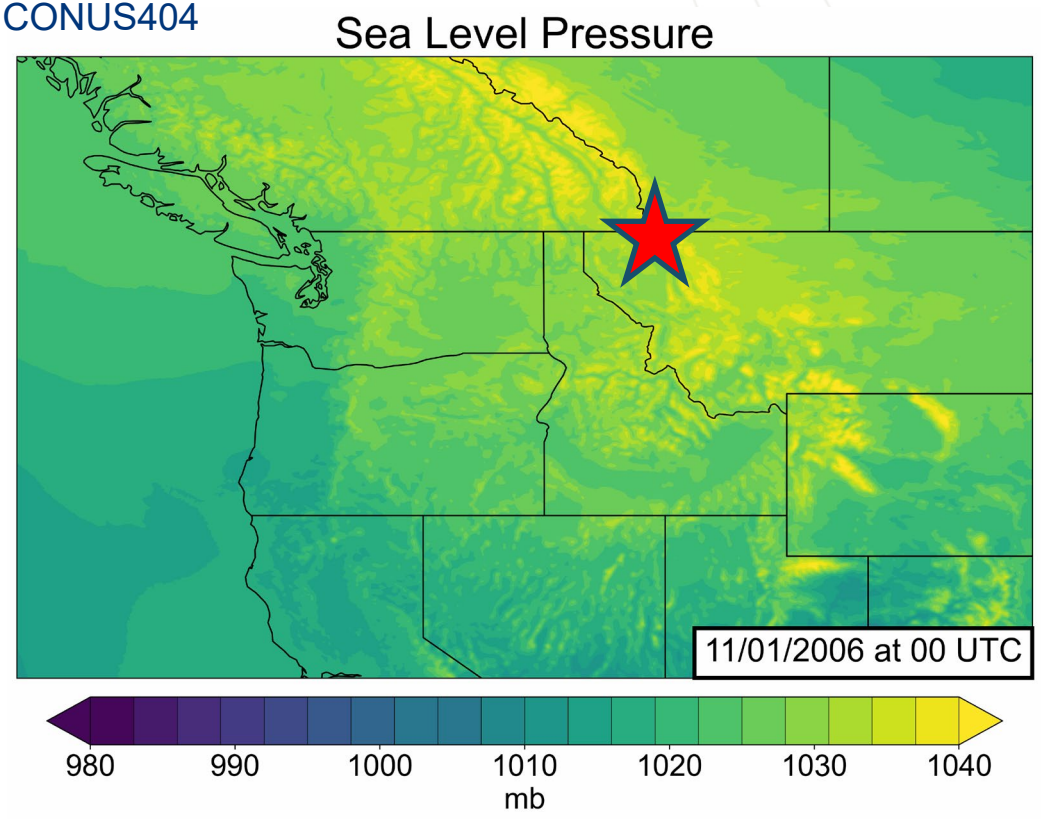
Synoptic Meteorological Conditions

From CONUS404

- Sequence of extratropical cyclones making landfall in British Columbia
- **Keep your eye on the second storm approaching British Columbia around November 6th**



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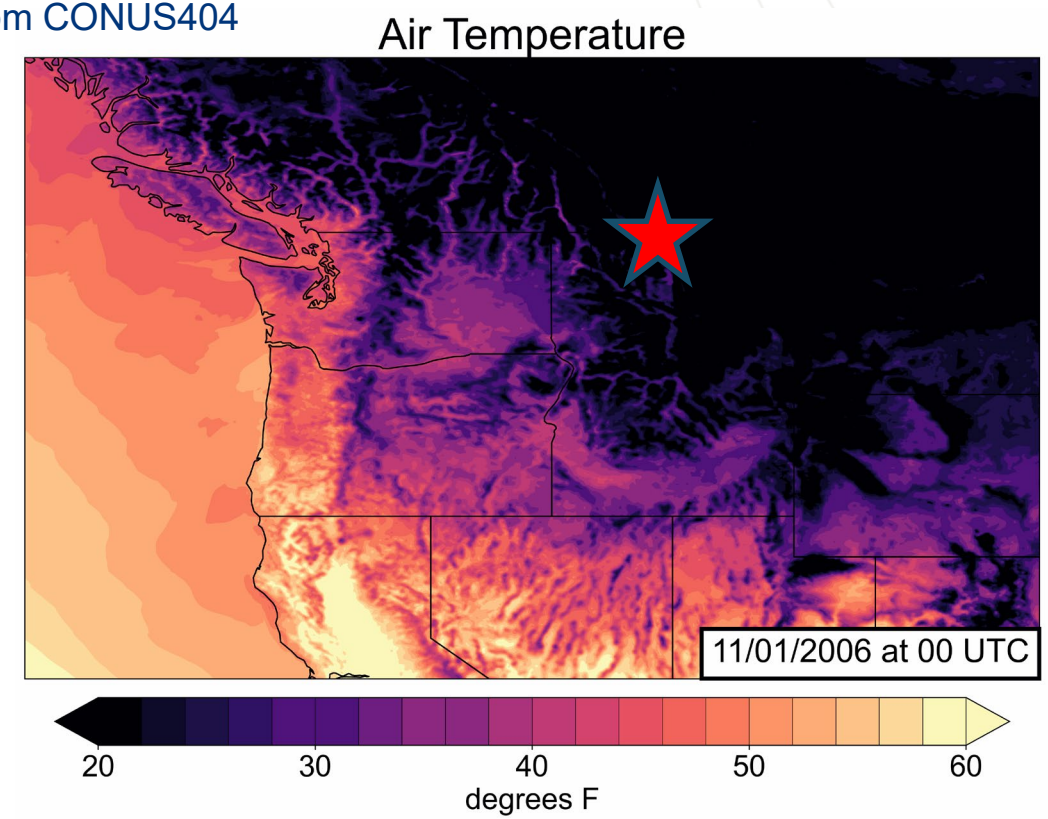
Synoptic Meteorological Conditions

- Southerly flow on the southeastern flank of the cyclone
- Anomalously warm conditions gradually build over the Mountain West

From CONUS404



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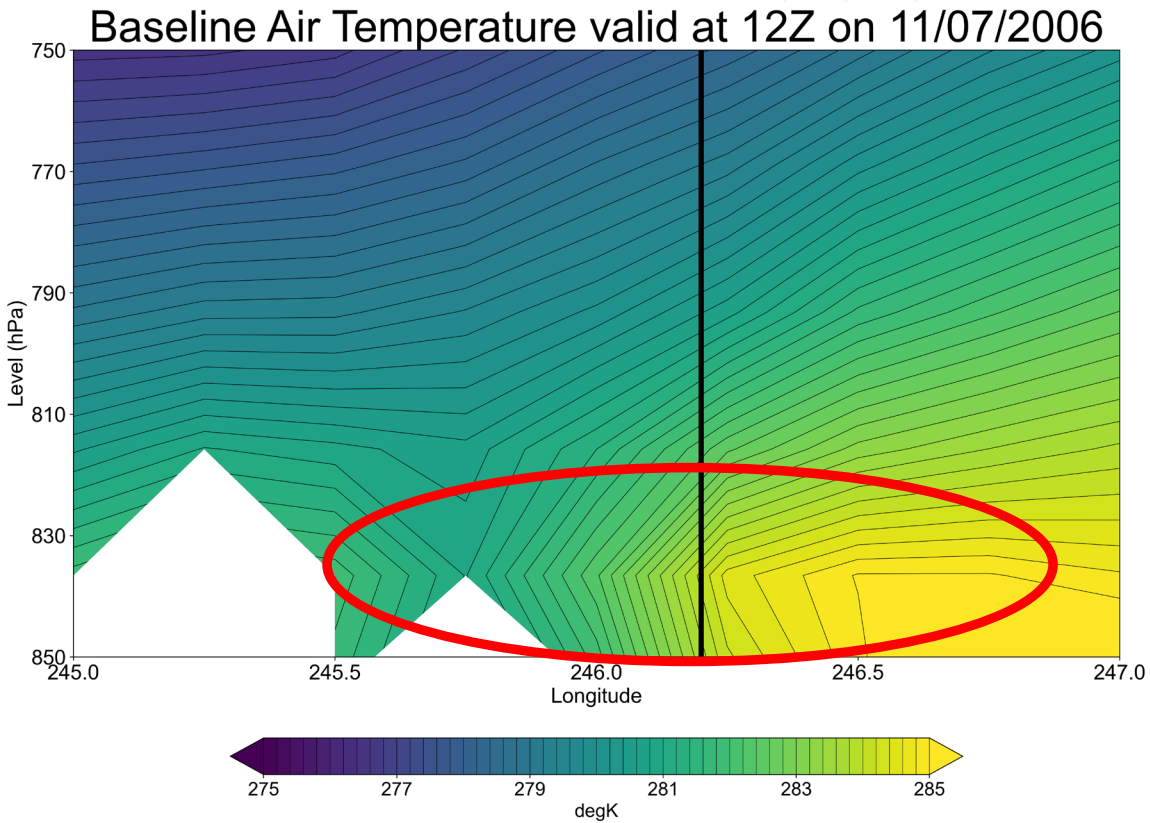
Modeled Temperature Field over Glacier Region

- Region located in sector of warm air advection on the southeastern flank of the cyclone
- **Temperature inversion exists in the lowest model levels near Glacier (black line)**



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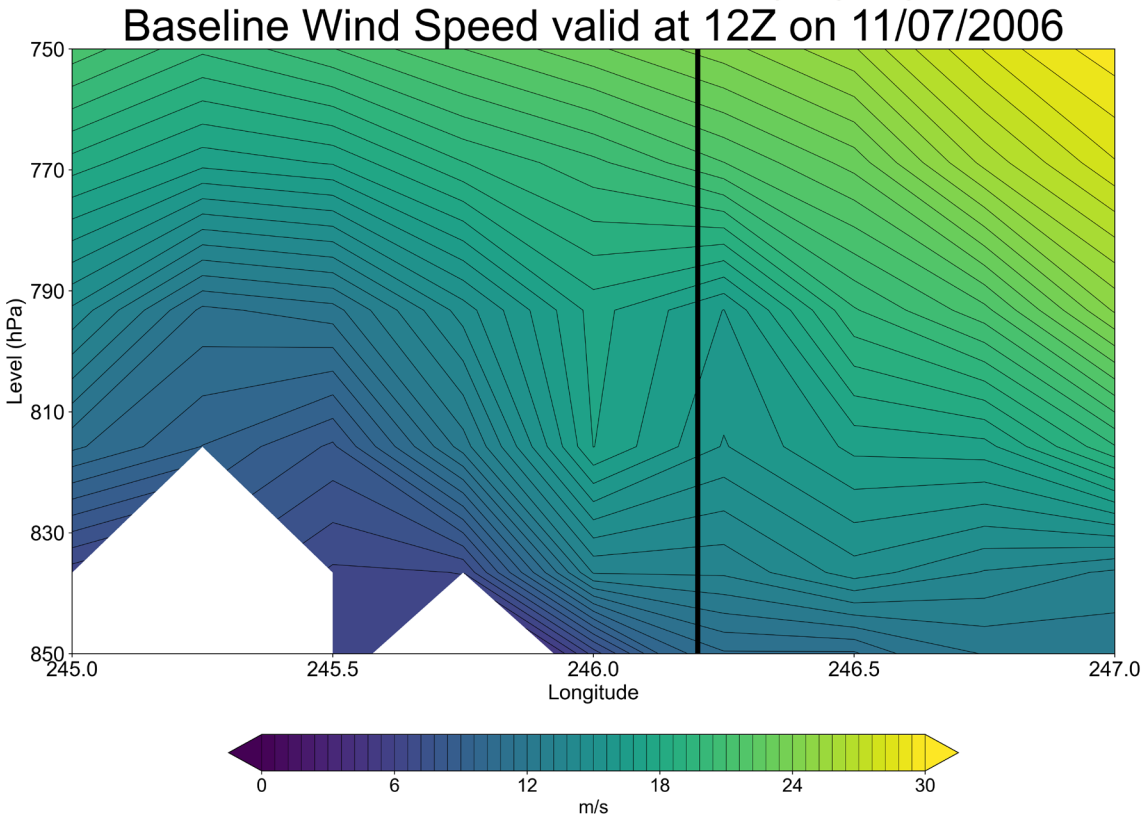
Modeled Temperature Field over Glacier Region

- Region located in a strongly dynamically-forced region with **high vertical wind shear**
- The parameterization of boundary layer turbulence in CAM has been shown to be **influential in sheared environments**



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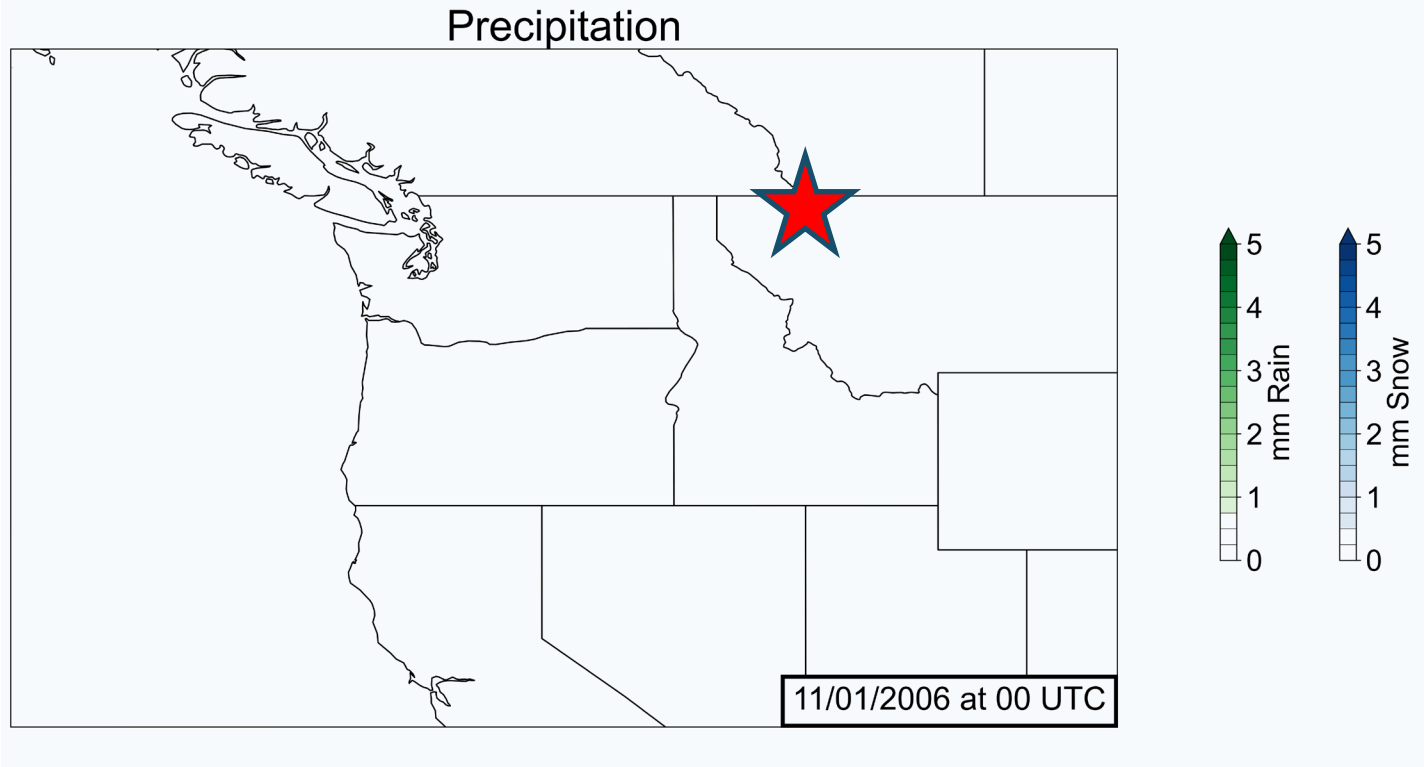
Synoptic Meteorological Conditions

- AR family brings periods of rain to western US
- **Strong AR on November 7-8 brings a prolonged period of heavy rain over western Montana**



From CONUS404

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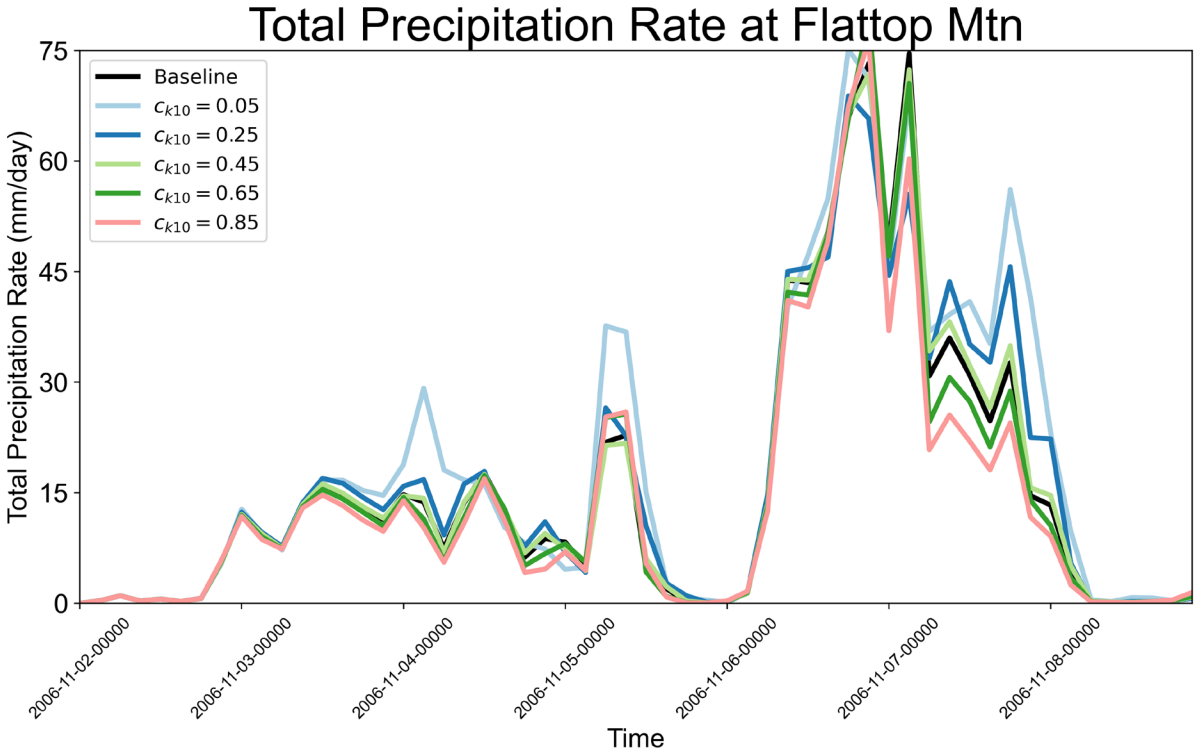
Mixing Parameter's Impact on Precipitation

- Configurations agree fairly well regarding timing of high precipitation during rain-on-snow event
- **Precipitation (falling as rain) during the event varies most on the tail end of the event**



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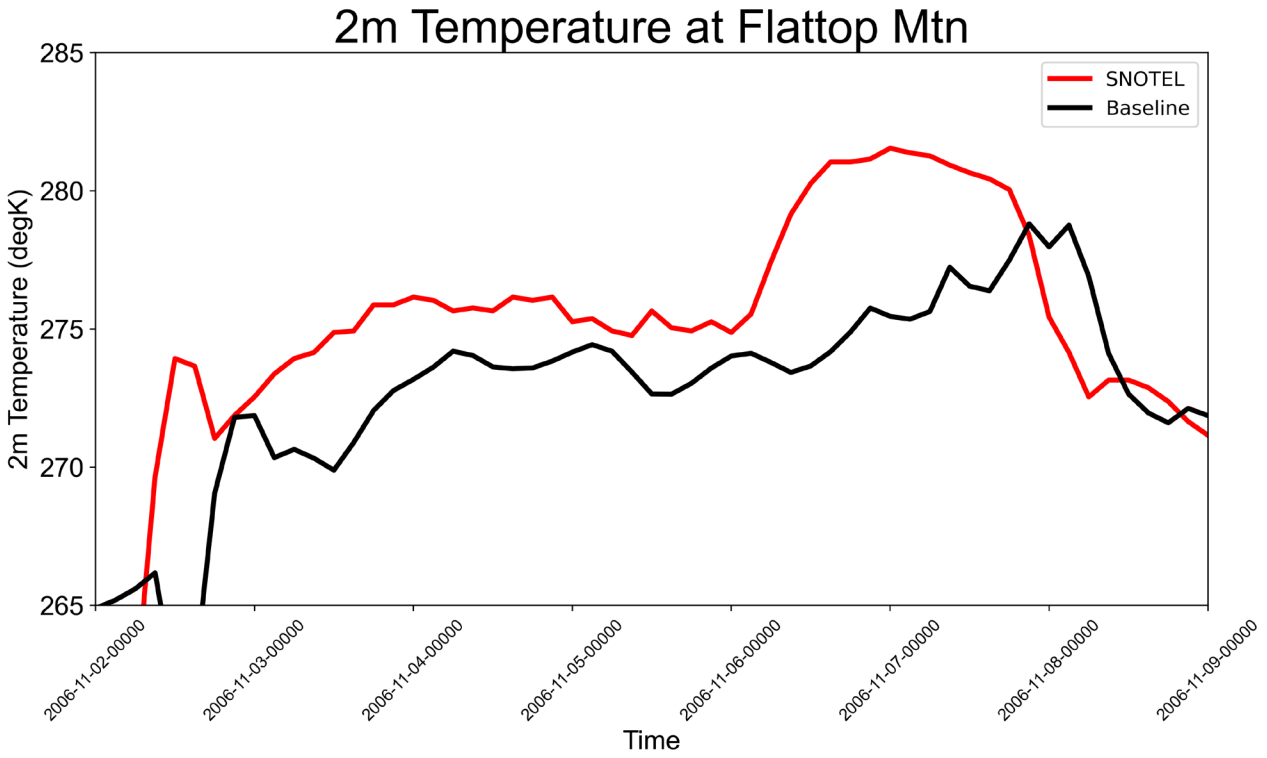

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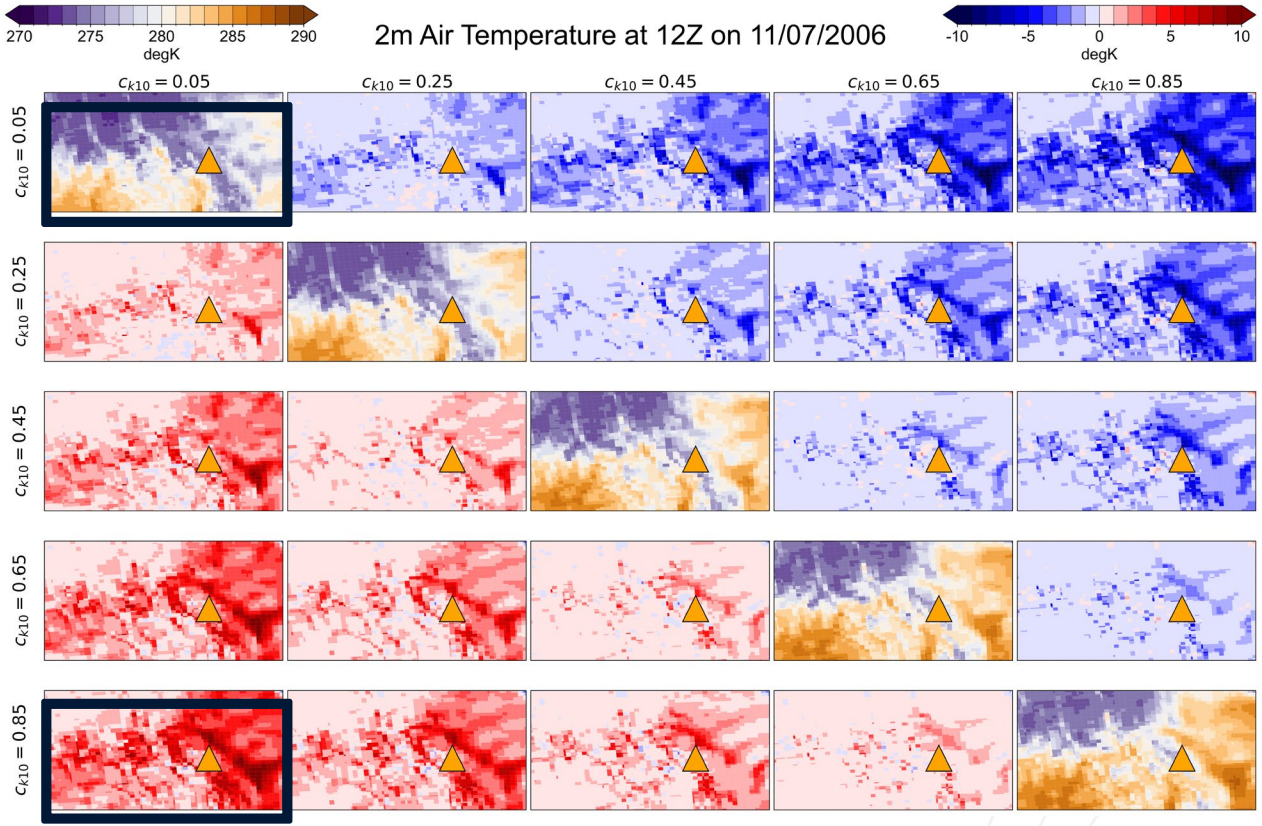
Influence of Mixing Parameter on 2m Temperature

The diagonal panels show the **configuration's modeled field**

Off-diagonal panels show the **difference between configurations: row minus column**

Configurations with higher mixing have warmer near-surface temperatures!



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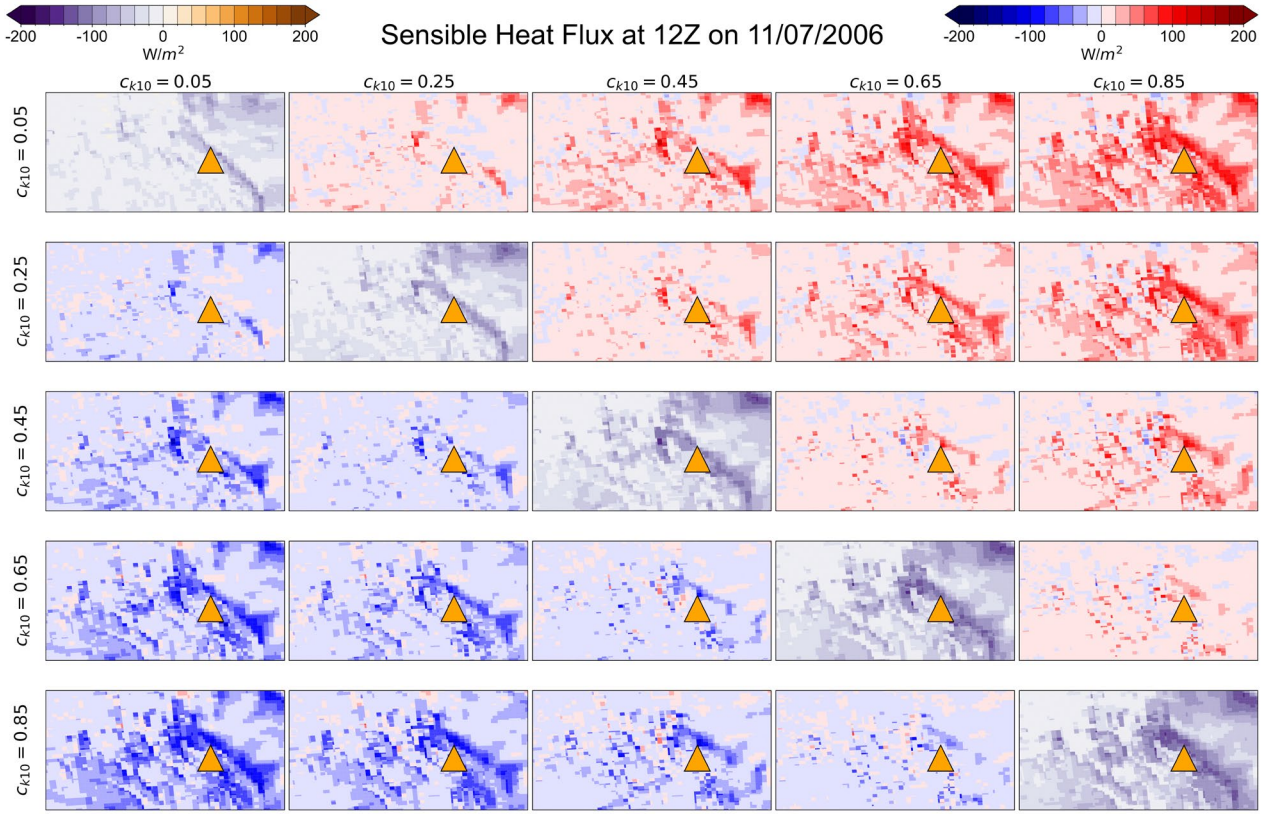
Influence of Mixing Parameter on Sensible Heat Flux

- During the event, modeled sensible heat flux is **directed downward into the snowpack**
- Increasing the mixing parameter (bottom left corner) results in a **downward flux that's higher in magnitude**



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Changing vertical mixing in sheared environments

The CLUBB PBL scheme in CAM uses a “downgradient diffusion” approach to diagnose vertical momentum fluxes:

$$\overline{u'w'} = -K_m \frac{\partial \overline{u}}{\partial z}$$

$$\overline{v'w'} = -K_m \frac{\partial \overline{v}}{\partial z}$$

The coefficient K_m is modulated with a handful of constants, c_k and c_{k10}

$$K_h = c_K L \overline{e}^{1/2}$$

$$K_m = c_{K10} K_h$$

Following prior studies, we’ll perturb c_{k10}

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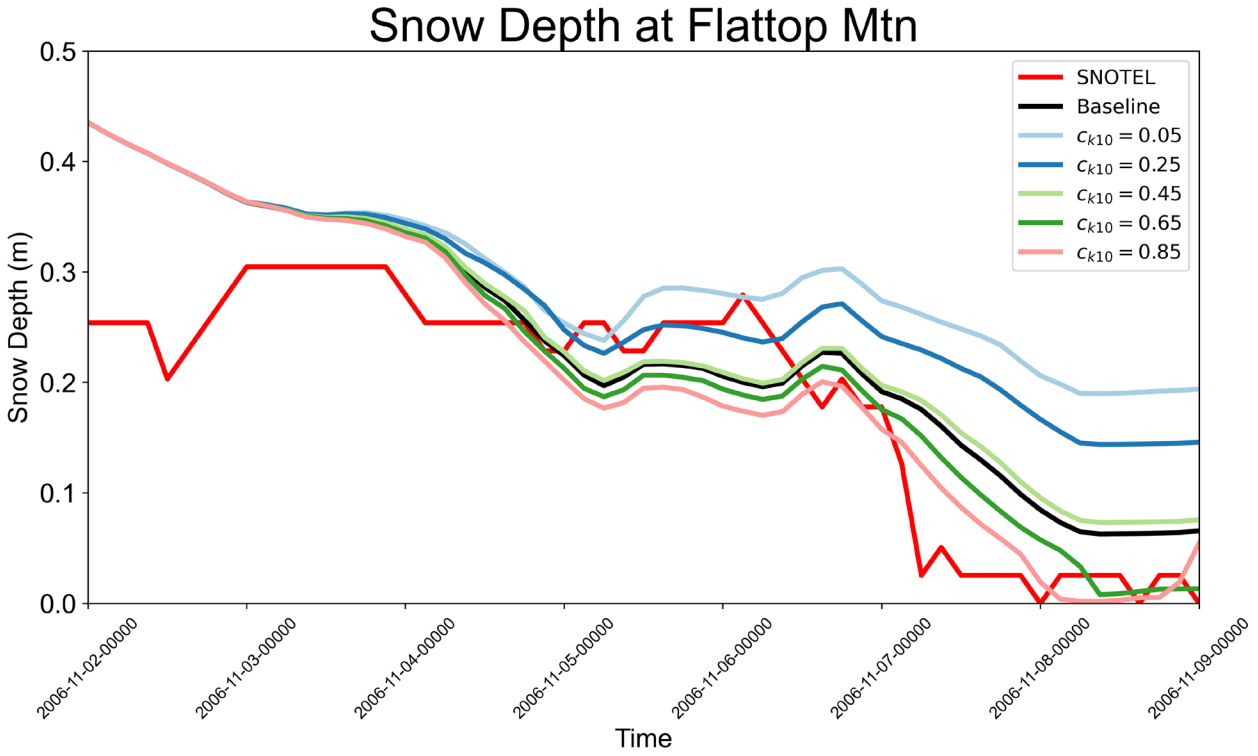
Mixing Parameter's Impact on Snow Depth in Glacier

- Configurations follow a similar trend toward SNOTEL and **start to diverge prior to rain-on-snow event**
- **Configurations with higher mixing coefficient more effectively reduce snow depth**



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