Large changes in surface temperature variability between CESM1 and CESM2 related to the representation of snow density and densification

Isla Simpson [1]

Dave Lawrence [1], *Sean Swenson* [1], *Cecile Hannay* [1], *Karen McKinnon* [2], *John Truesdale* [1]

1 = CGD, NCAR, 2 = UCLA

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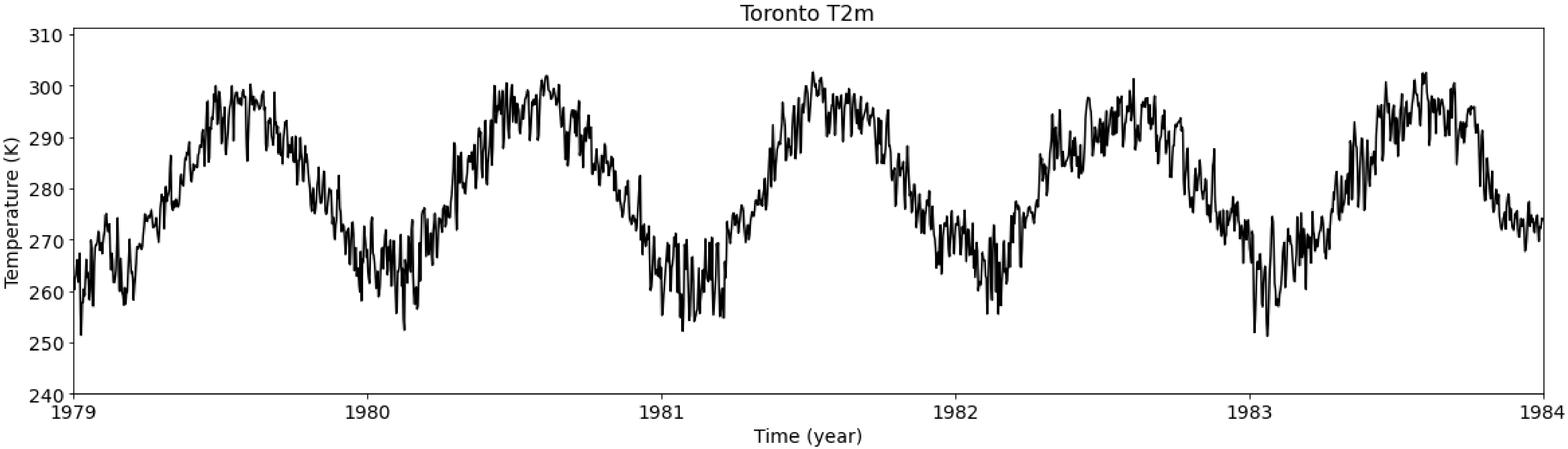
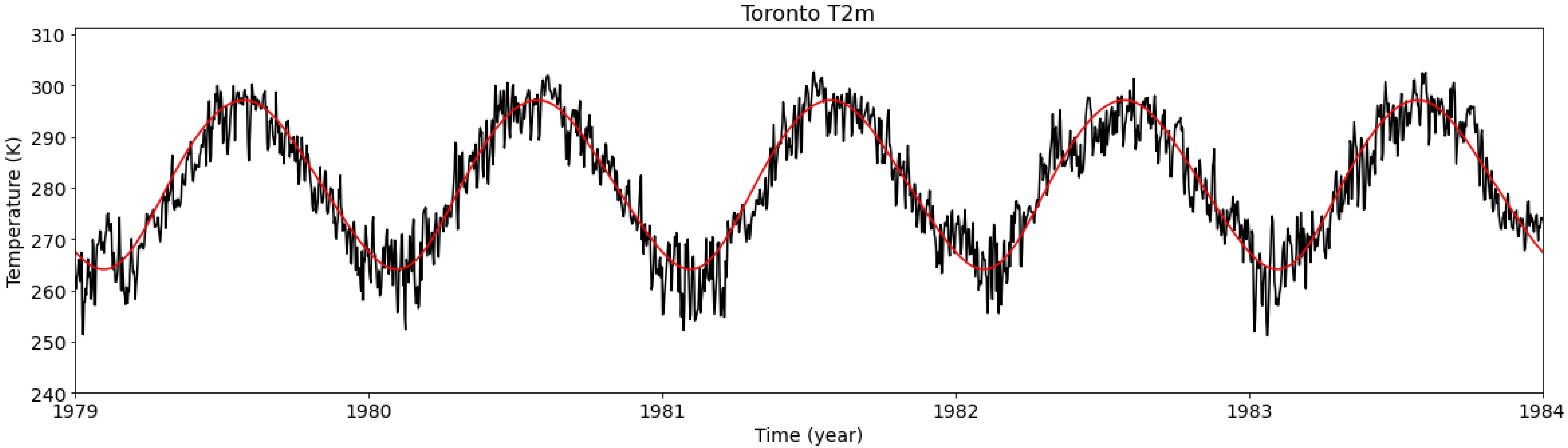
Methods

Daily average 2m temperature (T2m)



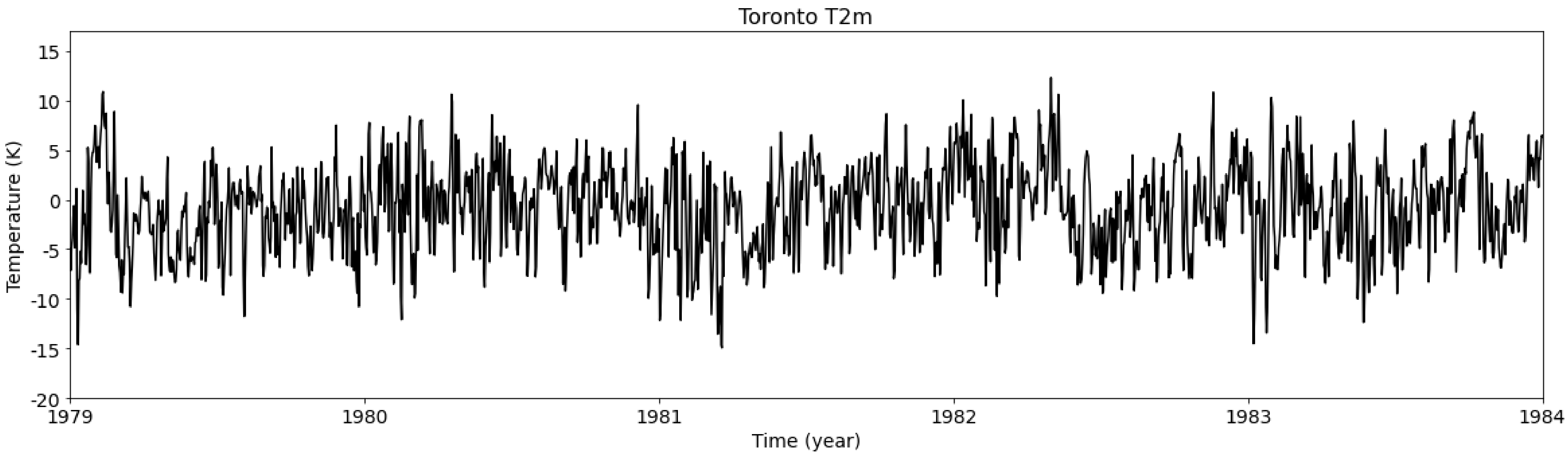
Methods

Calculate the seasonal cycle as the first 4 harmonics of the seasonally varying climatology



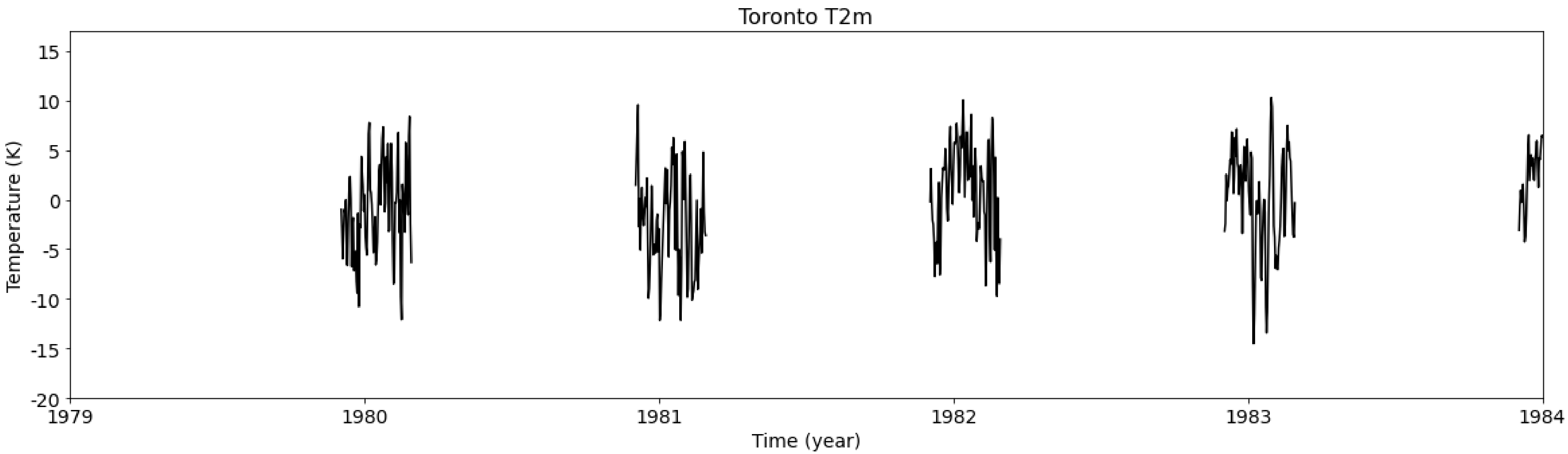
Methods

Remove the seasonal cycle



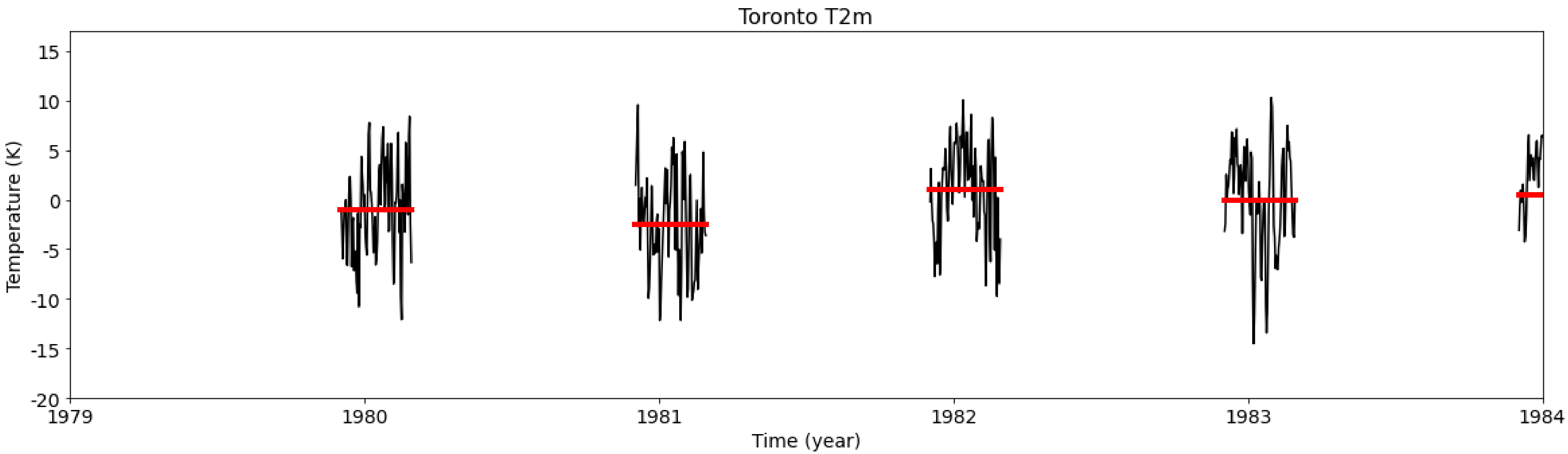
Methods

Focus on DJF



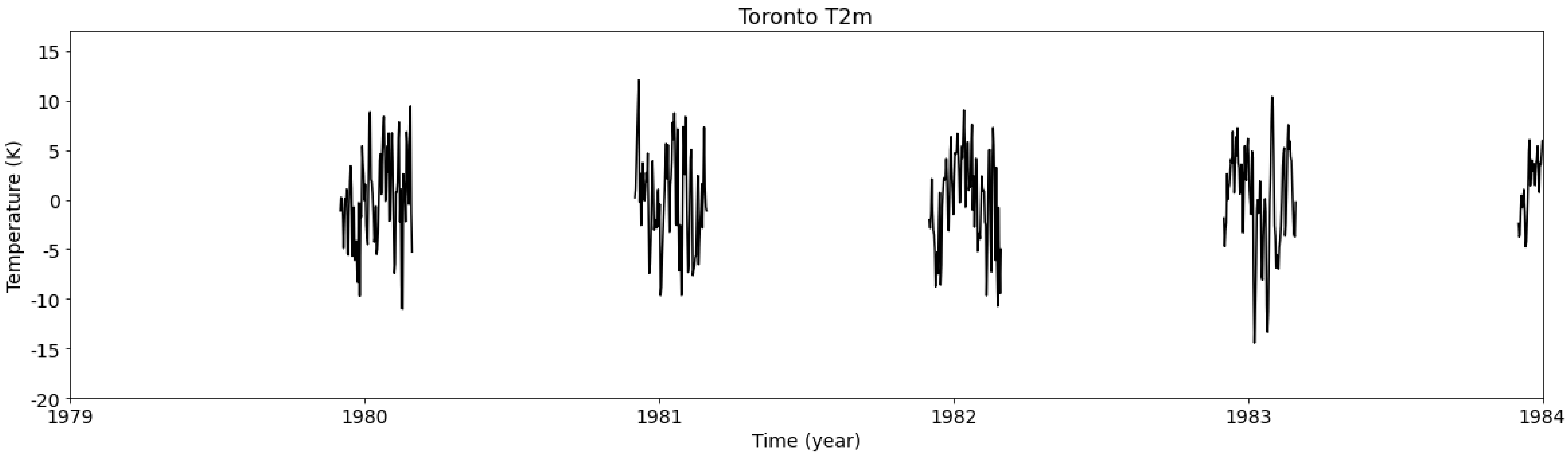
Methods

Remove the seasonal mean from each DJF (isolate sub-seasonal variability)



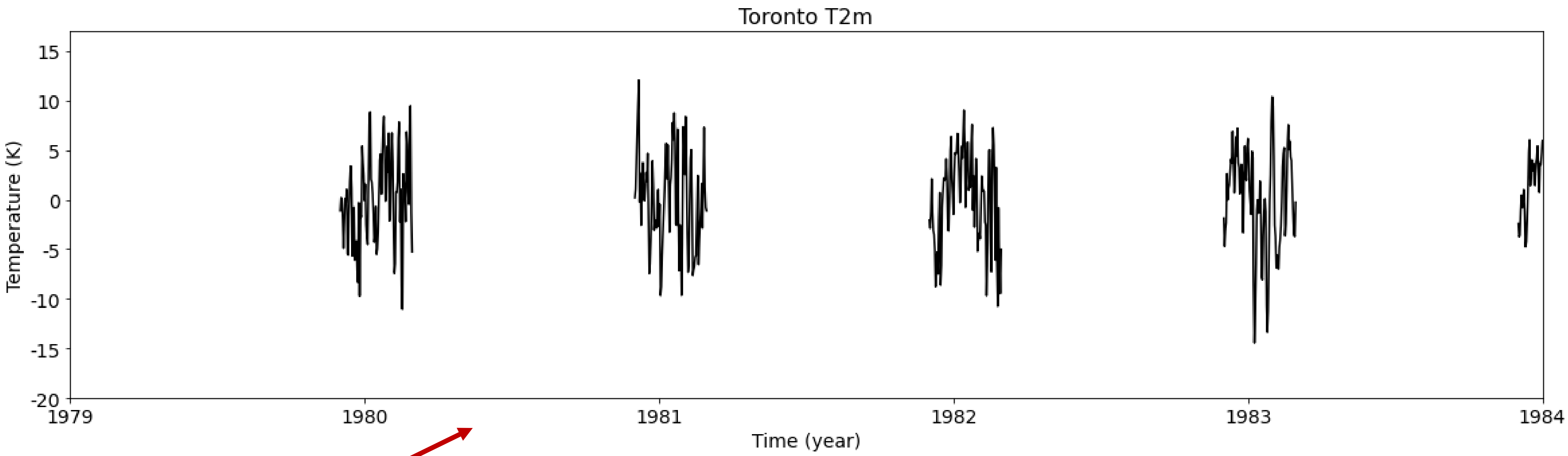
Methods

To give DJF anomalies…



Methods

To give DJF anomalies…



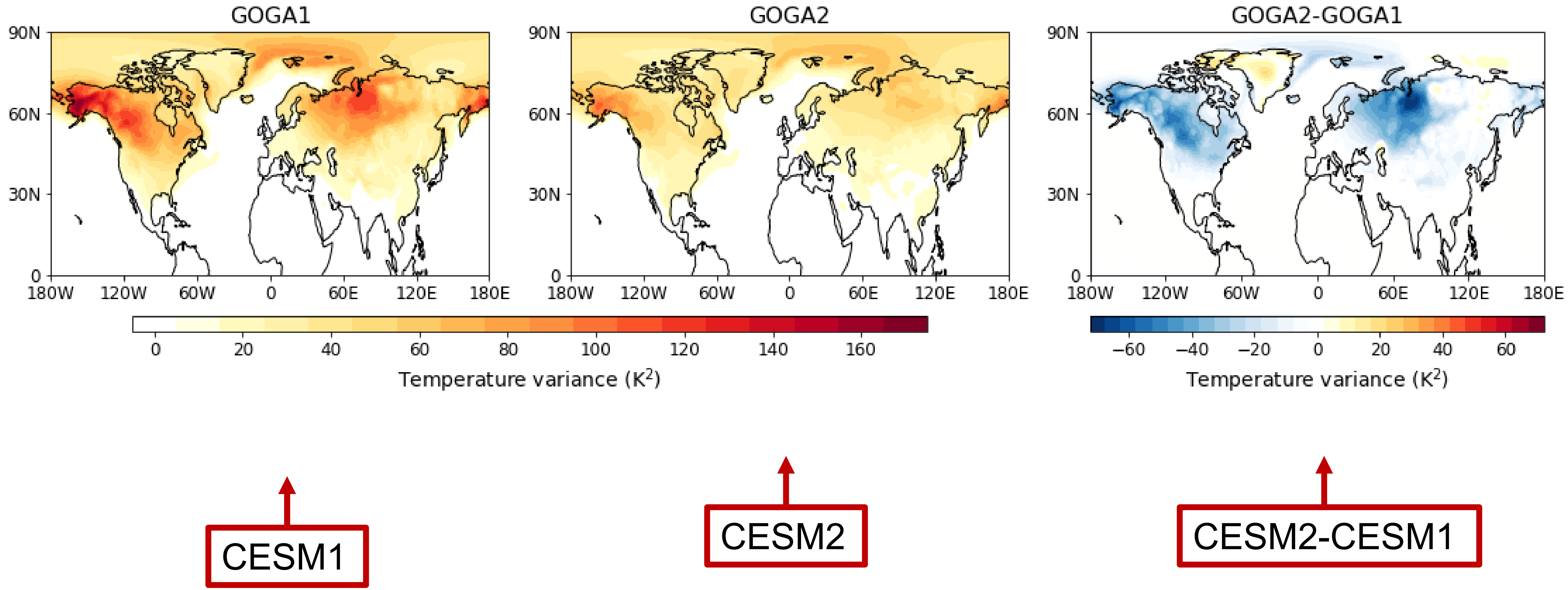
Look at the variance of this

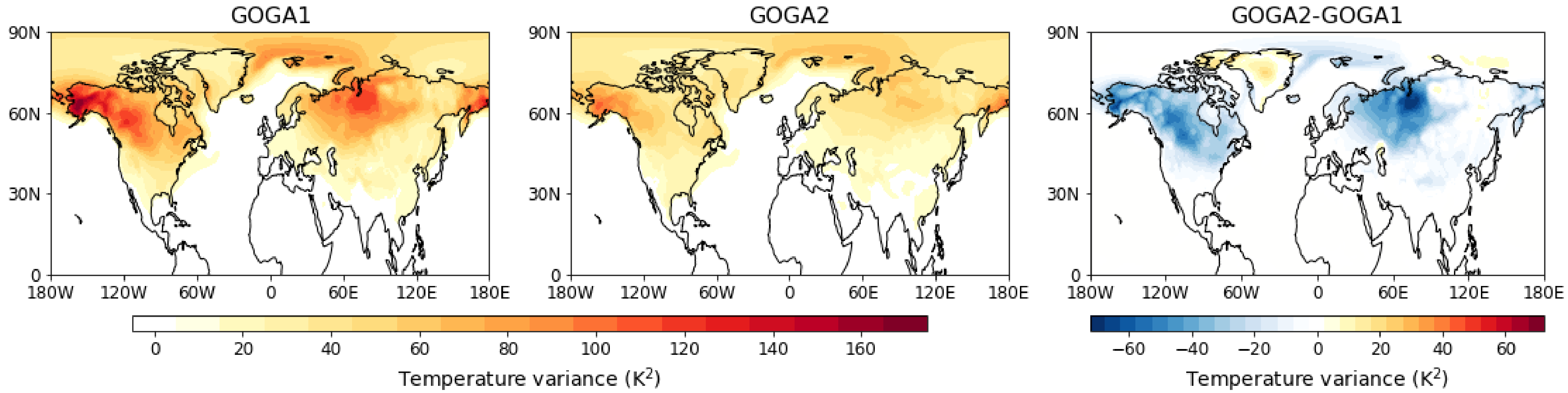
CESM1 GOGA
10 members
Focus on 1979-2014

CESM2 GOGA
10 members
Focus on 1979-2014

Both are run with prescribed time varying SSTs and sea ice from observations

Data available at https://www.cesm.ucar.edu/working_groups/CVC

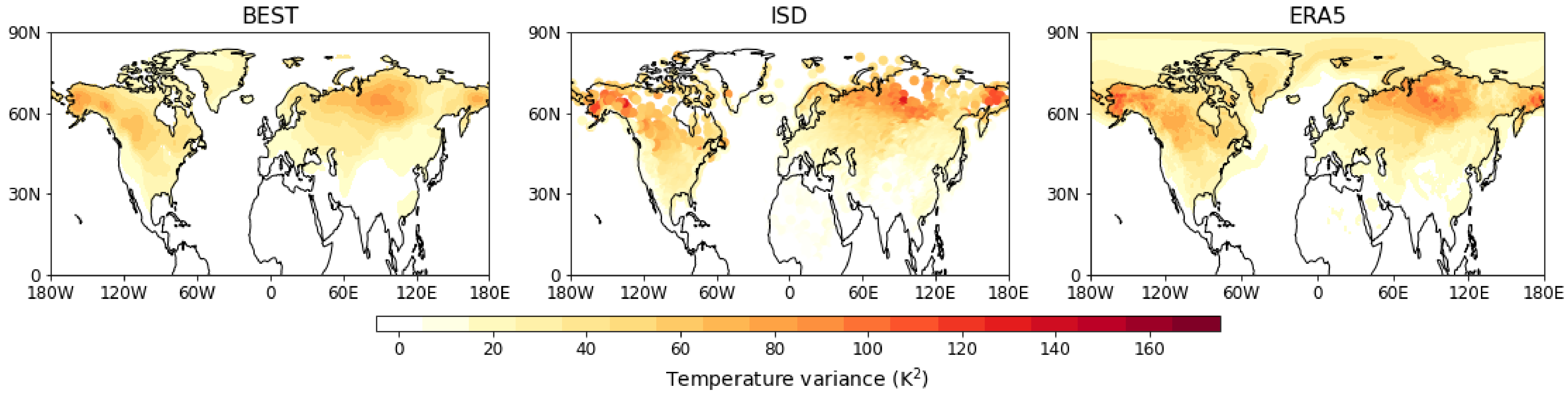

GOGA1
GOGA2
GOGA2-GOGA1
90N
60N
30N
0
180W
120W
60W
0
60E
120E
180E
0
20
40
60
80
100
120
140
160
Temperature variance (K^2)
−60
−40
−20
0
20
40
60
Temperature variance (K^2)
CESM1
CESM2
CESM2-CESM1



Berkeley Earth Surface Temperature daily product (experimental)

Integrated Surface database (ISD) station data

ERA5 reanalysis



What has caused this change in T2m variability?

CAM, CLM or both?

Atmospheric model

Land Model

CAM, CLM or both?

CAM: Atmospheric model

CLM: Land Model

CAM6 + CLM5	CAM5 + CLM5
CAM6 + CLM4	CAM5 + CLM4

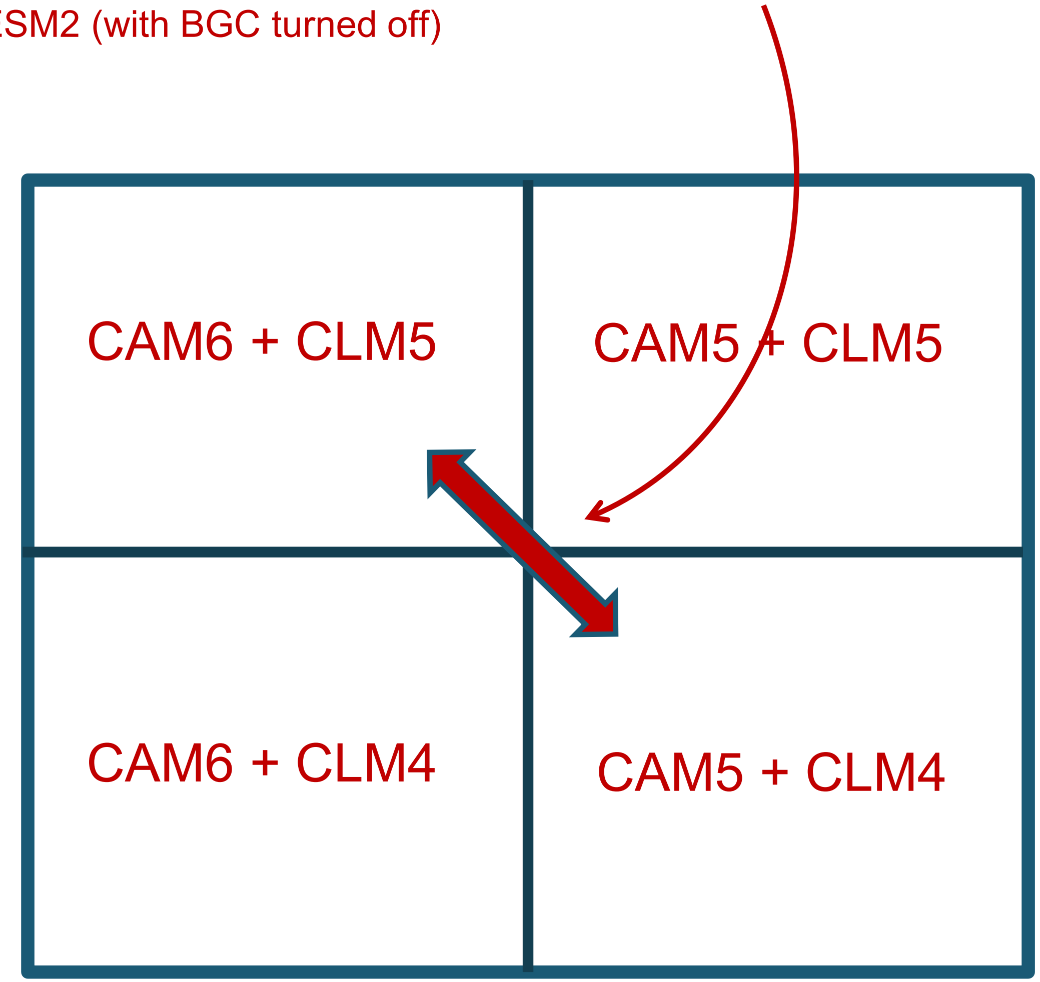
All within the CESM2 framework using historical forcings with prescribed time evolving historical SSTs and sea ice.

1979-2014 or 1979-2005

BGC is off

CAM, CLM or both?

Just checking we get the same answer as in the GOGA runs when reverting CAM6 back to CAM5 and CLM5 back to CLM4 within CESM2 (with BGC turned off)



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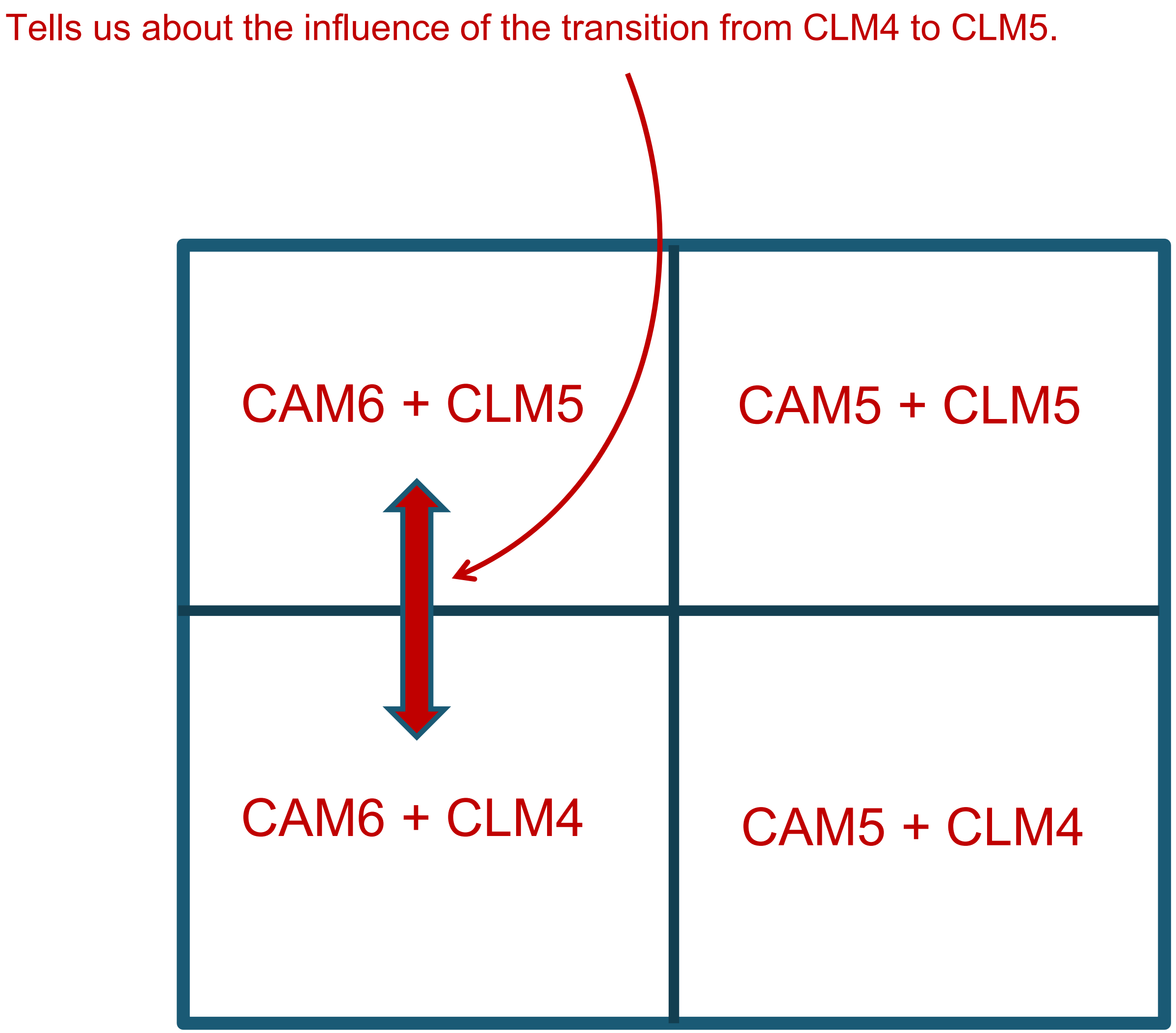
BGC is off

CAM, CLM or both?



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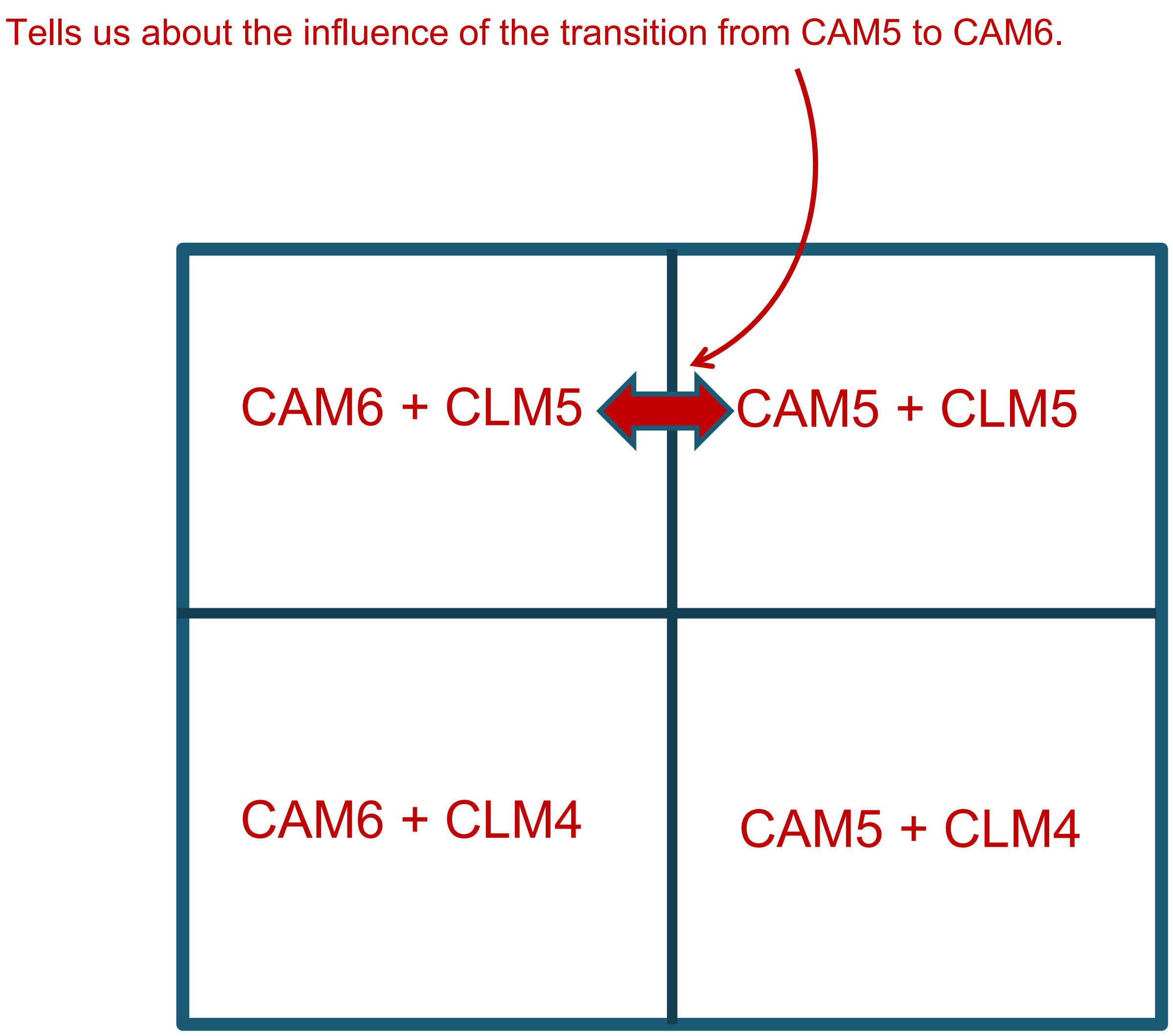

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1979-2014 or 1979-2005

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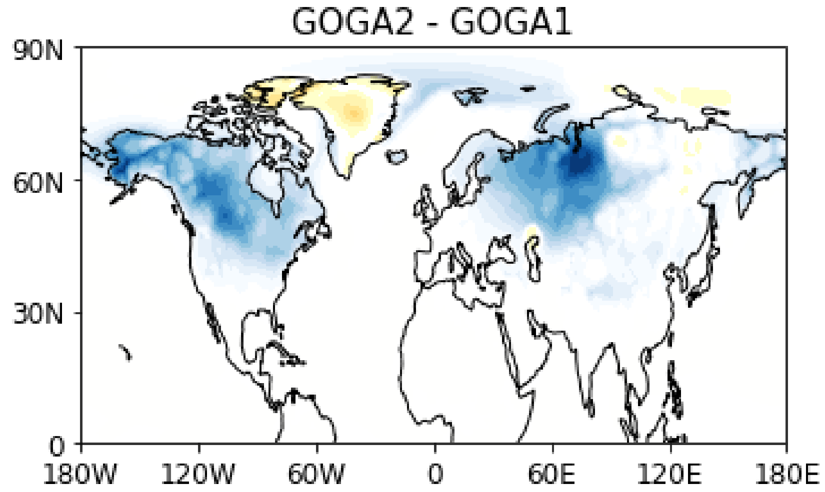
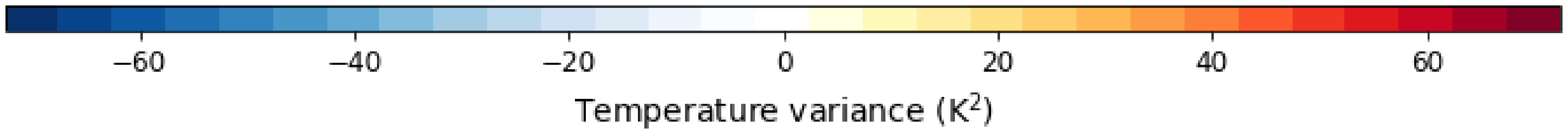
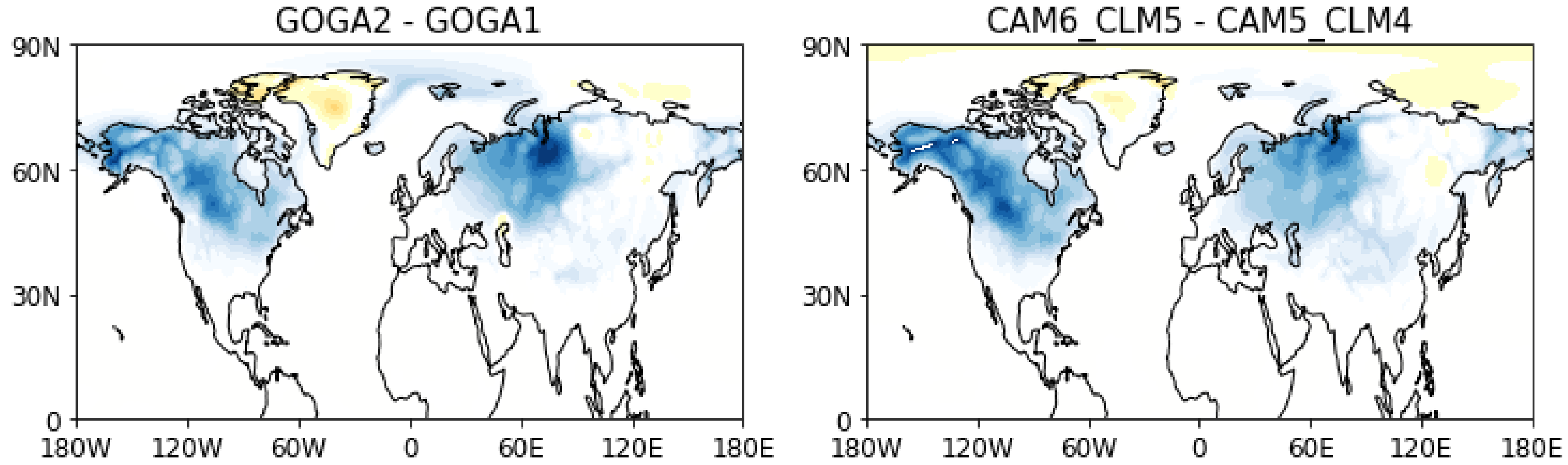

GOGA2 - GOGA1
90N
60N
30N
0
180W
120W
60W
0
60E
120E
180E

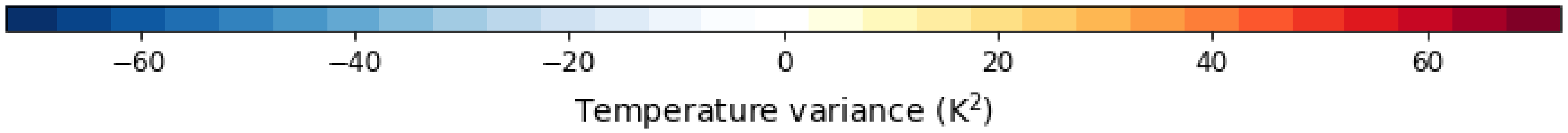
CESM2 – CESM1

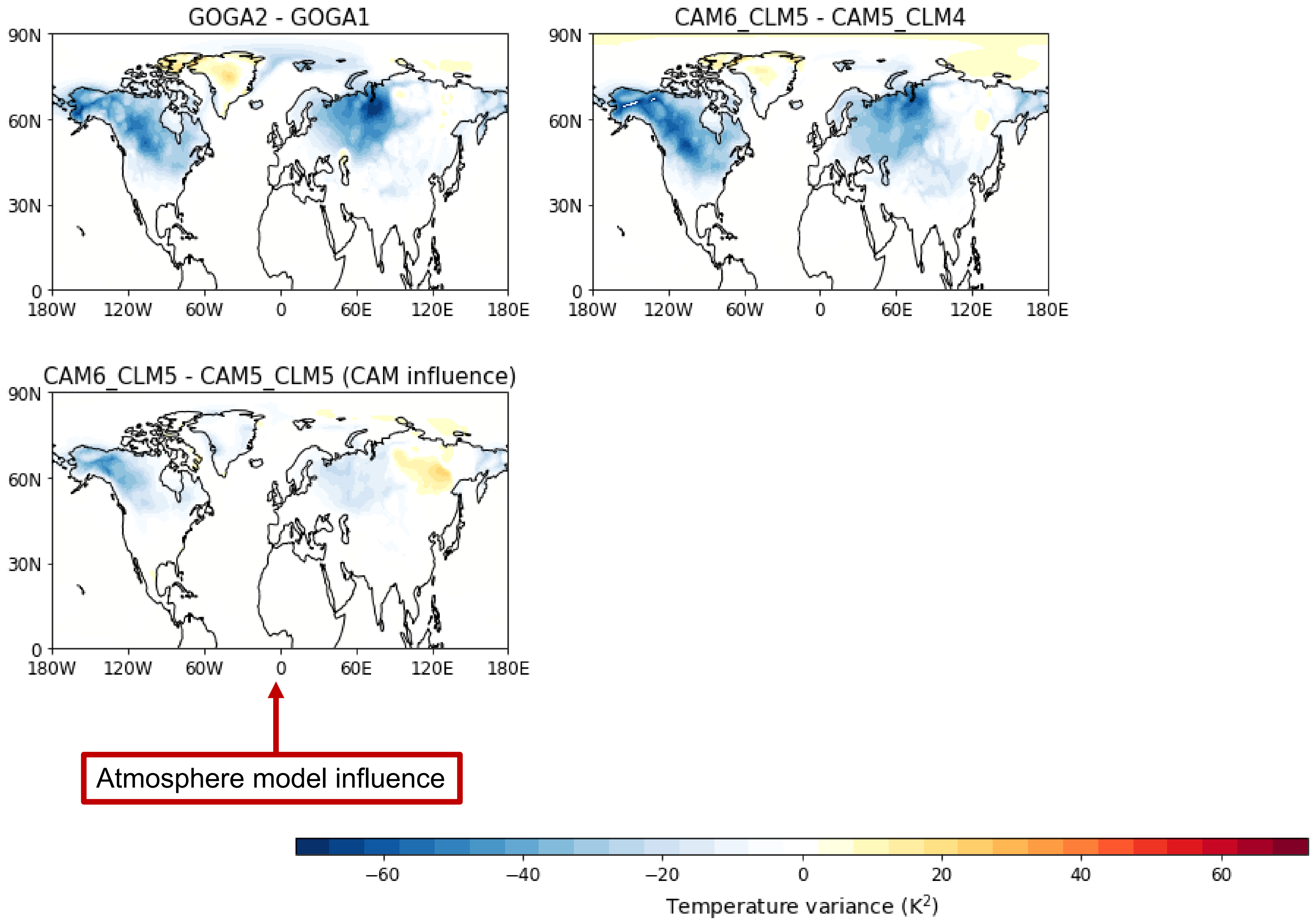

−60
−40
−20
0
20
40
60
Temperature variance (K2)

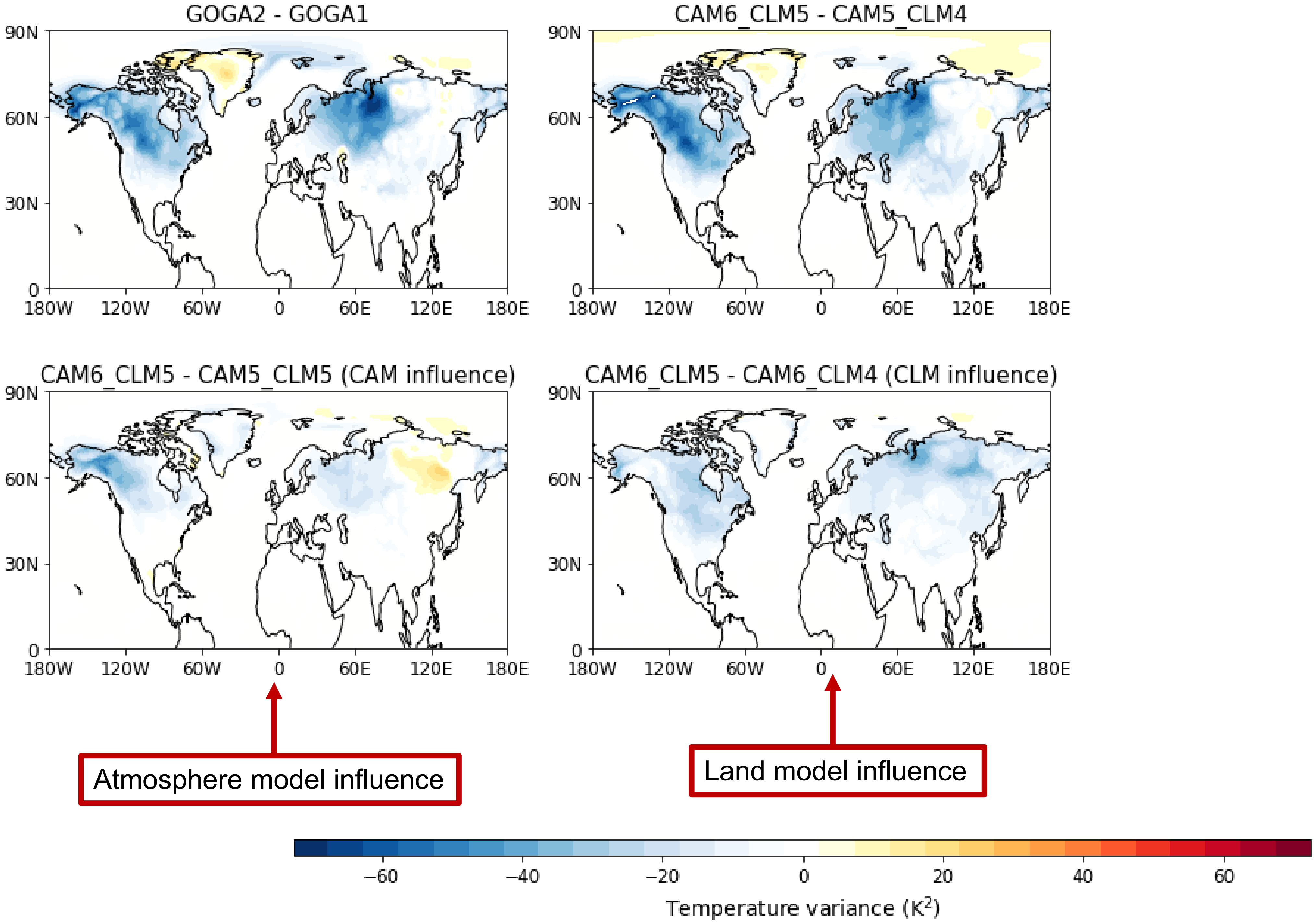


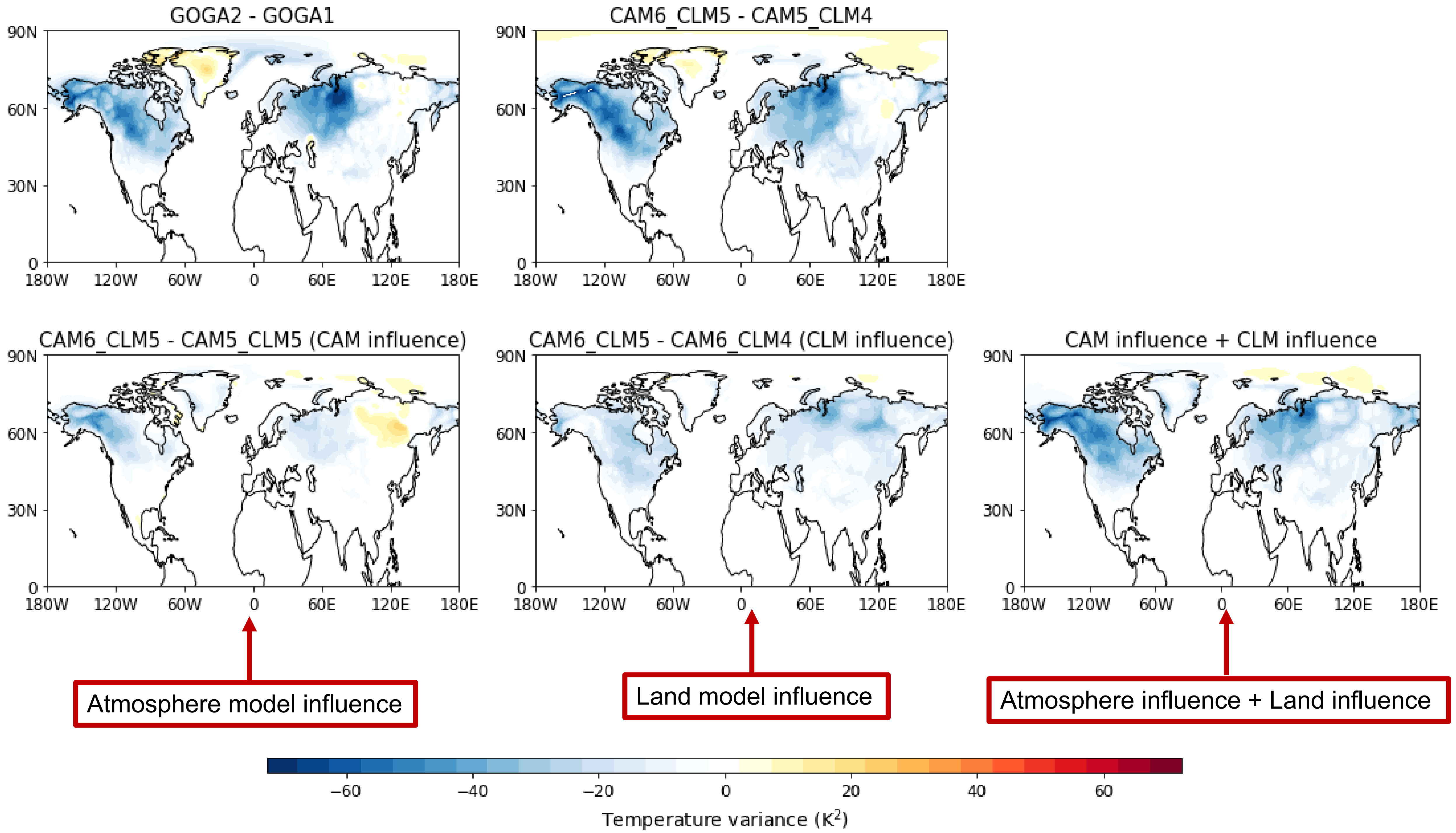
CESM2 – CESM1

Reverting both the atmosphere and land models back within CESM2

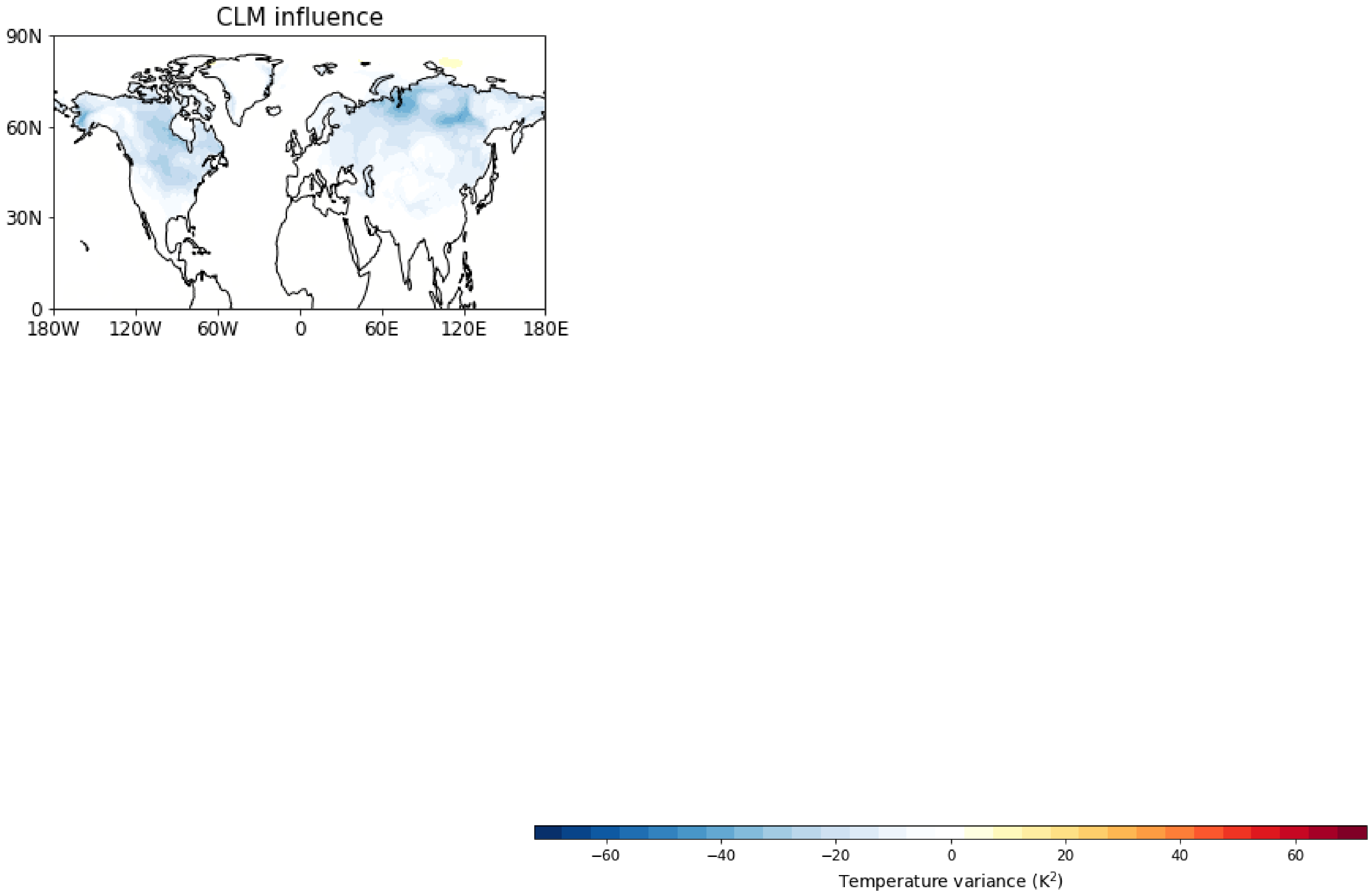



GOGA2 - GOGA1
CAM6_CLM5 - CAM5_CLM4
CAM6_CLM5 - CAM5_CLM5 (CAM influence)
90N
60N
30N
0
180W
120W
60W
0
60E
120E
180E
Atmosphere model influence
−60
−40
−20
0
20
40
60
Temperature variance (K²)

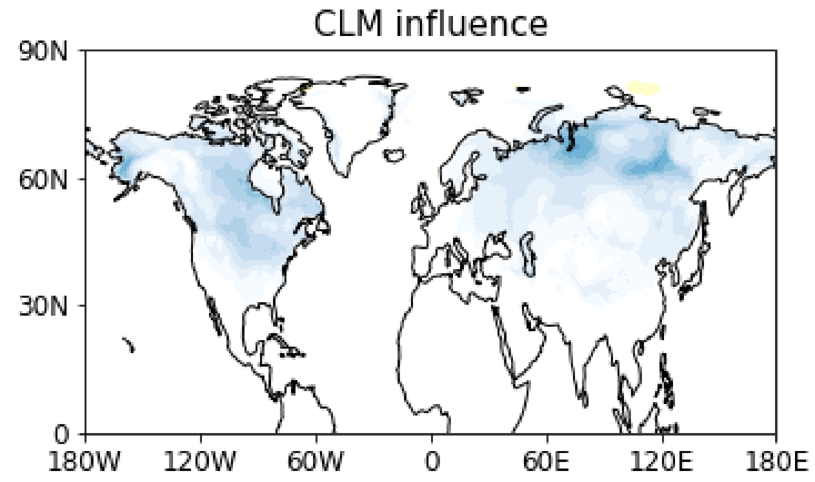

GOGA2 - GOGA1
CAM6_CLM5 - CAM5_CLM4
CAM6_CLM5 - CAM5_CLM5 (CAM influence)
CAM6_CLM5 - CAM6_CLM4 (CLM influence)
90N
60N
30N
0
180W
120W
60W
0
60E
120E
180E
Atmosphere model influence
Land model influence
−60
−40
−20
0
20
40
60
Temperature variance (K^2)


GOGA2 - GOGA1
CAM6_CLM5 - CAM5_CLM4
CAM6_CLM5 - CAM5_CLM5 (CAM influence)
CAM6_CLM5 - CAM6_CLM4 (CLM influence)
CAM influence + CLM influence
90N
60N
30N
0
180W
120W
60W
0
60E
120E
180E
Atmosphere model influence
Land model influence
Atmosphere influence + Land influence
−60
−40
−20
0
20
40
60
Temperature variance (K^2)

The land model influence

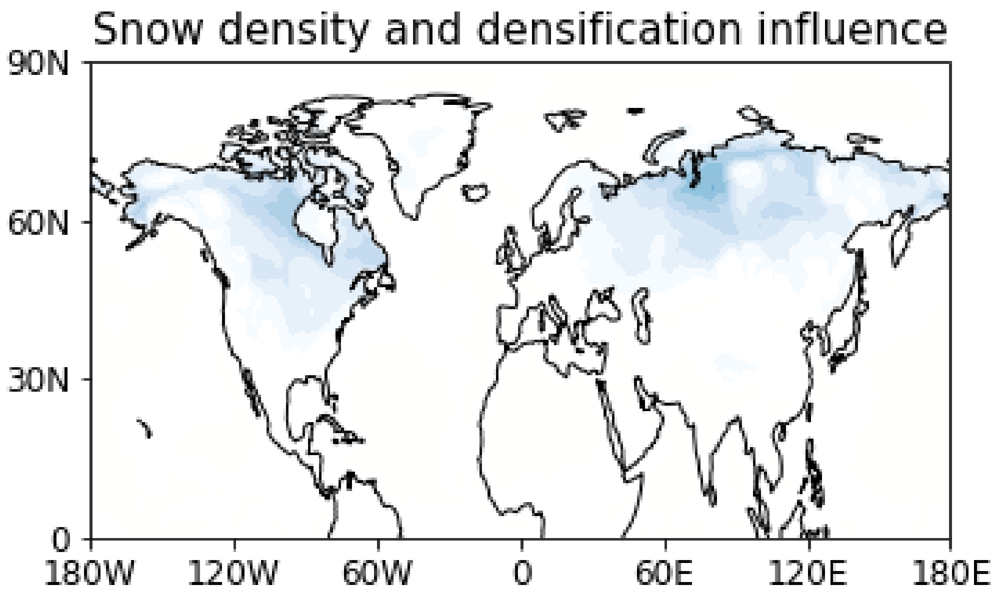


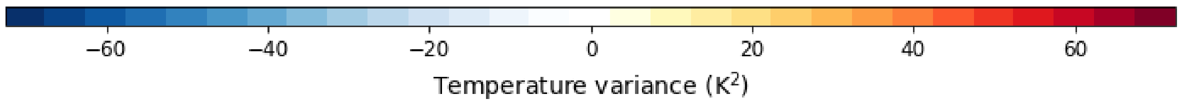
The land model influence



A simulation where the snow density and densification settings are reverted back to those in CLM4

CAM6_CLM5 – SNOWD





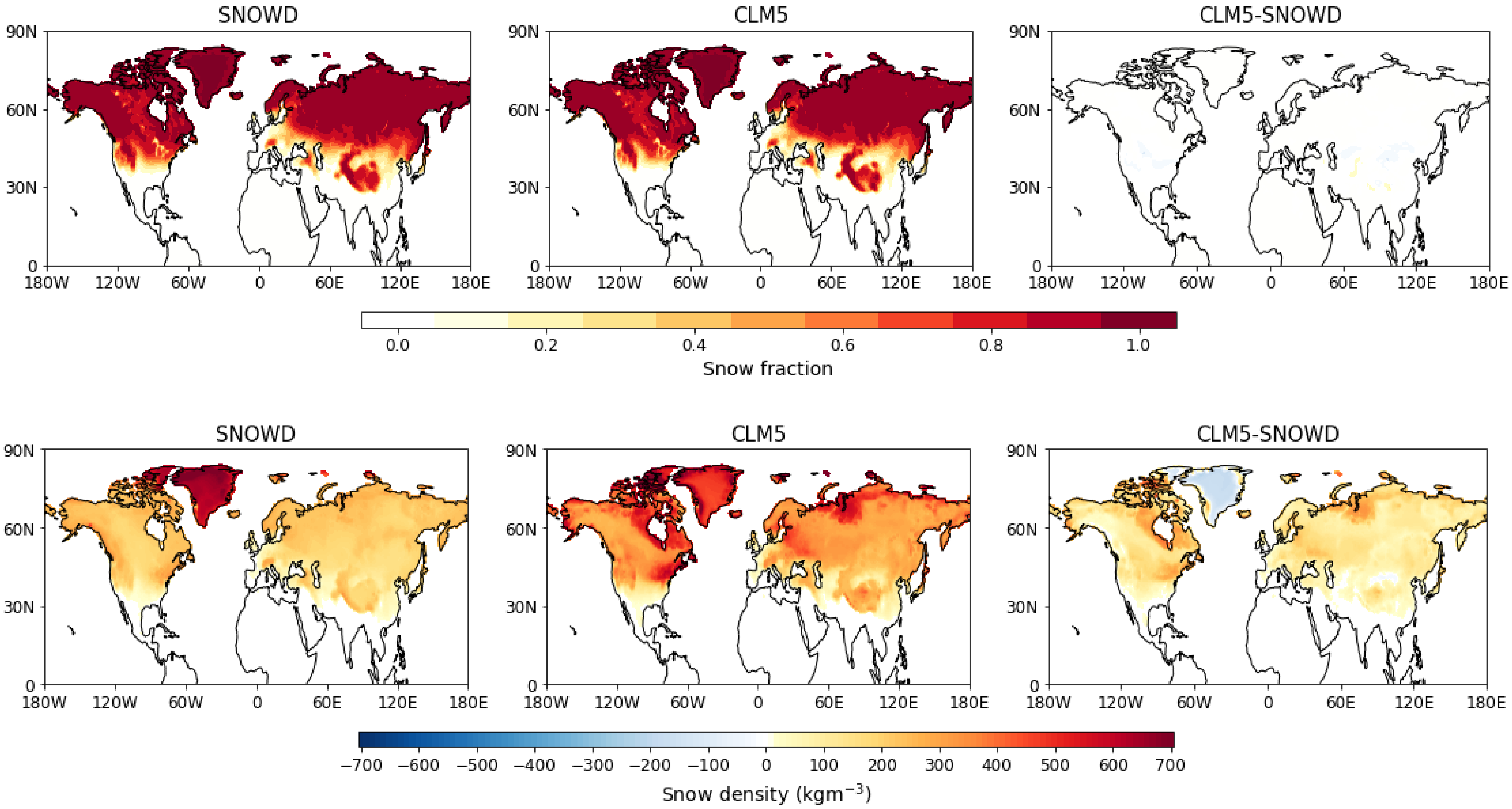
What is new about snow density and densification?

OLD SNOW | NEW SNOW | NEW - OLD

Snow fraction

DJF averages

Snow density



What is new about snow density and densification?

OLD SNOW

NEW SNOW

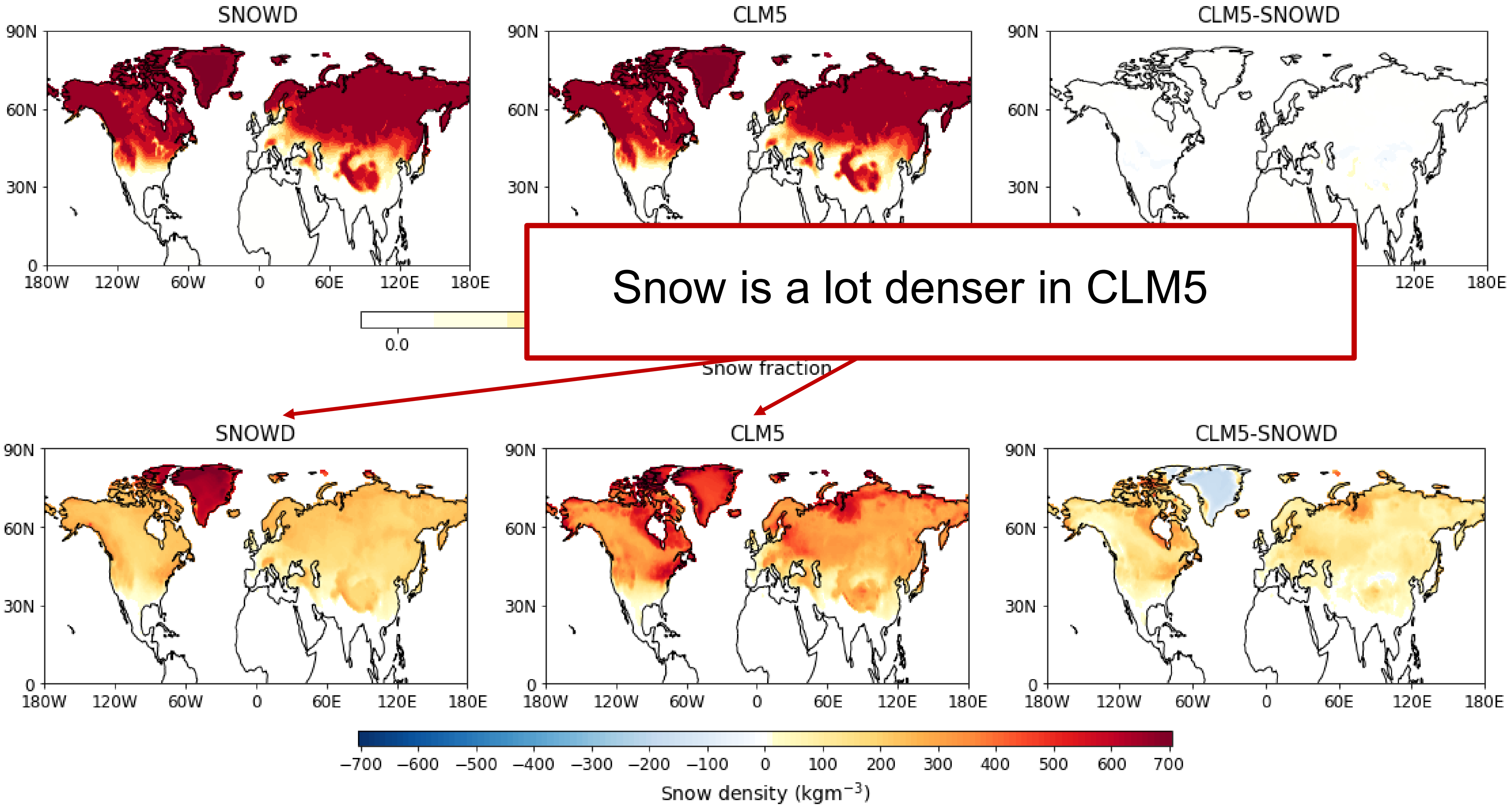
NEW - OLD

Snow fraction

Snow density

DJF averages

Snow is a lot denser in CLM5



Why? What changed about snow?

CLM4 namelist parameters

lotmp_snowdensity_method =‘TruncatedAnderson1976’
overburden_compress_tfactor =0.08d00
snow_overburden_compaction_method =‘Anderson1976’
upplim_destruct_metamorph =100.d00
wind_dependent_snow_density =.false.

CLM5 namelist parameters

lotmp_snowdensity_method =‘Slater2017’
snow_overburden_compaction_method =‘Vionnet2012’
upplim_destruct_metamorph =175.d00
wind_dependent_snow_density =.true.

Namelist parameters related to snow density and densification

Why? What changed about snow?

CLM4 namelist parameters

```
lotmp_snowdensity_method           ='TruncatedAnderson1976'
overburden_compress_tfactor        =0.08d00
snow_overburden_compaction_method  ='Anderson1976'
upplim_destruct_metamorph          =100.d00
wind_dependent_snow_density        =.false.
```

CLM5 namelist parameters

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```

AGU PUBLICATIONS

Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE

10.1002/2017MS000988

Improving the Representation of Polar Snow and Firn in the Community Earth System Model

Leonardus van Kampenhout[1], Jan T. M. Lenaerts[1], William H. Lipscomb[2,3], William J. Sacks[3], David M. Lawrence[3], Andrew G. Slater[4], and Michiel R. van den Broeke[1]

Why? What changed about snow?

CLM4 namelist parameters

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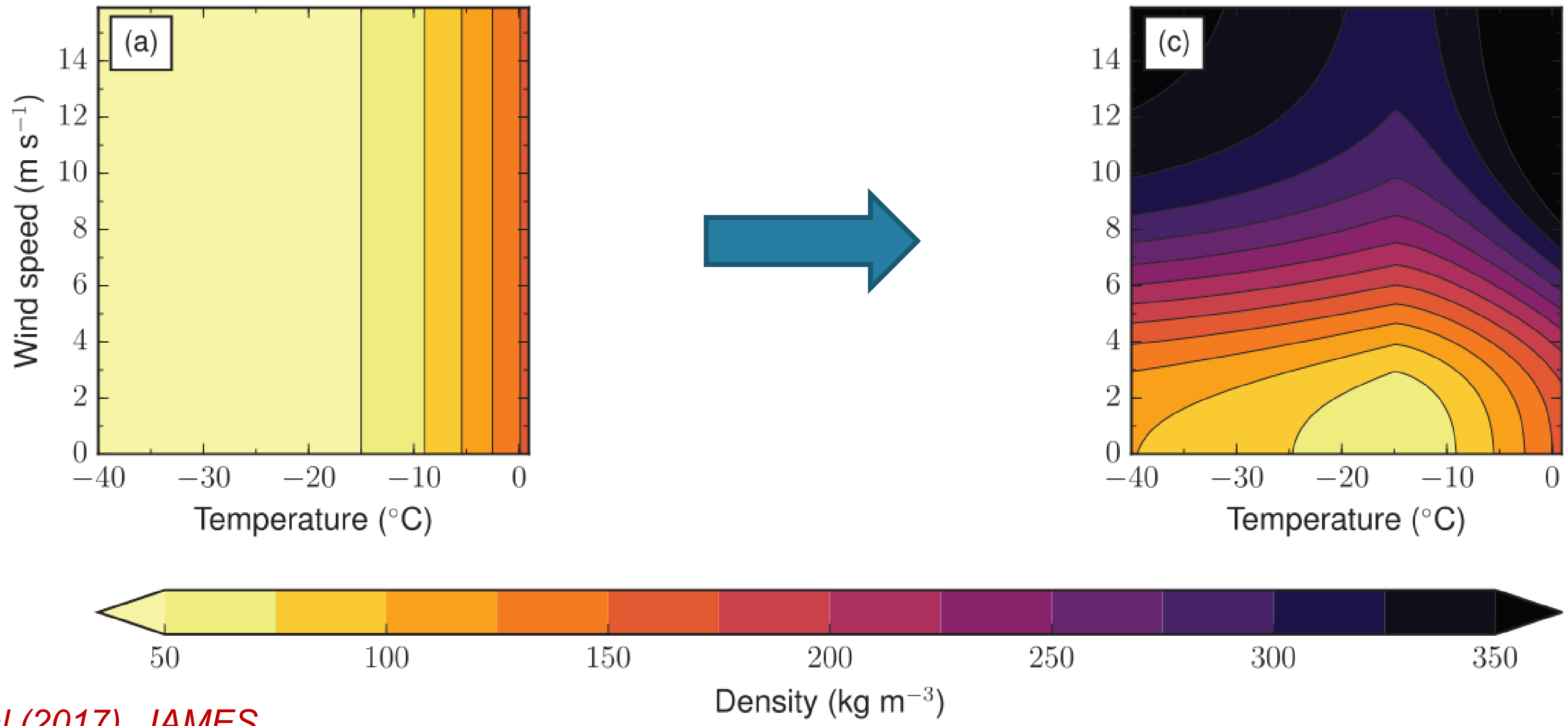

van Kampenhout et al (2017), JAMES

Why? What changed about snow?

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upplim_destruct_metamorph =175.d00
wind_dependent_snow_density =.true.

Snow Densification

- An increase in the density limit below which destructive metamorphism can lead to an increase in density
- An increase the viscosity used for in the calculation for compaction by overburden pressure (should reduce the density of firn)
- An inclusion of the representation of drifting snow and its impacts on compaction

van Kampenhout et al (2017), JAMES

Local or non -local influences?

Local or non -local influences?

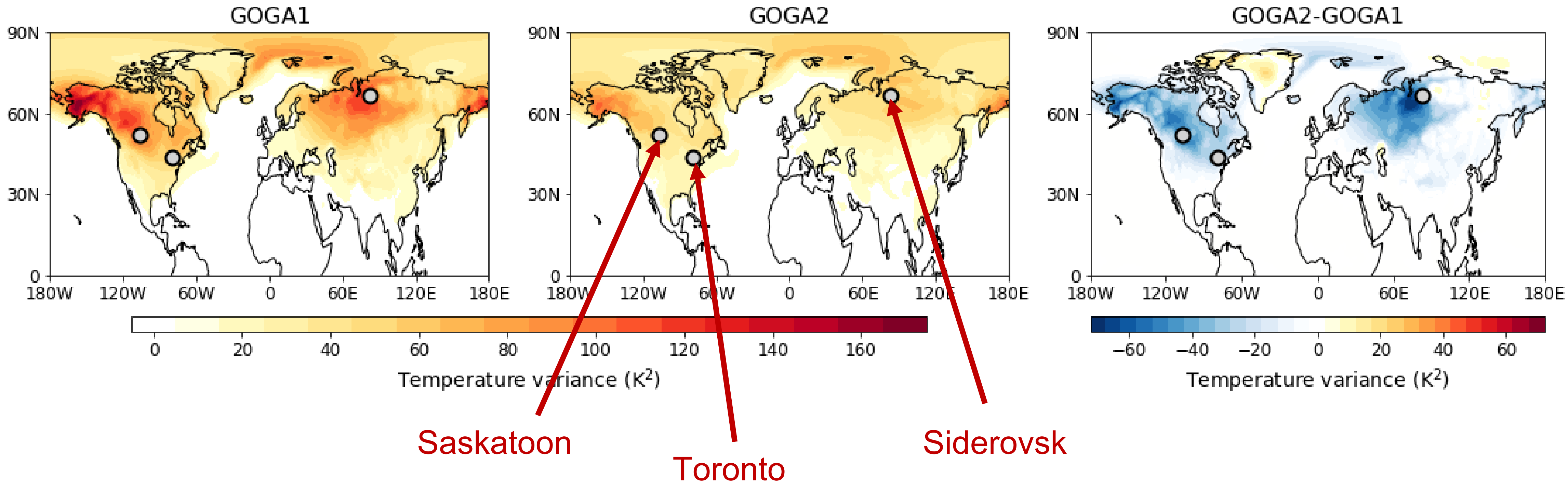
Answer = Local. The single column model can reproduce the changes in variability when the snow density and densification settings are reverted but it is forced with large scale forcing taken from a CESM run with CLM5.

Composites conditioned on T2m

Let's bin DJF days in CAM6_CLM5 and SNOWD according to their T2m temperature anomalies and look at how the surface energy balance plays out.

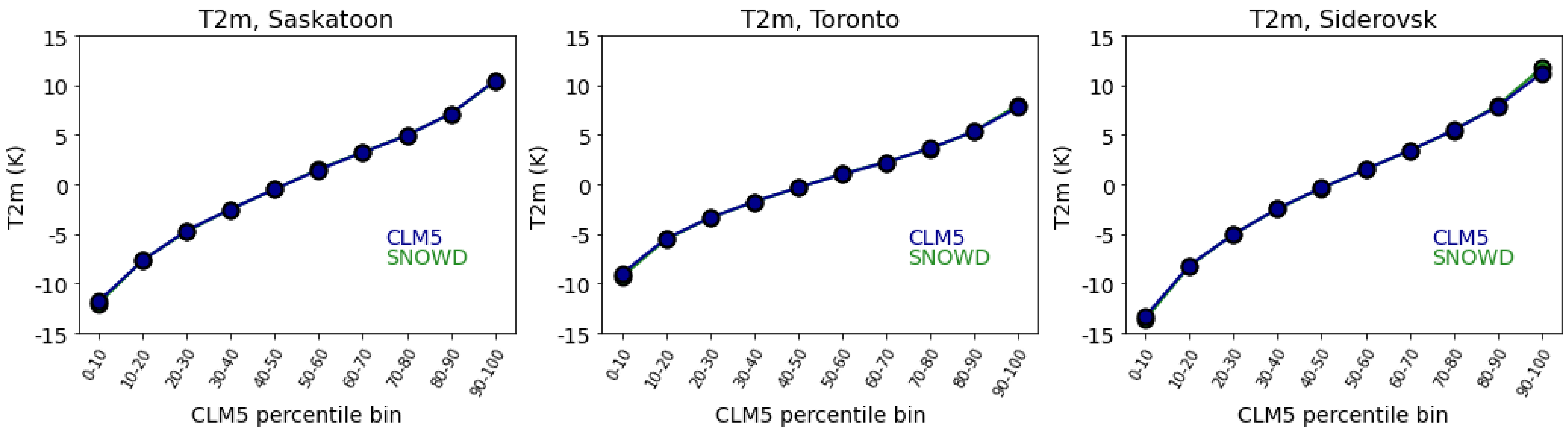
Bin limits determined from the distribution of T2m for CAM6_CLM5 (the narrower of the distributions)

Use, 10 bins corresponding to the 0-10th percentile range, 10th-20th percentile range and so on



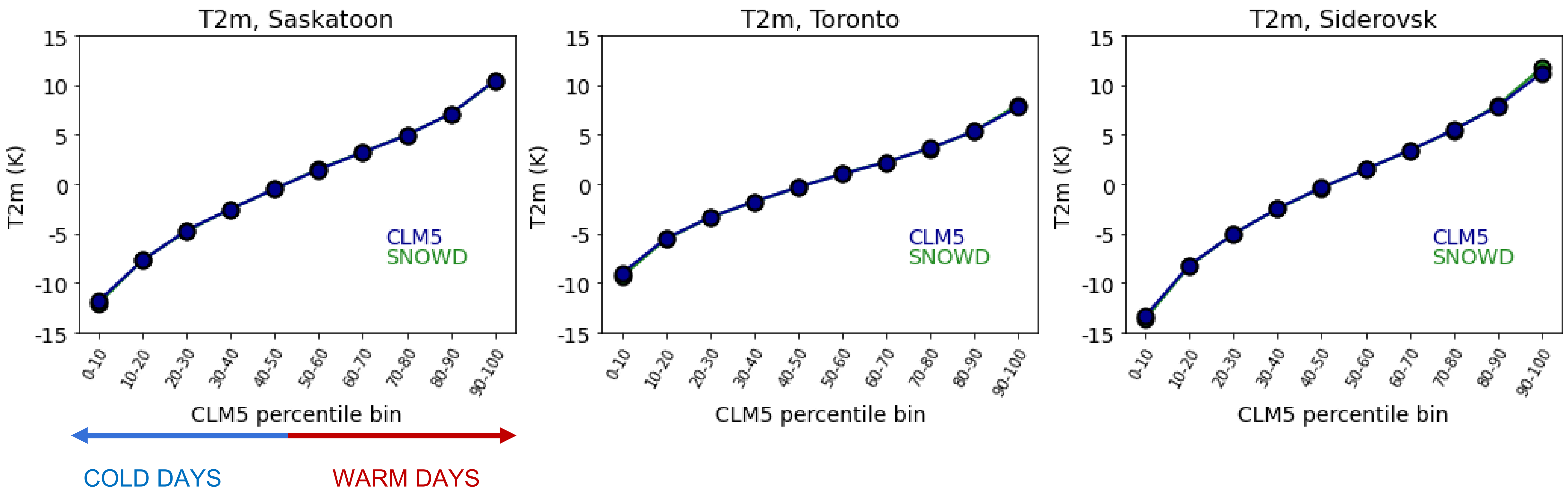
Composites conditioned on T2m

T2m composites



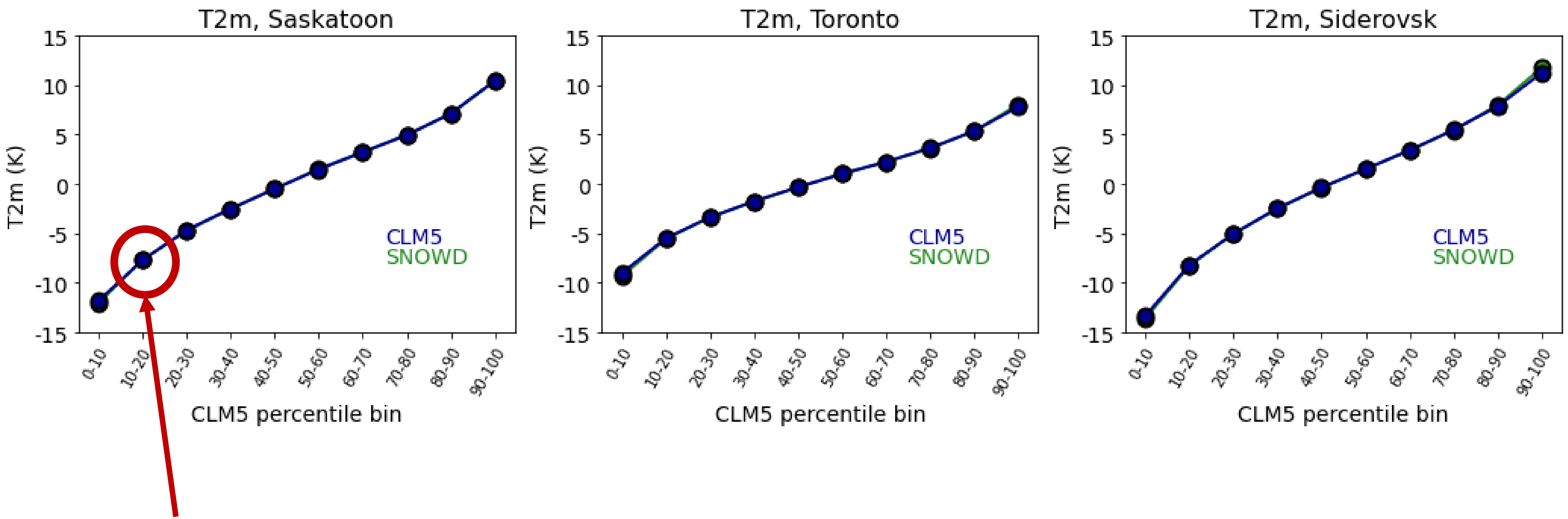
Composites conditioned on T2m

T2m composites



Composites conditioned on T2m

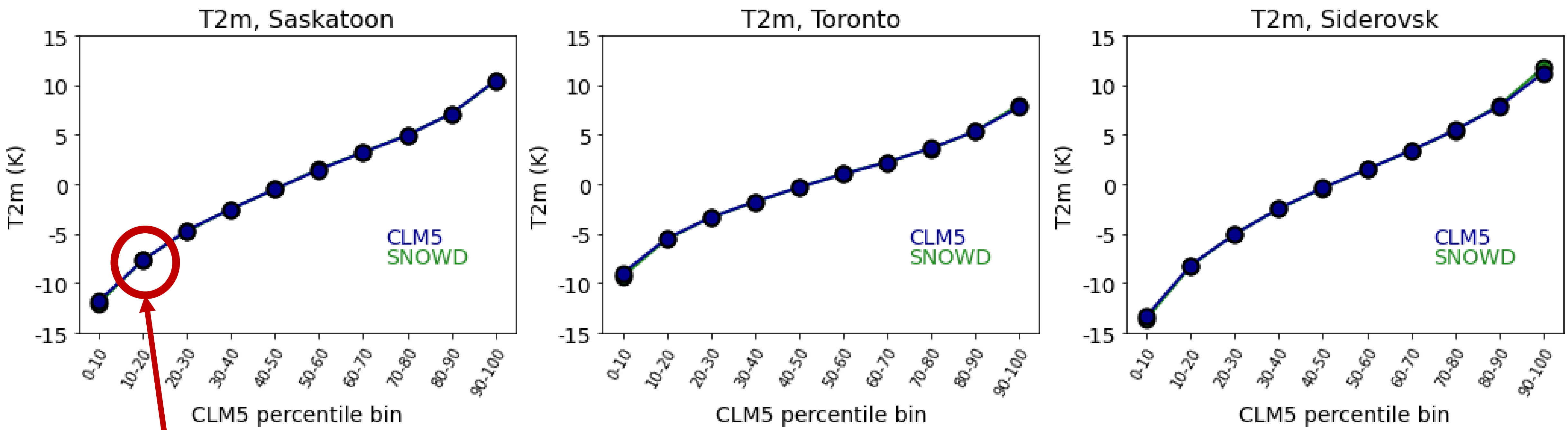
T2m composites



The average of days that have -9.54<T2m<-5.96

Composites conditioned on T2m

T2m composites

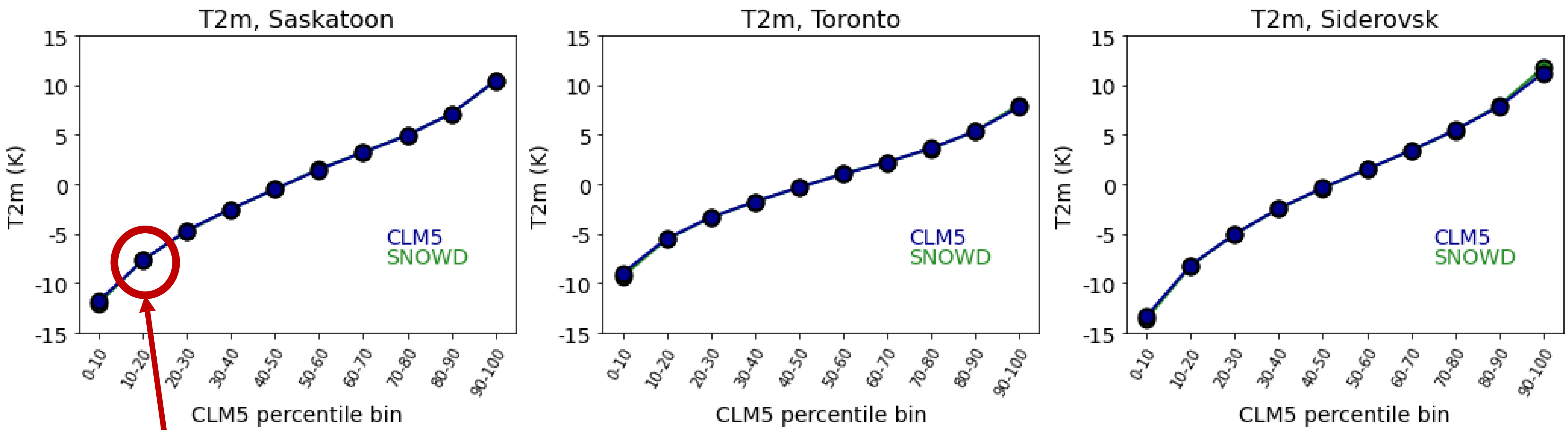


The average of days that have -9.54<T2m<-5.96

The 10^{th} percentile of the CAM6_CLM5 distribution

Composites conditioned on T2m

T2m composites



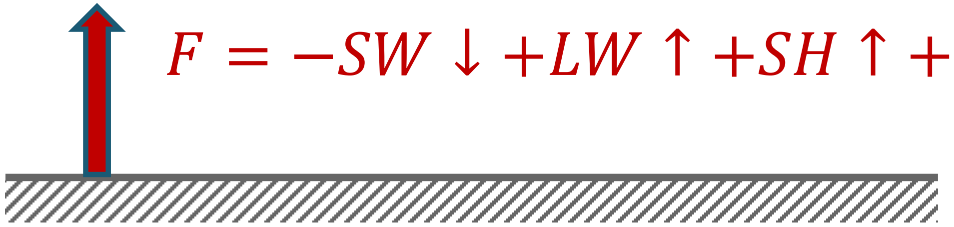
The average of days that have -9.54<T2m<-5.96

The 10th percentile of the CAM6_CLM5 distribution

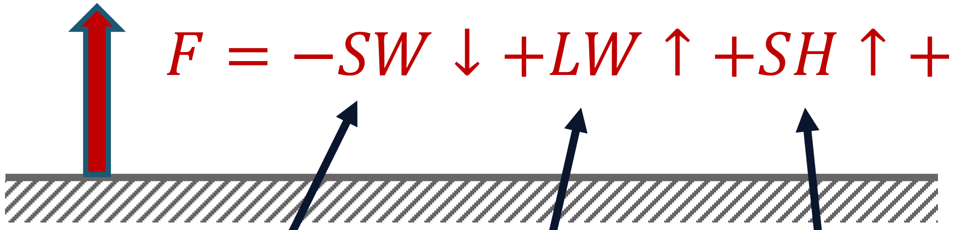
The 20th percentile of the CAM6_CLM5 distribution

Surface energy balance

$$F = -SW \downarrow + LW \uparrow + SH \uparrow + LH \uparrow$$



Surface energy balance



$$F = -SW \downarrow + LW \uparrow + SH \uparrow + LH \uparrow$$

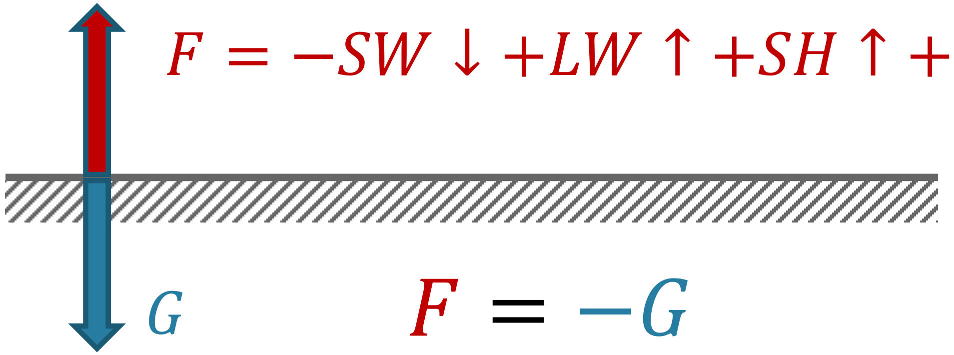
Net shortwave radiation

Net longwave radiation

Sensible heat flux

Latent heat flux

$$F = -SW\downarrow + LW\uparrow + SH\uparrow + LH\uparrow$$

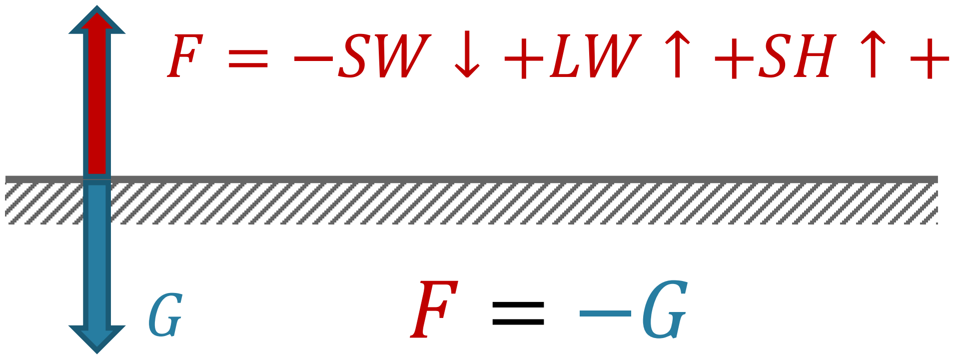


$$F = -G$$

Any imbalance in the terms of the atmospheric surface energy budget must be accompanied by a net heat flux into or out of the ground.

(There are some other terms e.g., melting of snow, but F ~ -G)

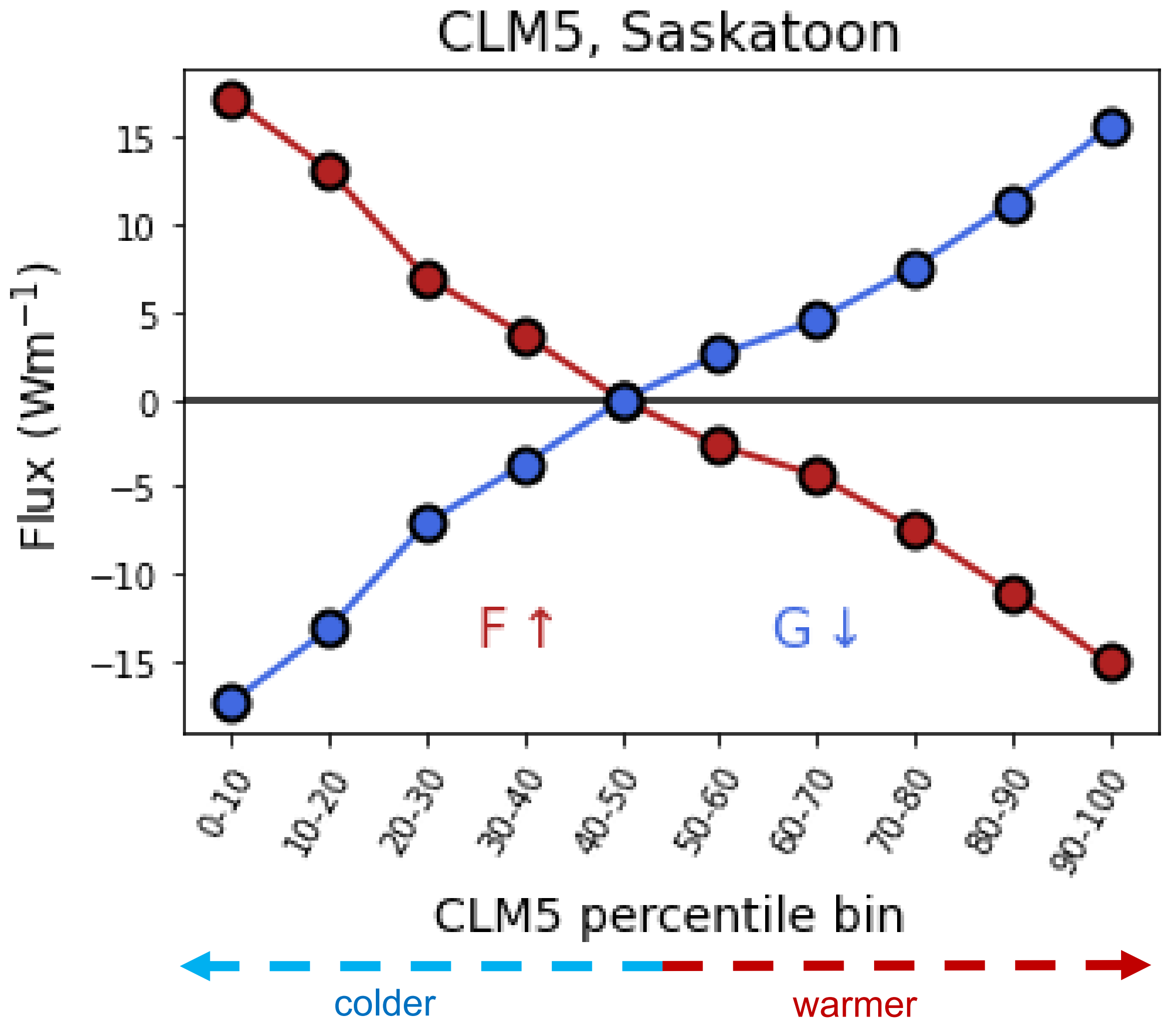
Surface energy balance



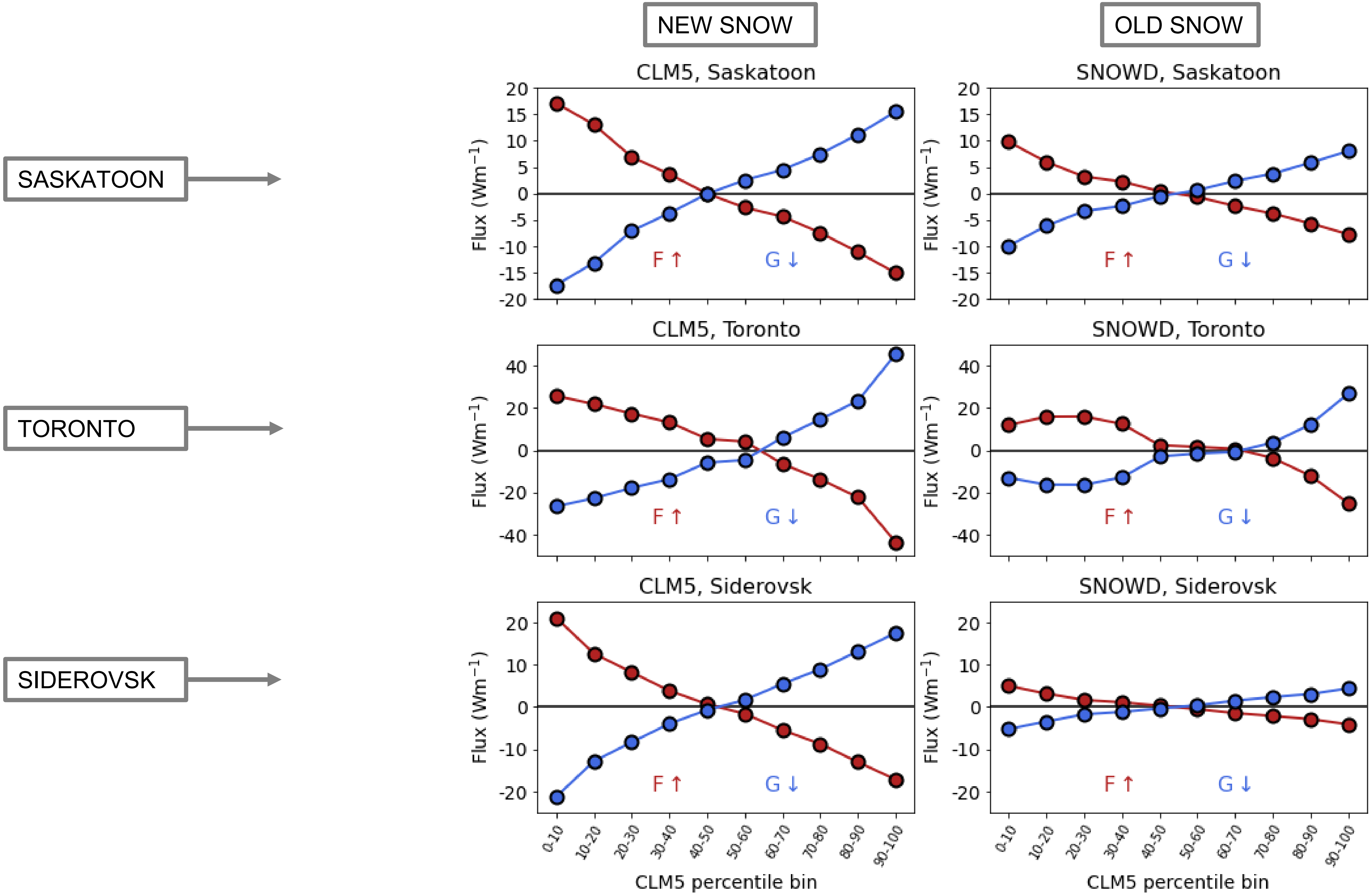
$$F = -SW\downarrow + LW\uparrow + SH\uparrow + LH\uparrow$$

$$F = -G$$

When it gets cold, there is an anomalous upward energy flux from ground to atmosphere which would dampen the atmospheric temperature anomalies

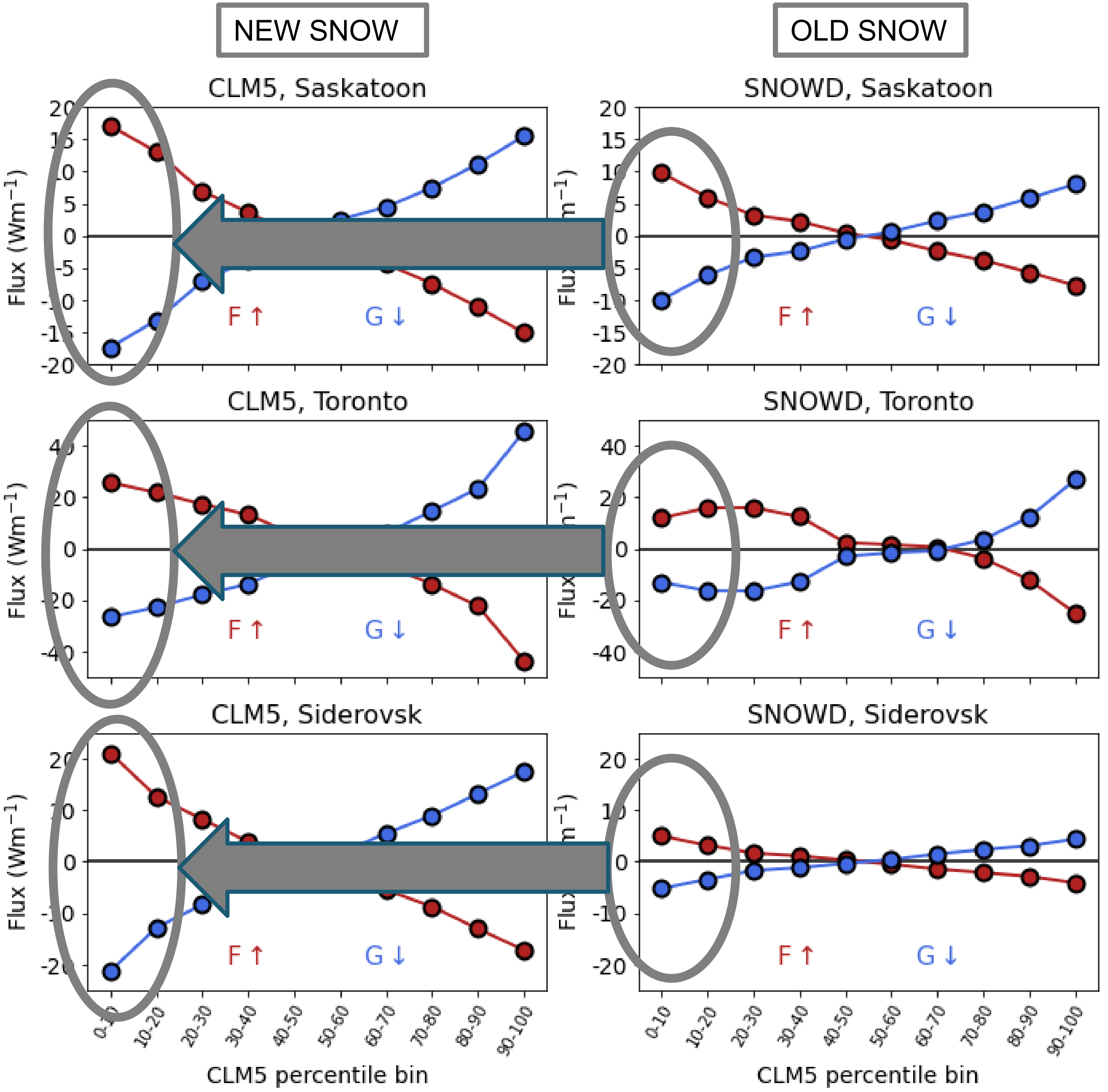


When it gets warm, there is an anomalous energy flux from atmosphere to ground or less upward heat flux from ground to atmosphere which would dampen the temperature anomalies.


SASKATOON
TORONTO
SIDEROVSK
NEW SNOW
OLD SNOW
CLM5, Saskatoon
SNOWD, Saskatoon
CLM5, Toronto
SNOWD, Toronto
CLM5, Siderovsk
SNOWD, Siderovsk
Flux (Wm^{-1})
F ↑
G ↓
0-10
10-20
20-30
30-40
40-50
50-60
60-70
70-80
80-90
90-100
CLM5 percentile bin

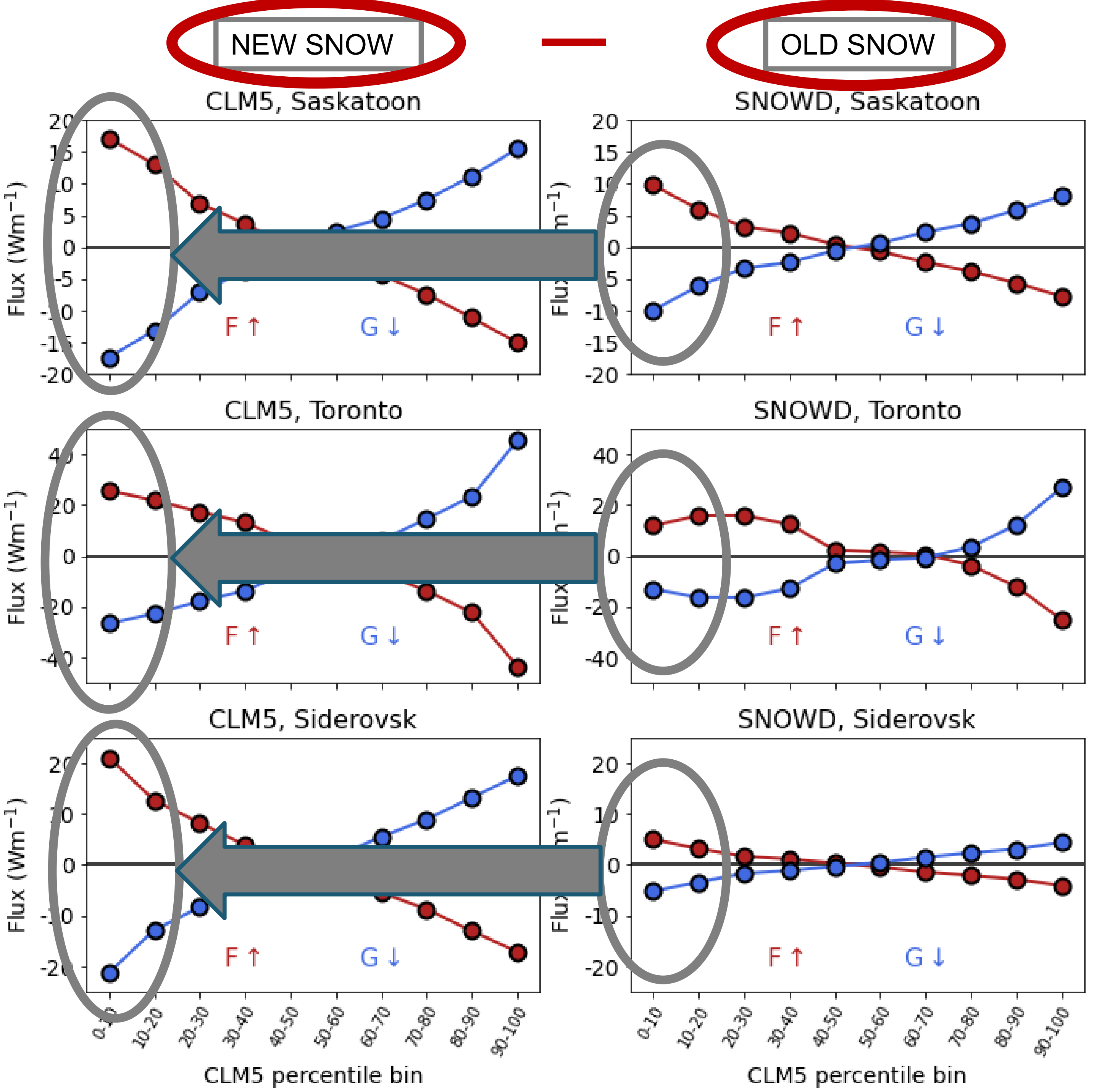
With the new snow, when it gets cold, there is a bigger anomalous upward flux from ground to atmosphere and vice-versa i.e., bigger dampening of atmospheric temperature anomalies

SIDEROVSK

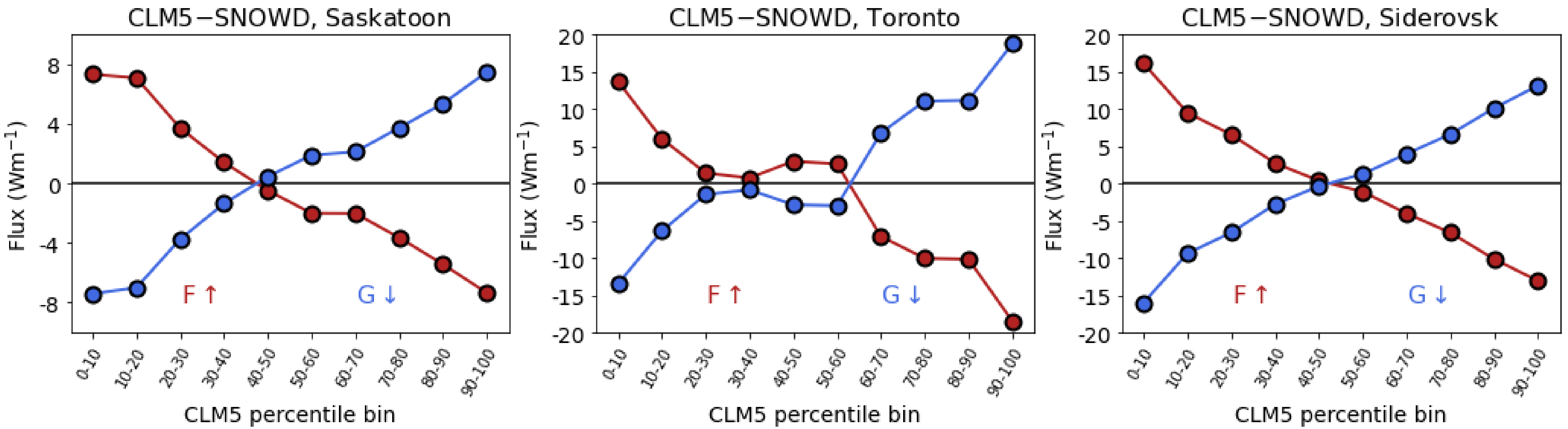


With the new snow, when it gets cold, there is a bigger anomalous upward flux from ground to atmosphere and vice-versa i.e., bigger dampening of atmospheric temperature anomalies

SIDEROVSK



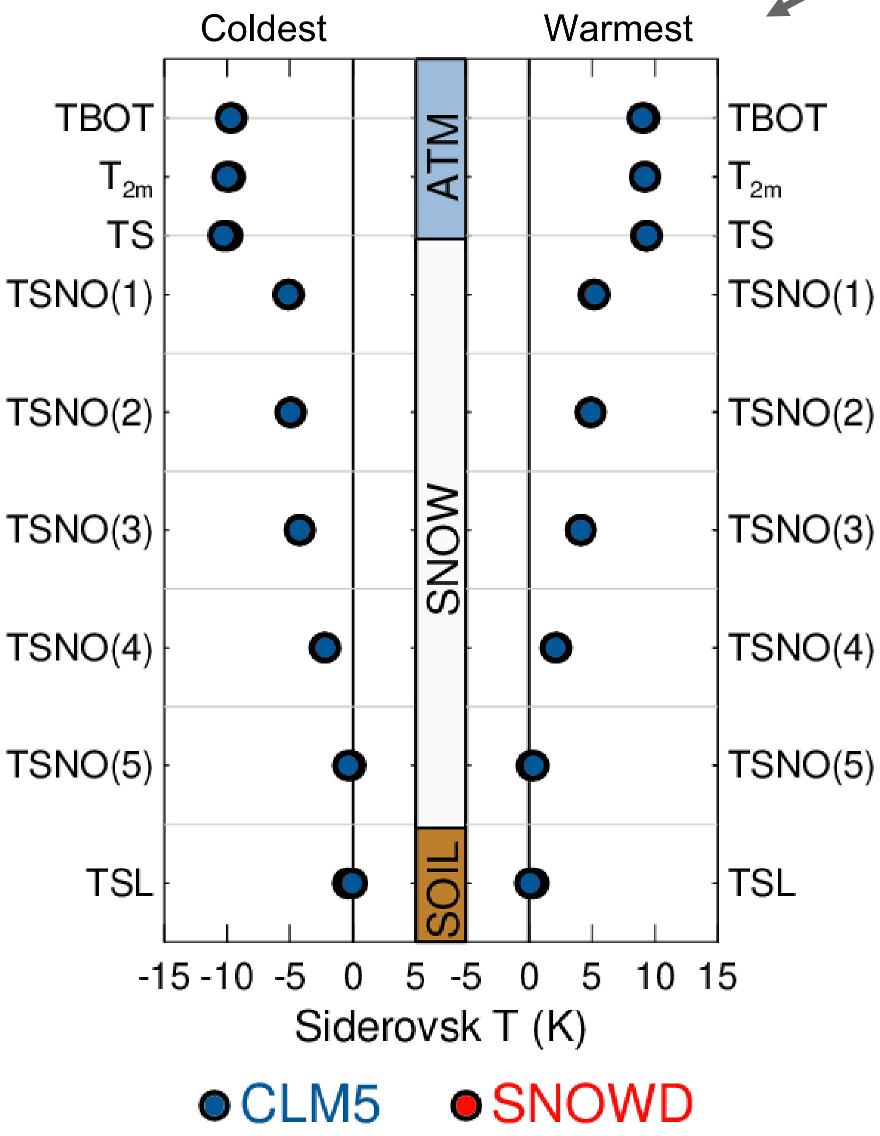
New Snow – Old Snow



Why would there be a bigger anomalous upward energy flux from ground to atmosphere when it’s cold with the new snow settings compared to the old snow settings?

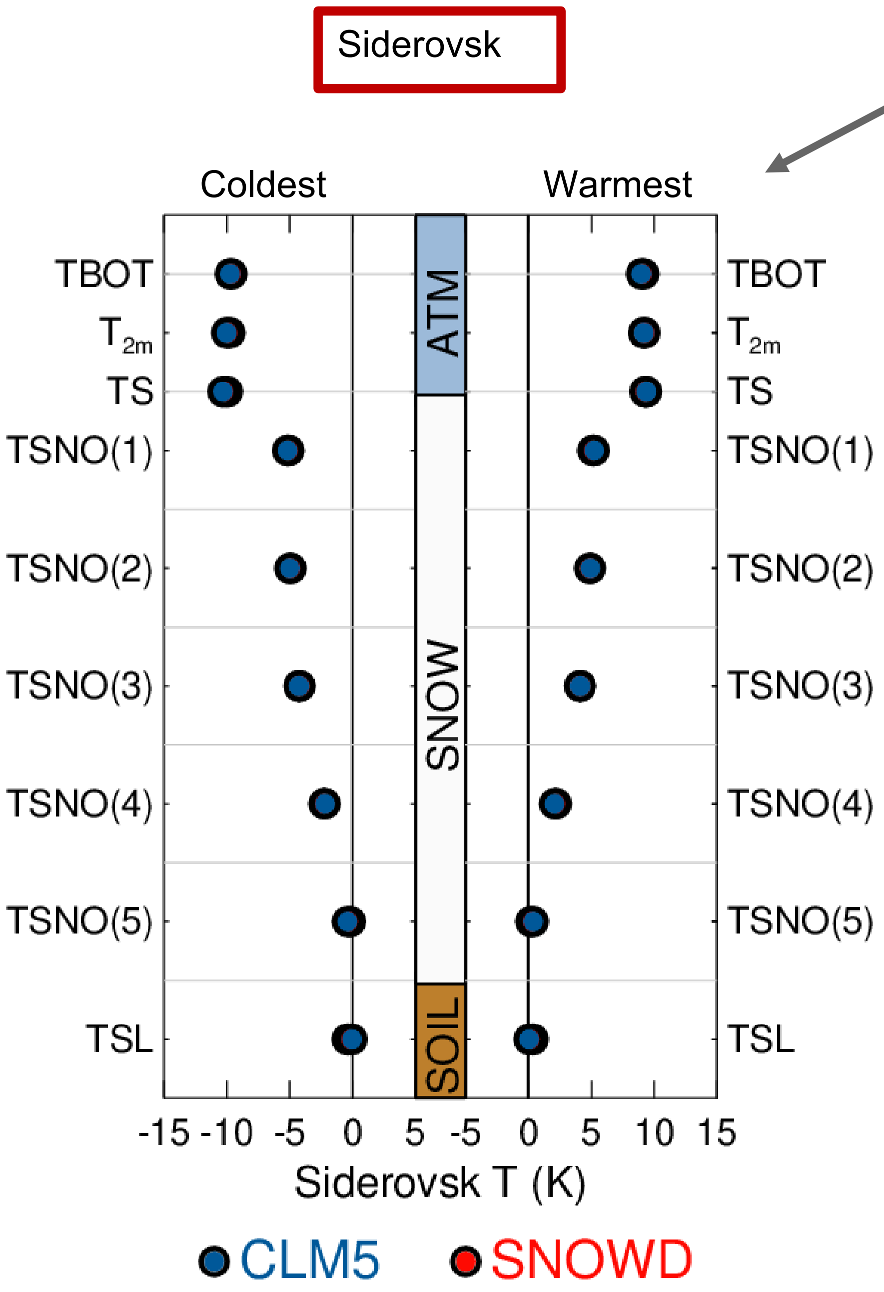
Siderovsk

Temperature anomalies for the coldest and warmest bins



Temperature anomalies for the coldest and warmest bins

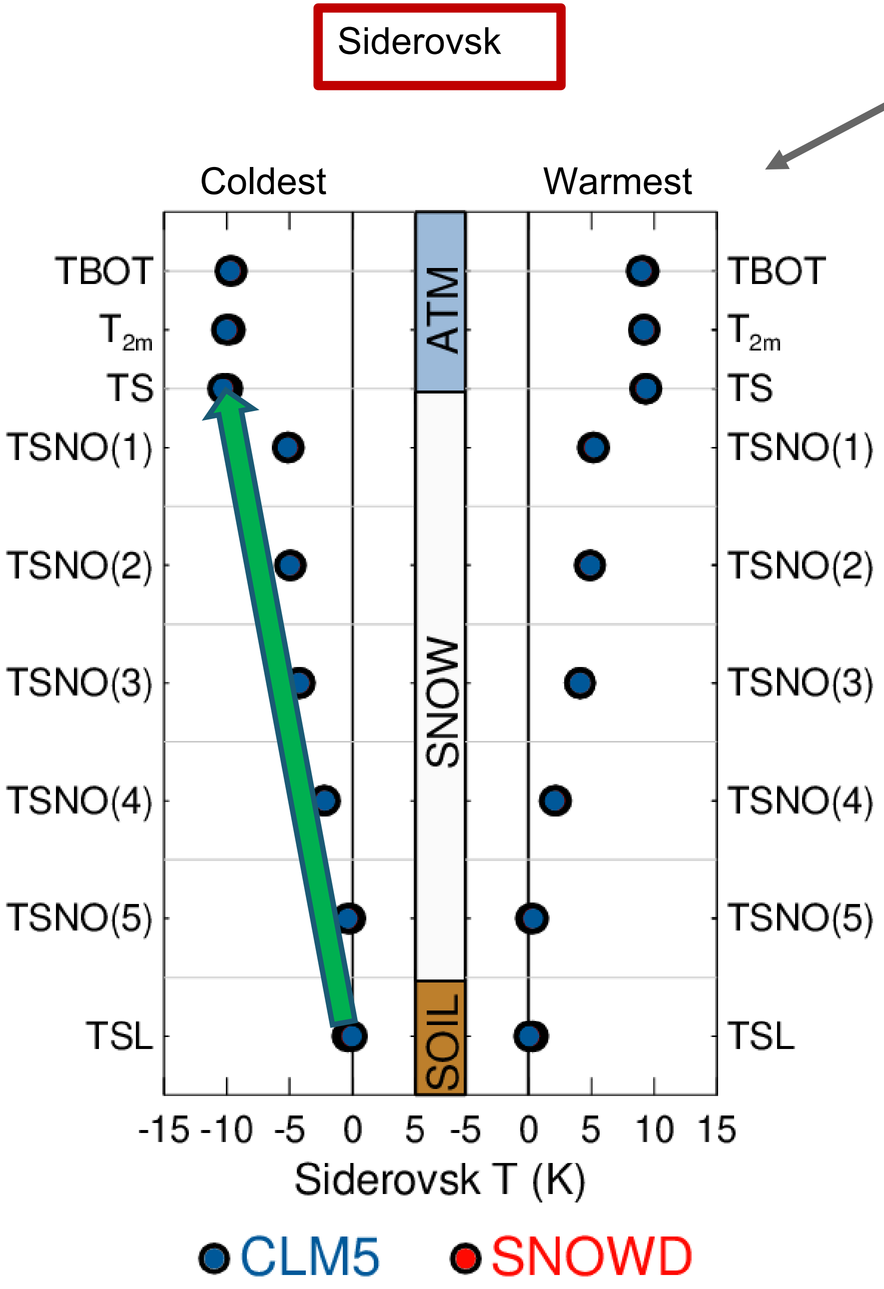
When it gets anomalously cold at the surface, it gets less anomalously cold in the snow layers and at the soil surface below.

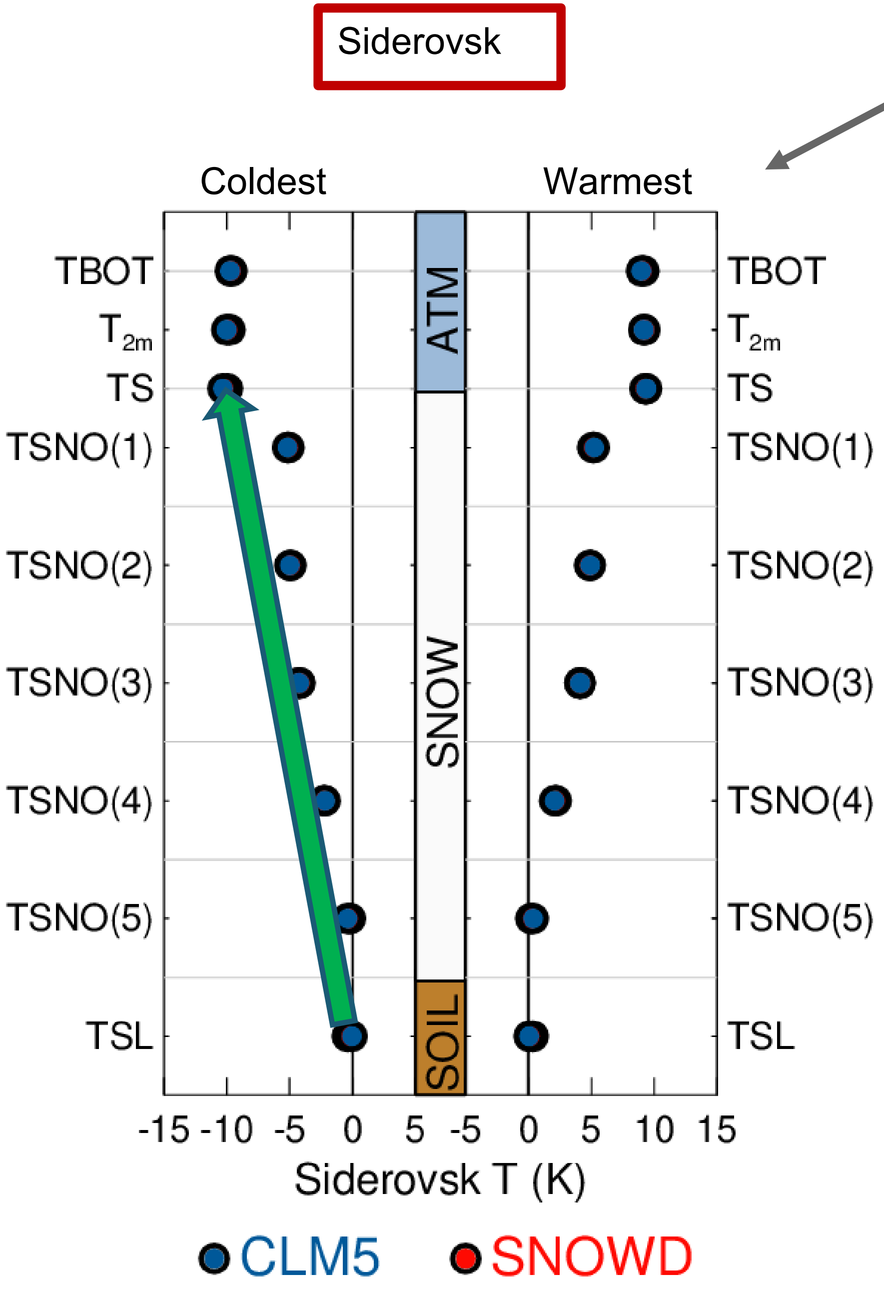


Temperature anomalies for the coldest and warmest bins

When it gets anomalously cold at the surface, it gets less anomalously cold in the snow layers and at the soil surface below.

A temperature gradient is induced.





Temperature anomalies for the coldest and warmest bins

When it gets anomalously cold at the surface, it gets less anomalously cold in the snow layers and at the soil surface below.

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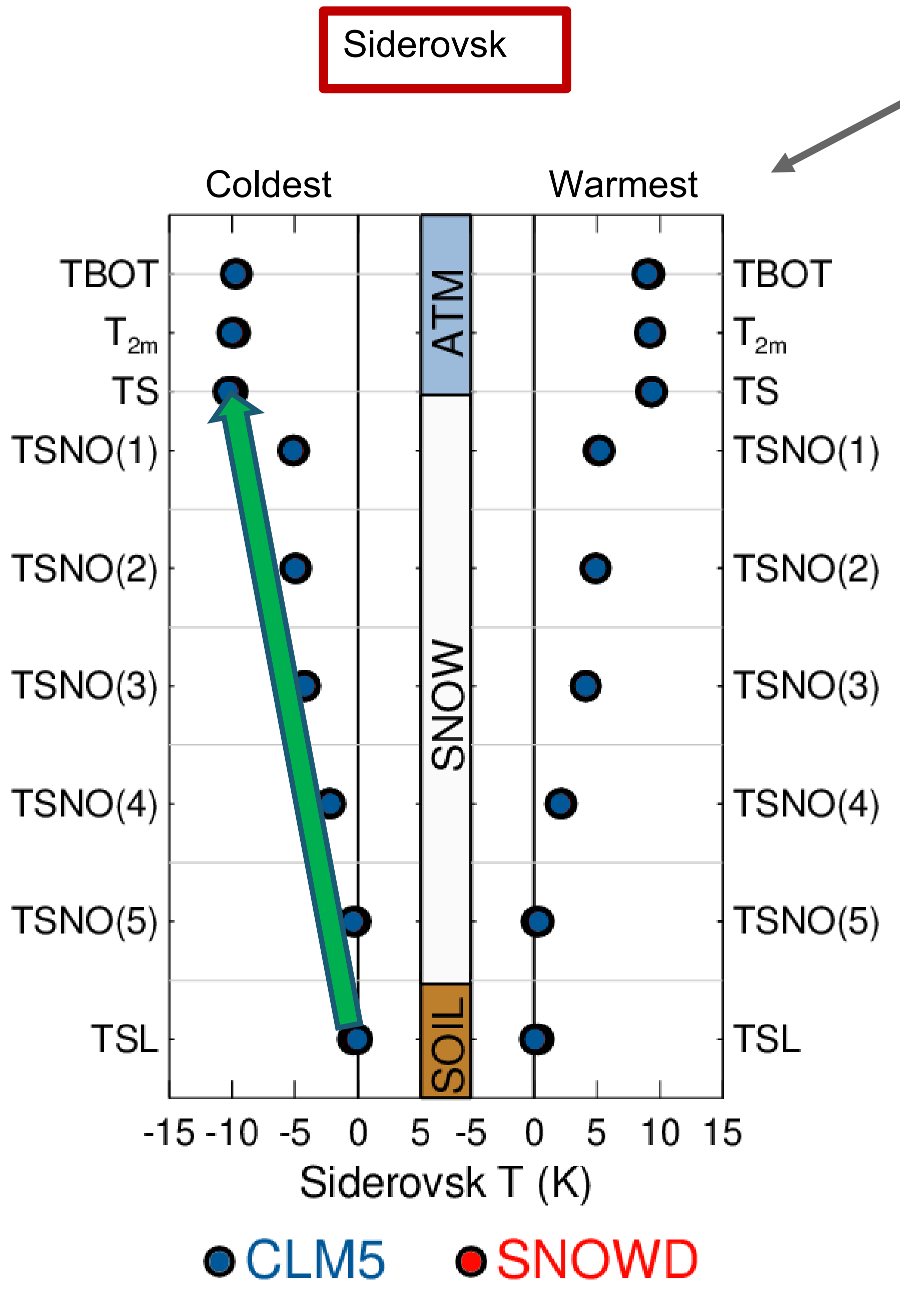
As a result we'd expect an upward heat flux across the snow layer



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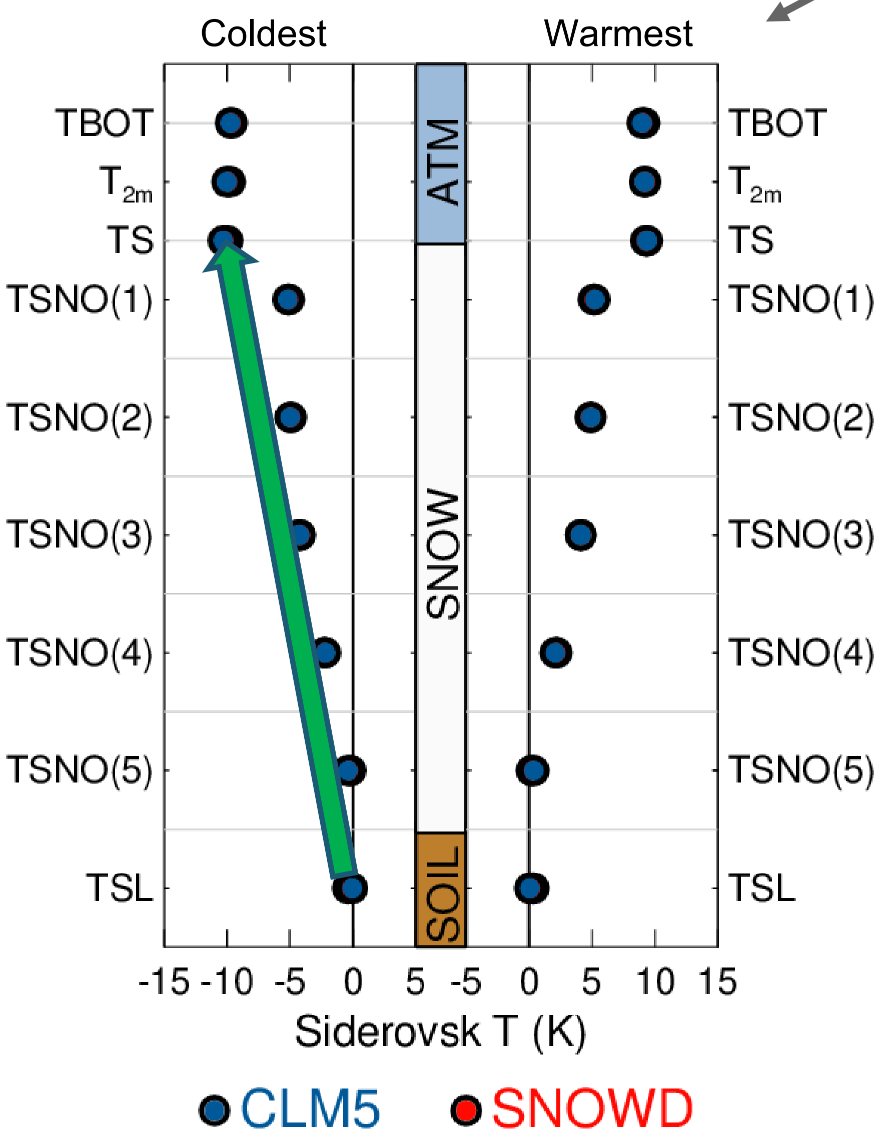
Flux (+ve upward)

Conductance

Temperature gradient

Siderovsk



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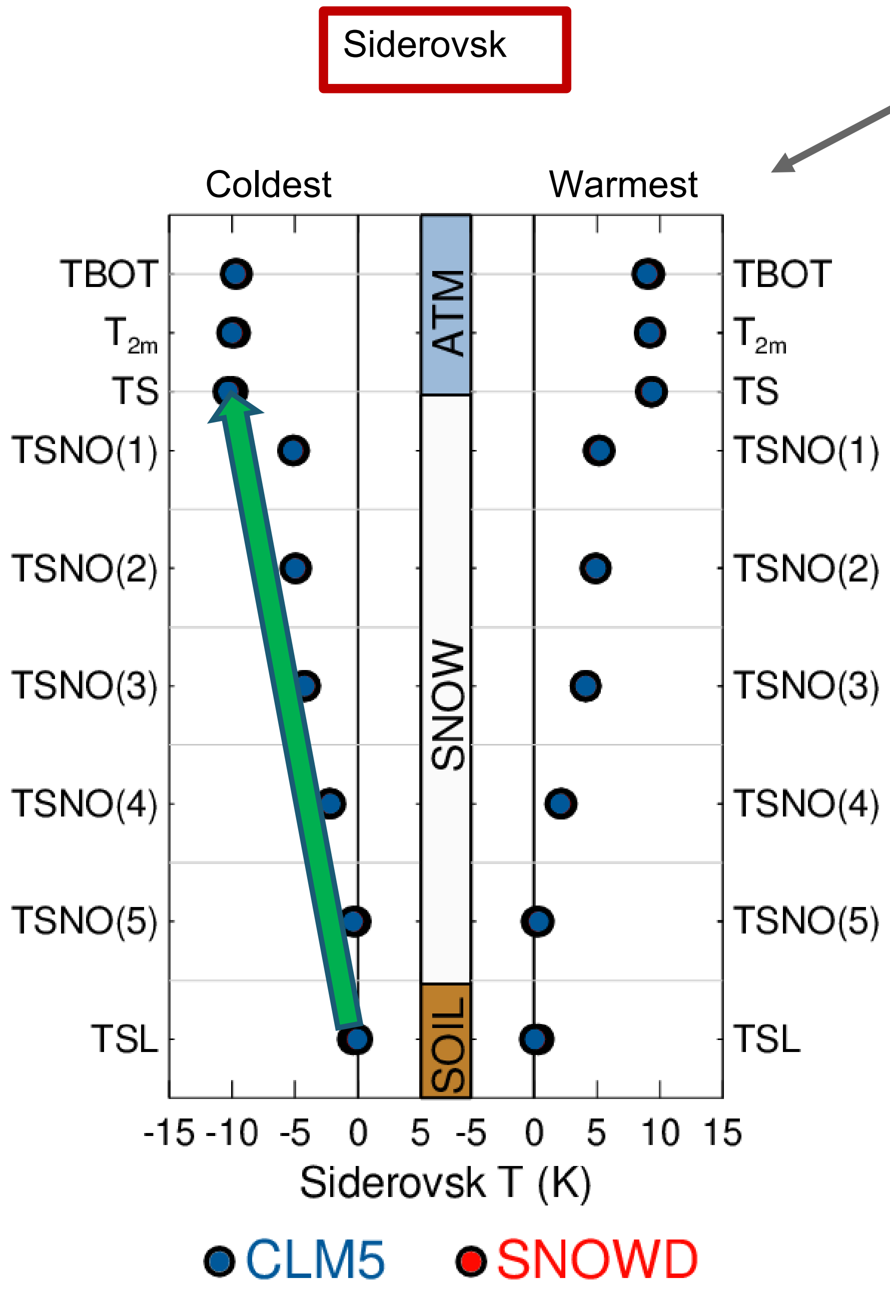
$$\lambda_{ice} = 2.29Wm^{-1}K^{-1} \qquad \lambda_{air} = 0.023Wm^{-1}K^{-1}$$



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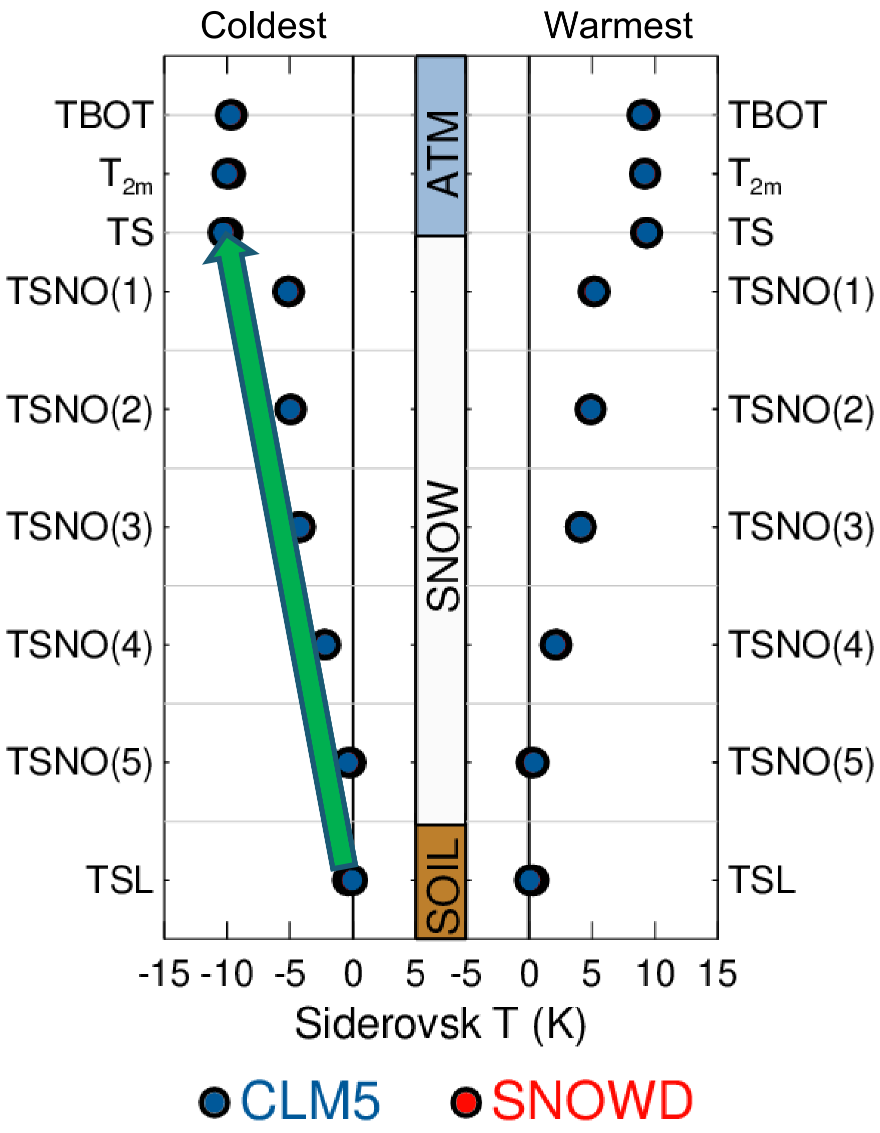
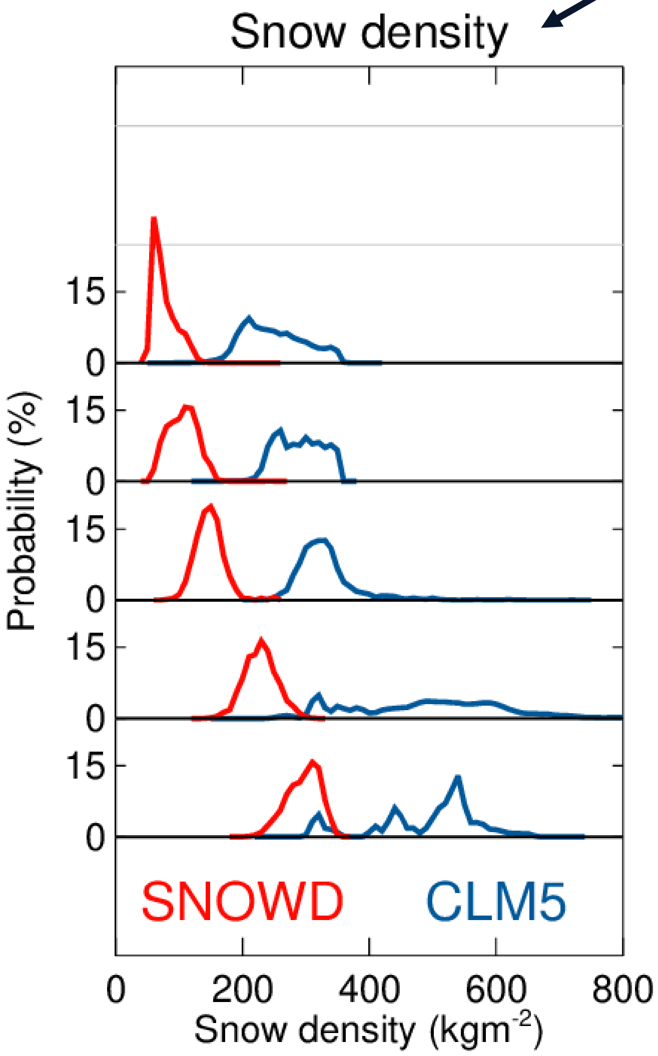
Higher ρ_{sno} → Higher λ

Siderovsk

PDFs of snow density using timestep data from SCAM





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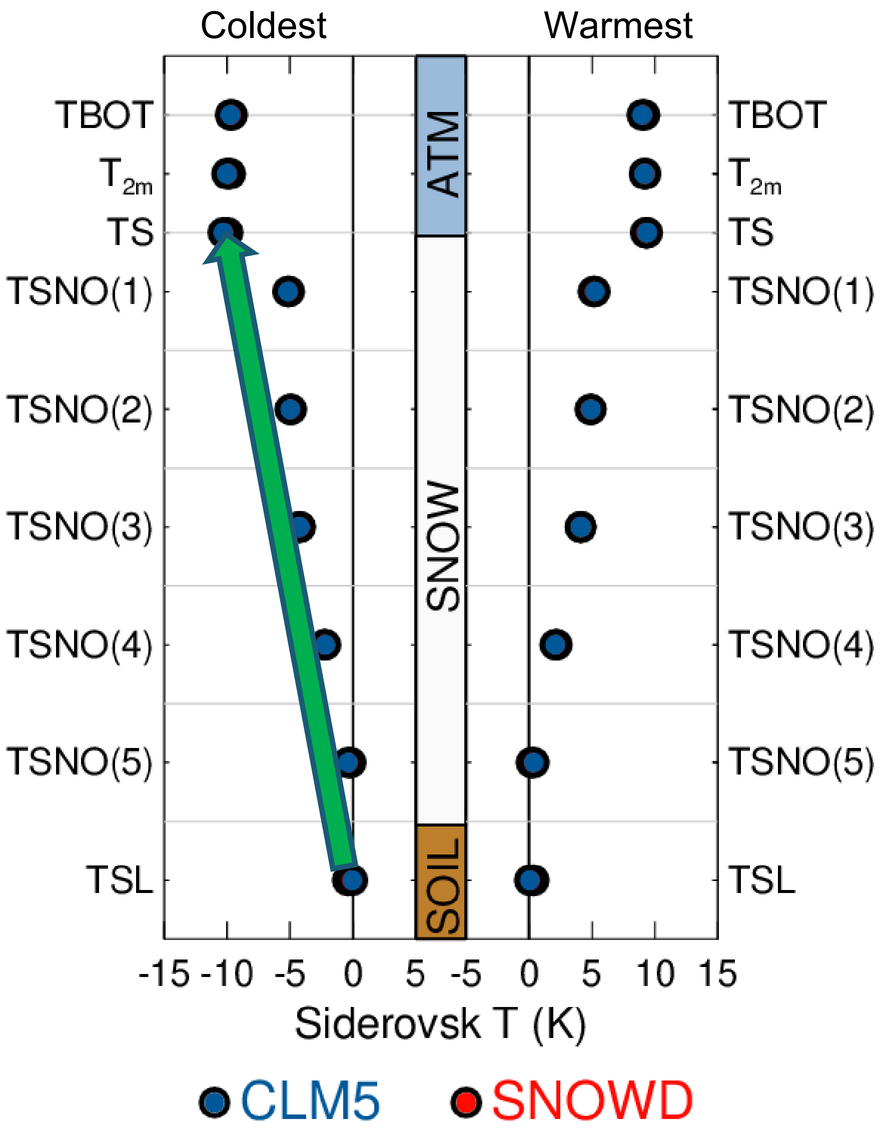

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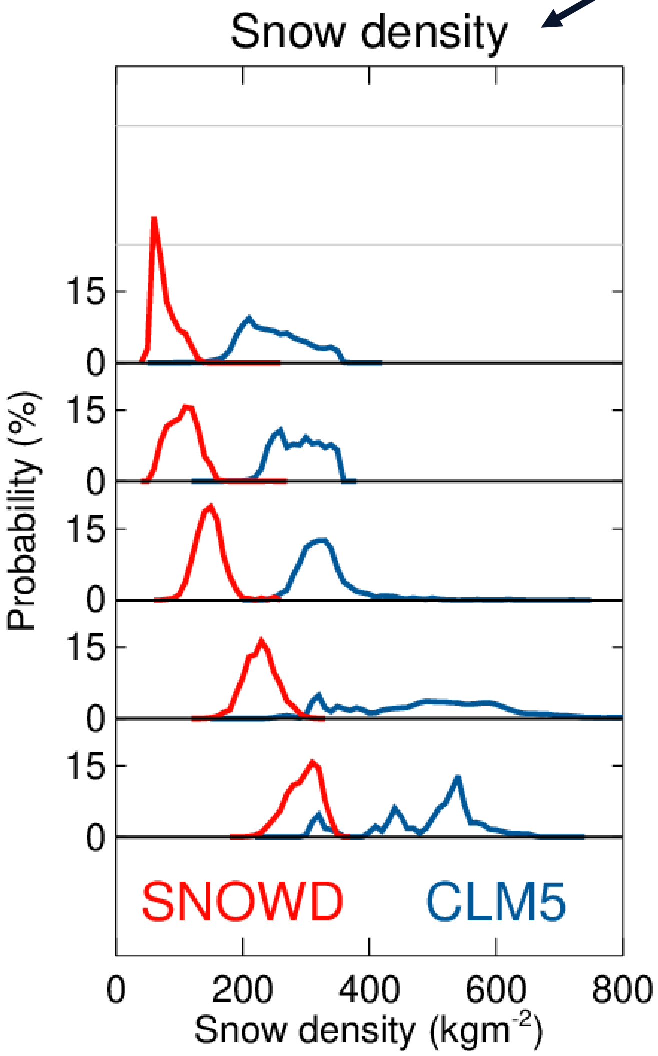
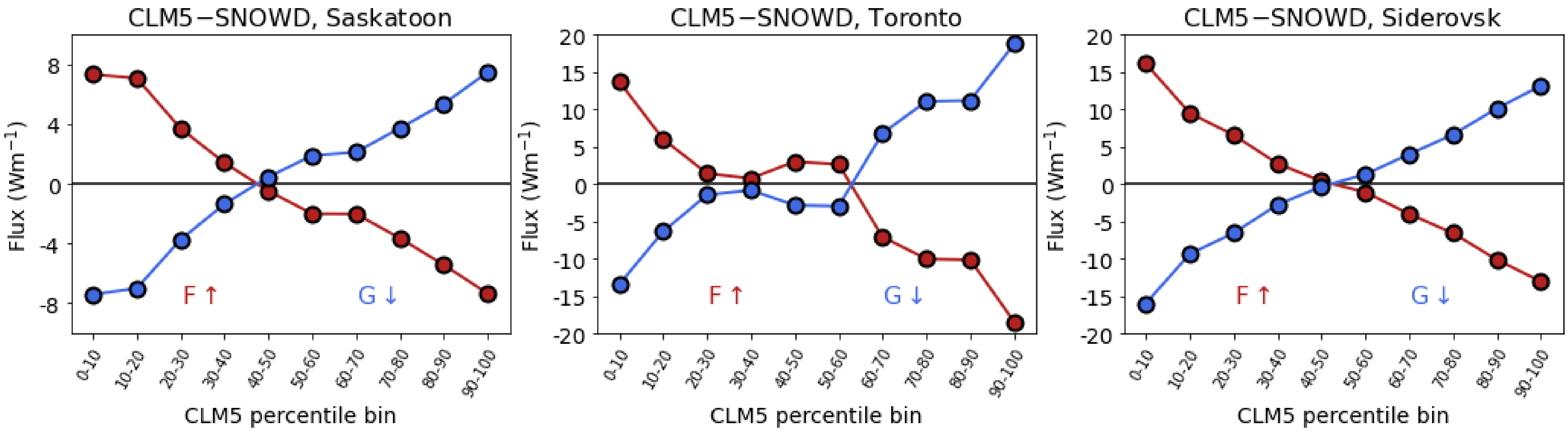


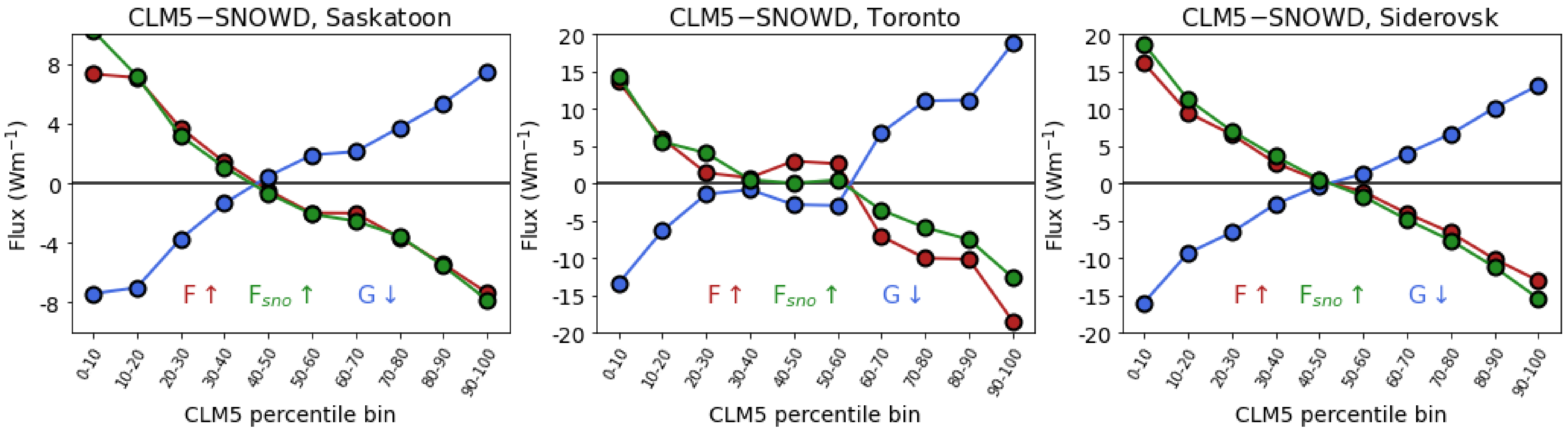
What if we considered the snow layers to be a constant flux layer with an average density and, therefore, average conductance?

$$\hat{F}_{SNO} = \bar{\lambda}\frac{TSNO(1) - TSL}{\Delta z}$$

New Snow – Old Snow



New Snow – Old Snow



Temperature of top snow layer

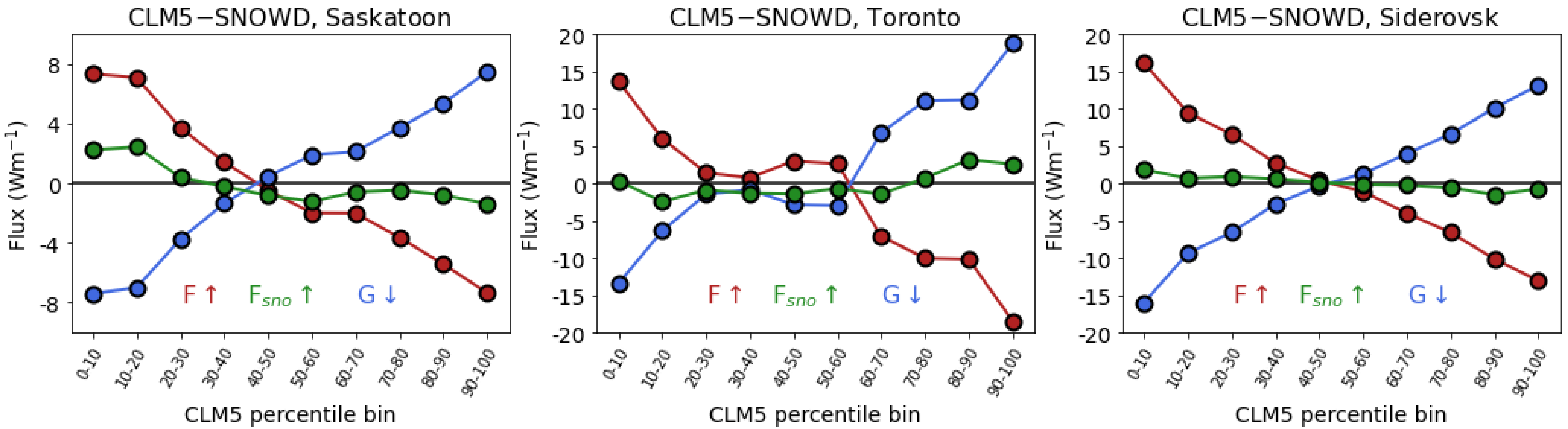
Temperature of top soil layer

$$F_{SNO} = \lambda \frac{SNOTTOPL - TSL}{SNOWDP}$$

Conductance

Snow depth

New Snow – Old Snow



Temperature of top snow layer

Temperature of top soil layer

$$F_{SNO} = \lambda_o \frac{SNOTTOPL - TSL}{SNOWDP}$$

Average conductance from CLM5

Snow depth

Conclusions

- There has been a big reduction in surface temperature variance in going from CESM1 to CESM2
- This is an improvement
- The changes in CLM in going from CLM4 to CLM5 are playing an important role
- The relevant change in CLM is the change in snow density and densification

Snow is more dense → Higher conductance → Larger anomalous flux of heat across the snow layer when it gets cold or warm → More effective dampening of atmospheric temperature anomalies

Ongoing work:

- Which snow settings matter most?
- Can we check we're getting the answer right for the right reasons e.g., compared surface energy balance anomalies with obs.
- Impact on future projected changes and the variability in those changes.

Extra Slides

What is the atmosphere doing with this change in flux across the snow layer?

-

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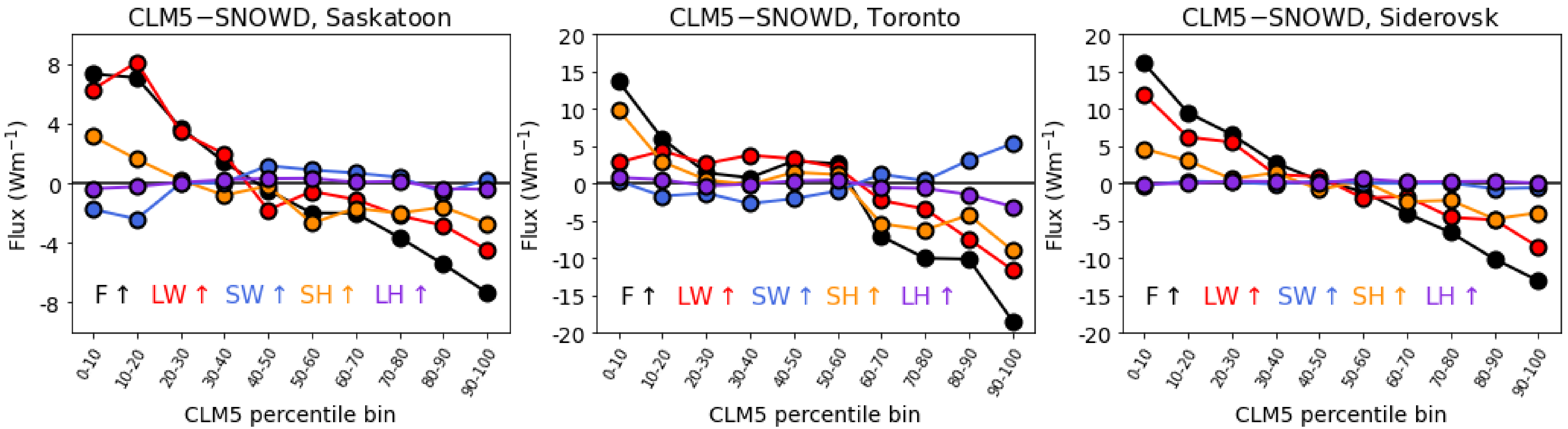

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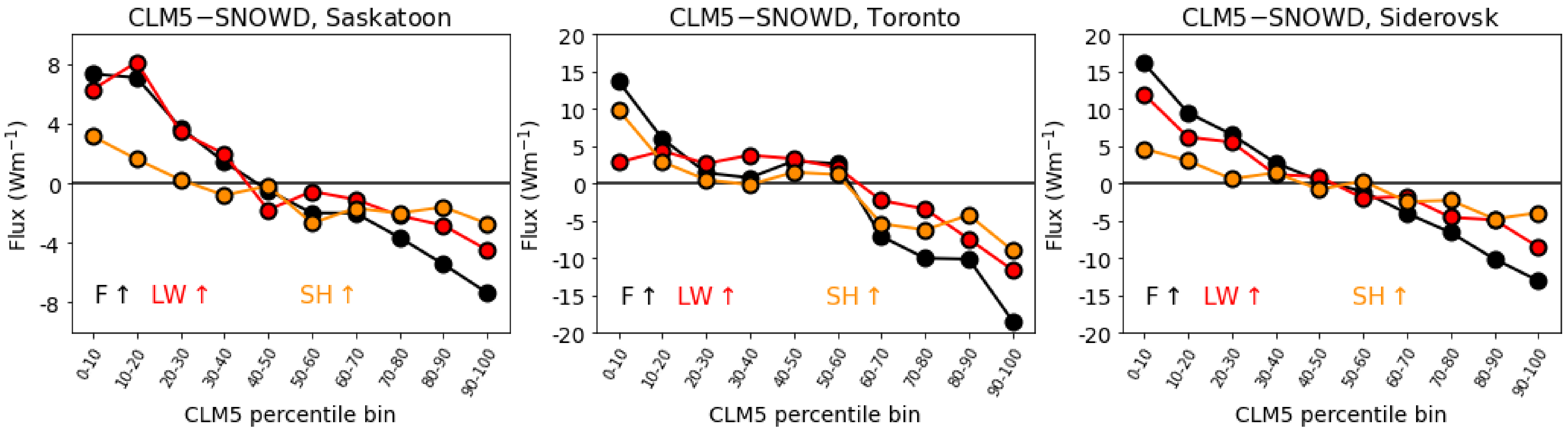
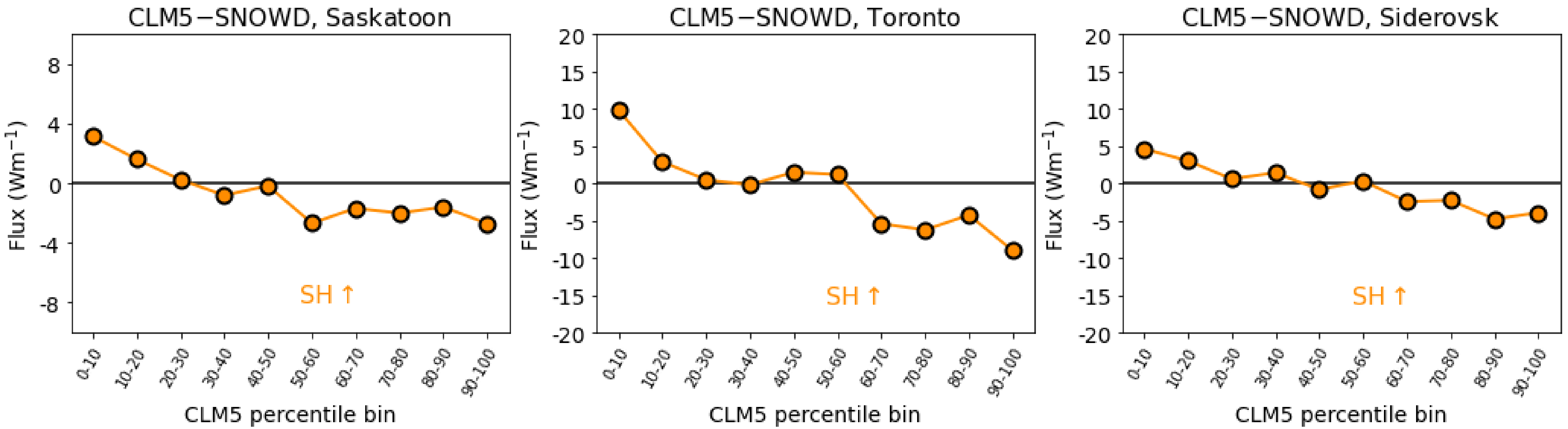


The change in sensible heat flux



The change in sensible heat flux

Potential temperature difference between the surface and the lowest CAM model level

Density at the lowest model level

$$SH = \rho_1 c_p \frac{\theta_s - \theta_1}{r_{ah}}$$

Upward heat flux from surface to lowest CAM model level

Specific heat capacity of dry air at constant pressure

Aerodynamic resistance for sensible heat between the lowest model level at height z_1 and the surface at height $z_{0h} + d$

Roughness length

Displacement height

The change in sensible heat flux

$$SH \sim K(TS - TBOT)$$

Temperature at the surface

Temperature on the lowest atmospheric level

The change in sensible heat flux

$$SH \sim K(TS - TBOT)$$

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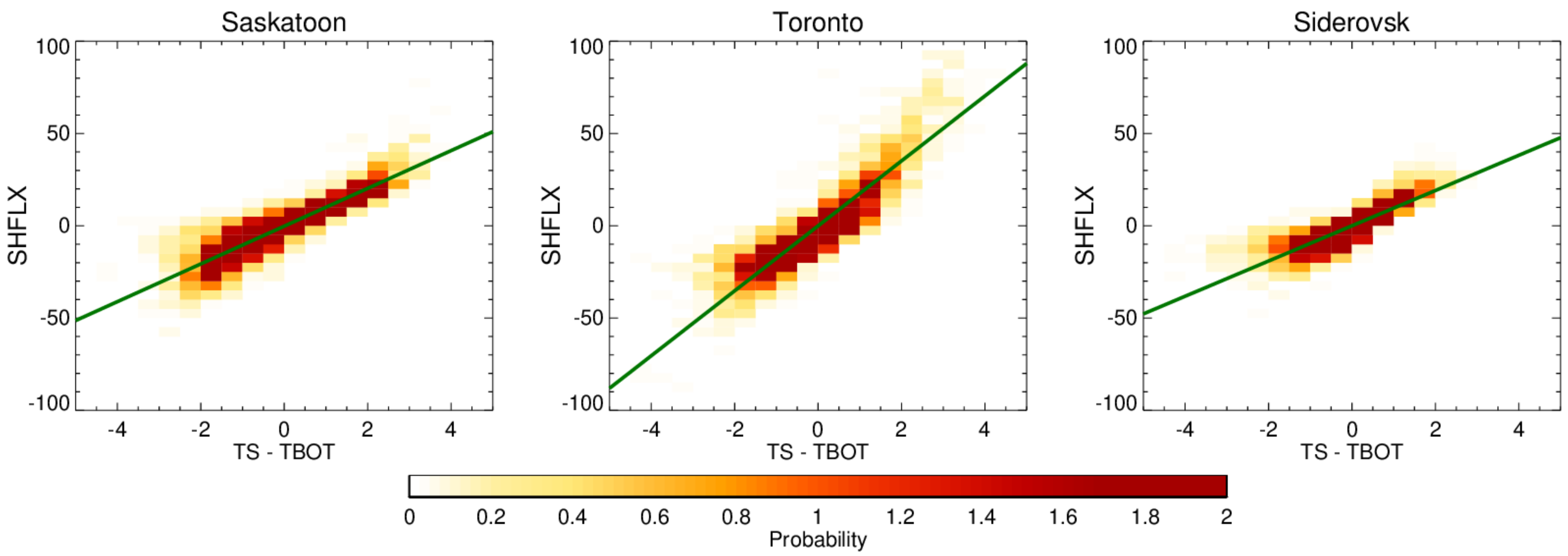
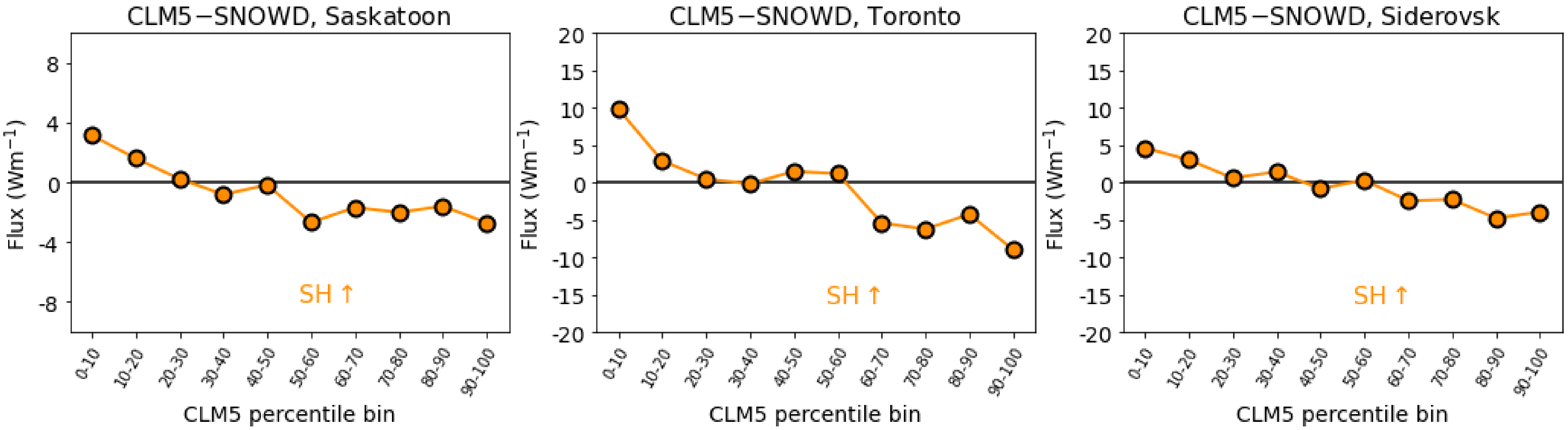


The change in sensible heat flux

$$SH^{*} \sim K_o(TS - TBOT)$$

Lets assume a constant slope, derived from CLM5



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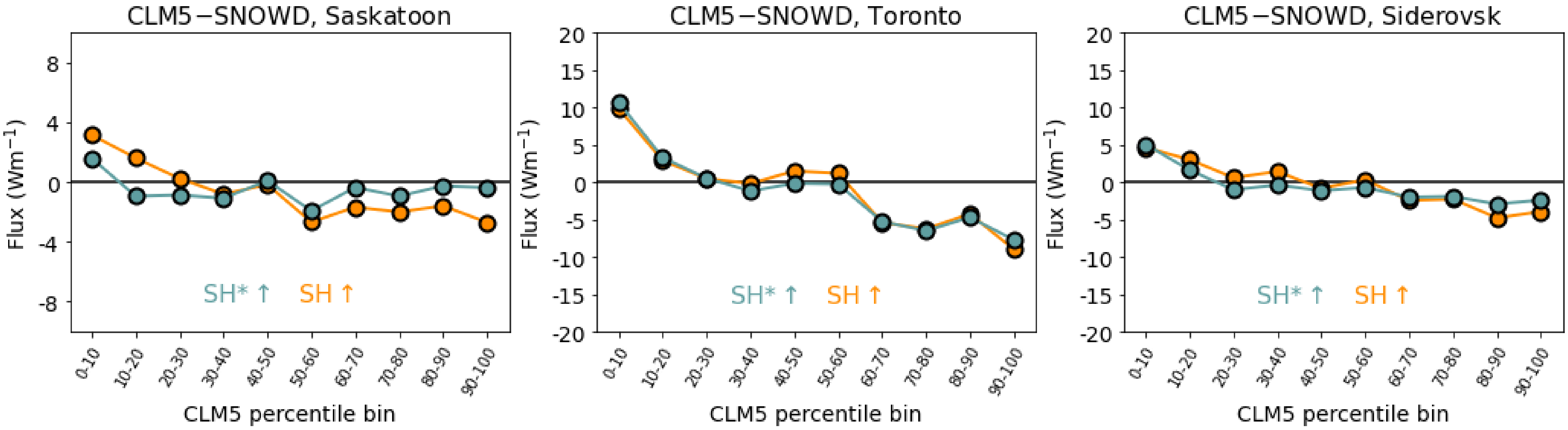

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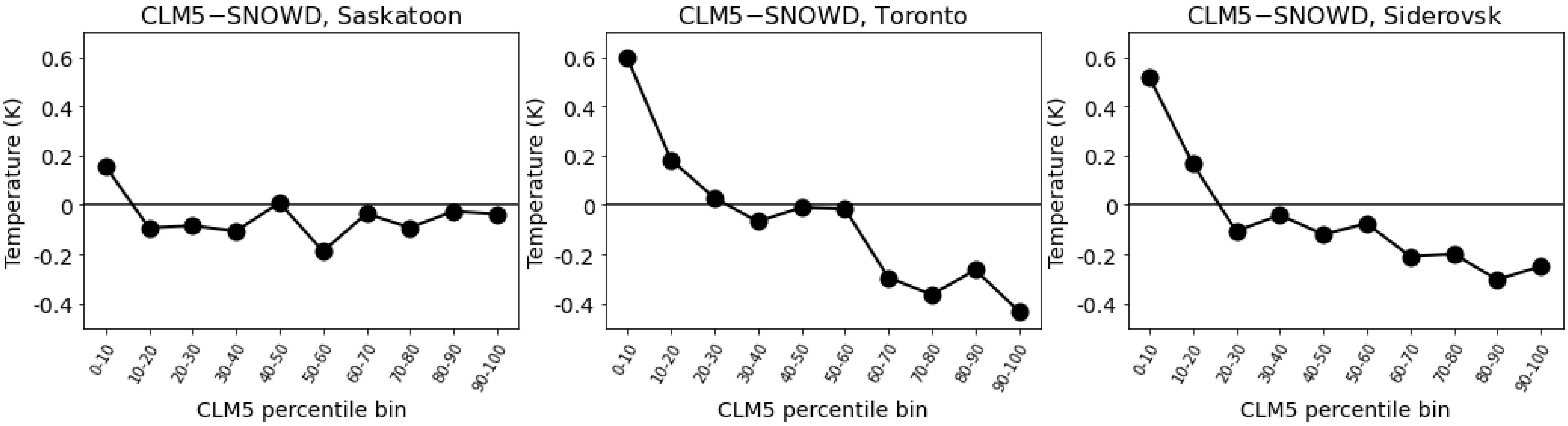
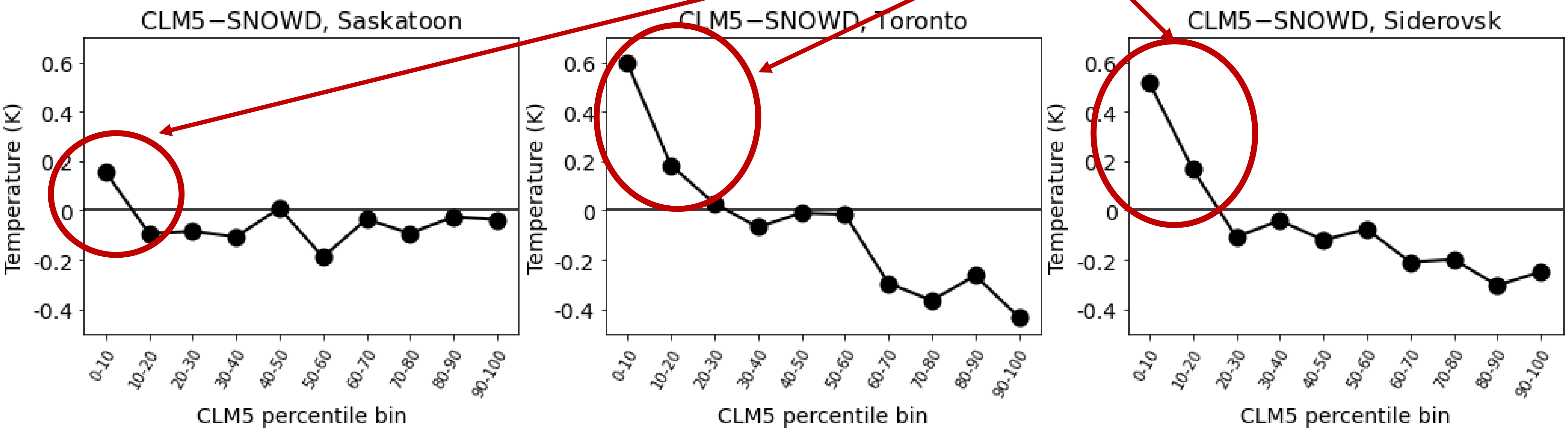


The change in sensible heat flux

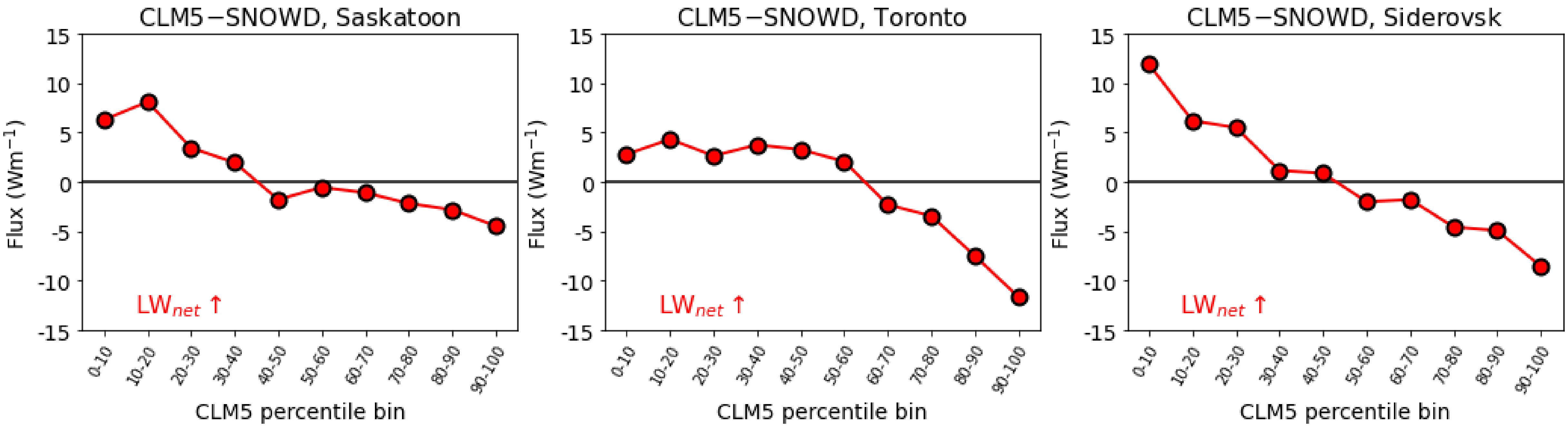
$$SH^{*} \sim K_{o}(TS - TBOT)$$

Lets assume a constant slope, derived from CLM5

In CLM5, when it gets cold, the surface is relatively less cold compared to the lowest atmospheric model level → enhanced upward sensible heat flux. Opposite is true when it's warm



The change in longwave radiation



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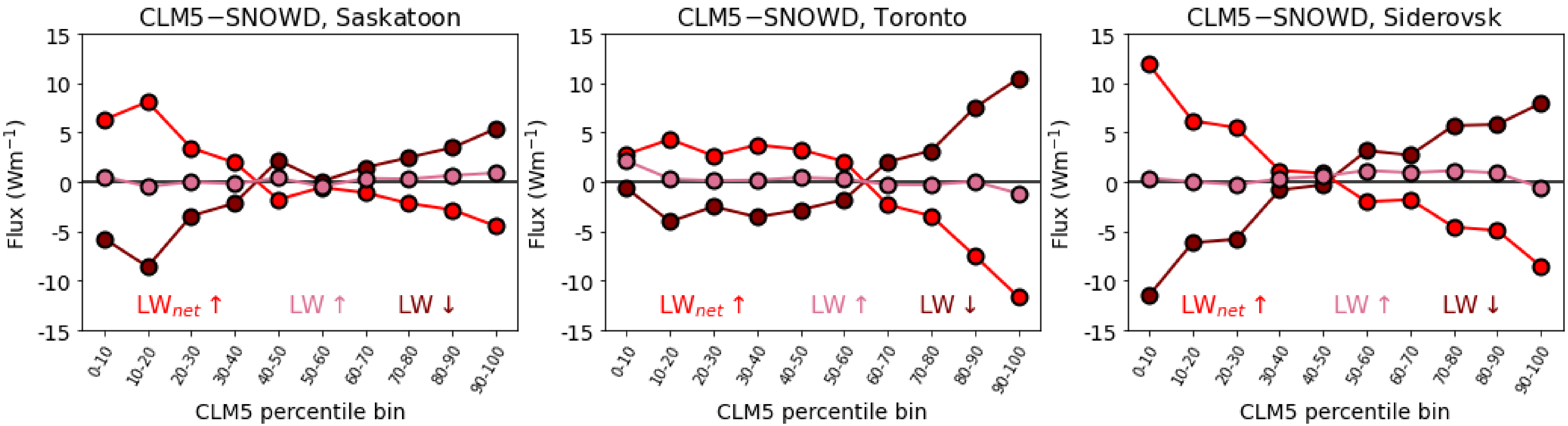

CREATING ACCESSIBLE POWERPOINTS

(DELETE SLIDE AFTER READING)

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- Use “Alt text” for slide elements
- Ensure appropriate color contrasts are used
- Reference the detailed instructions for each operating system

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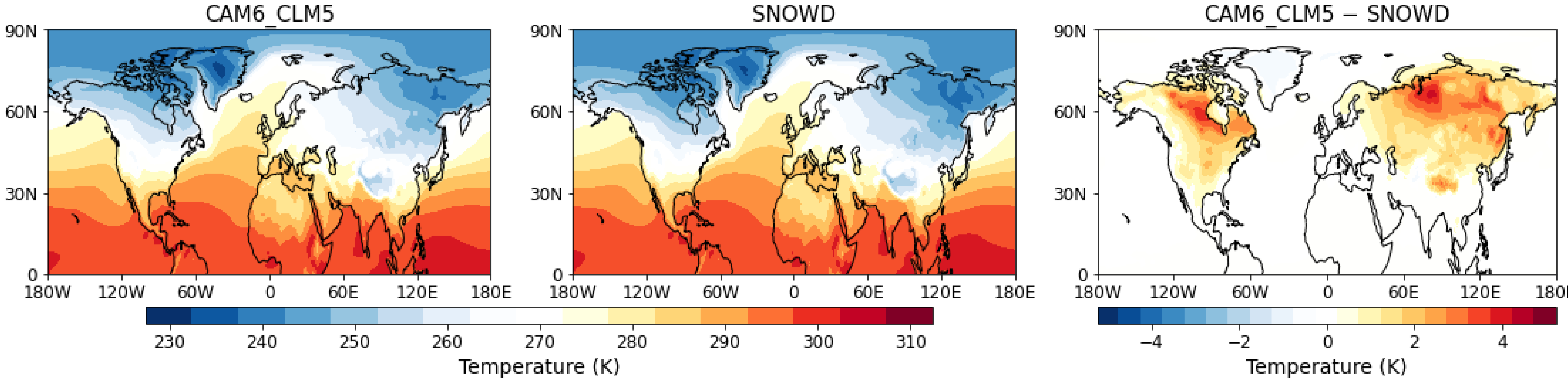
Watch Microsoft Accessibility Tutorial

Local or non -local influences?

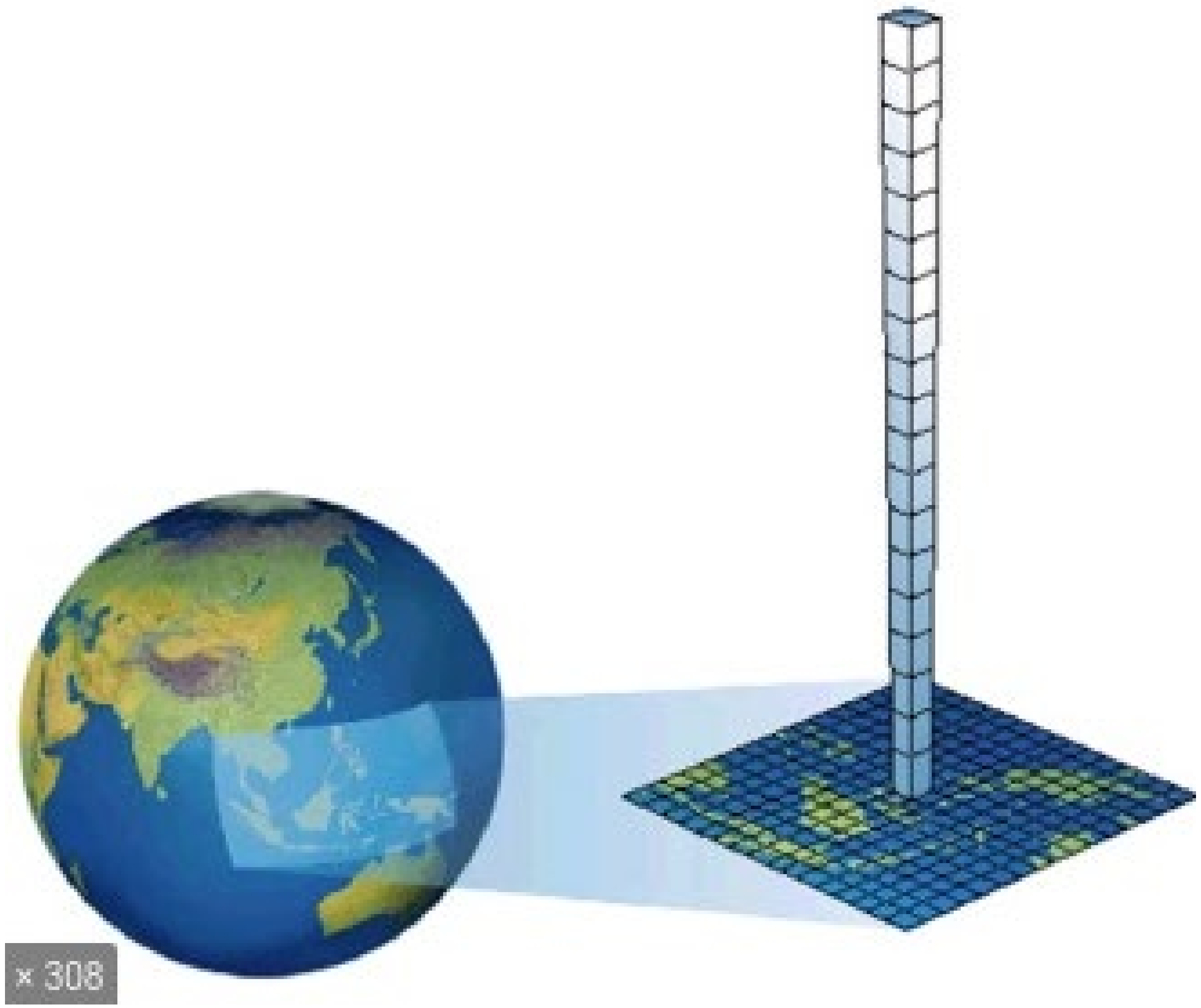
DJF surface temperature climatology



To understand the influence of snow density/densification should we be thinking about local column physics or the non-local influence of altered temperature advection due to altered temperature gradients?

Single Column Model Experiments

SCAM = The CESM single column model (Gettelman et al 2018)



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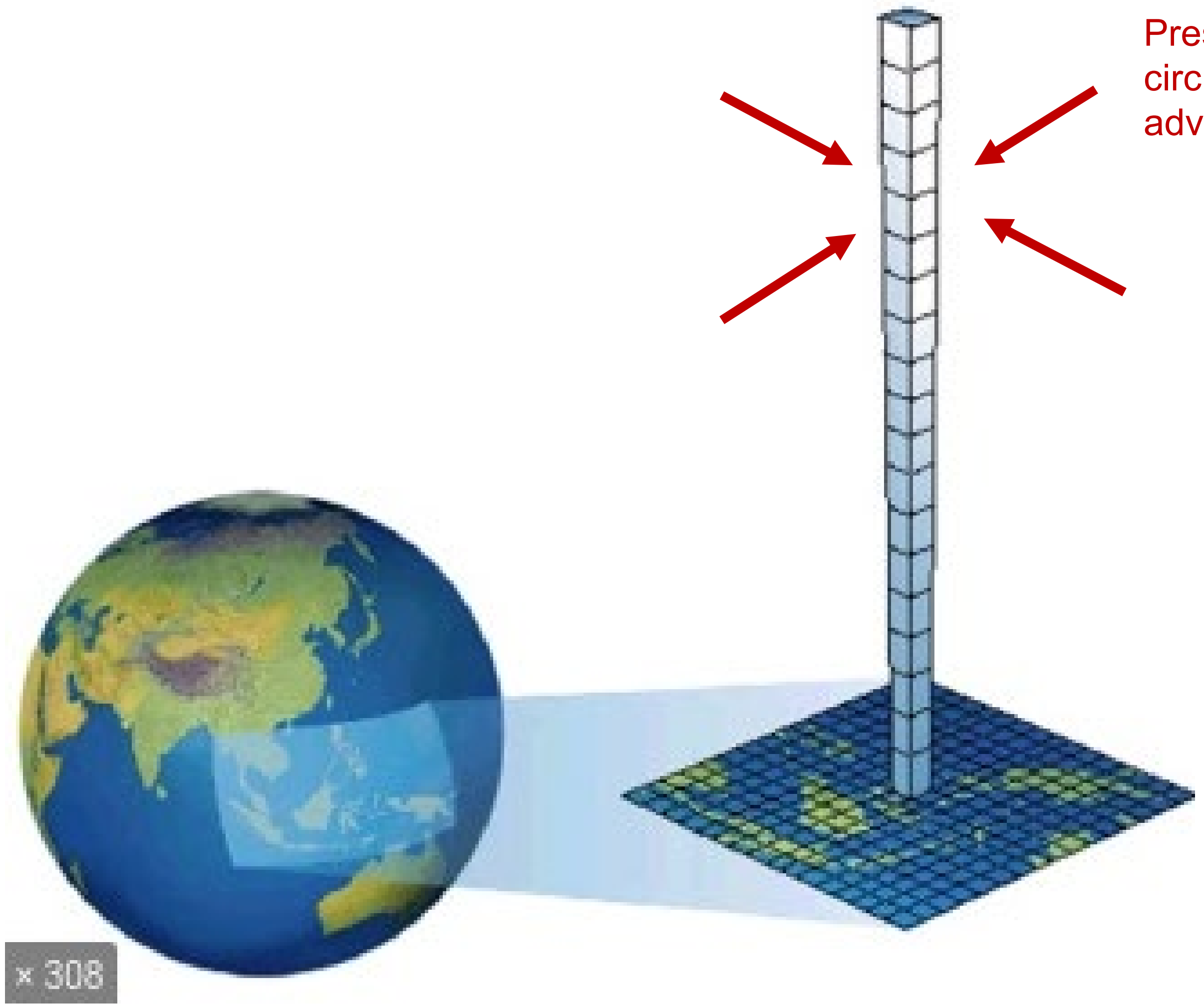

Prescribe the atmospheric circulation and associated advection terms

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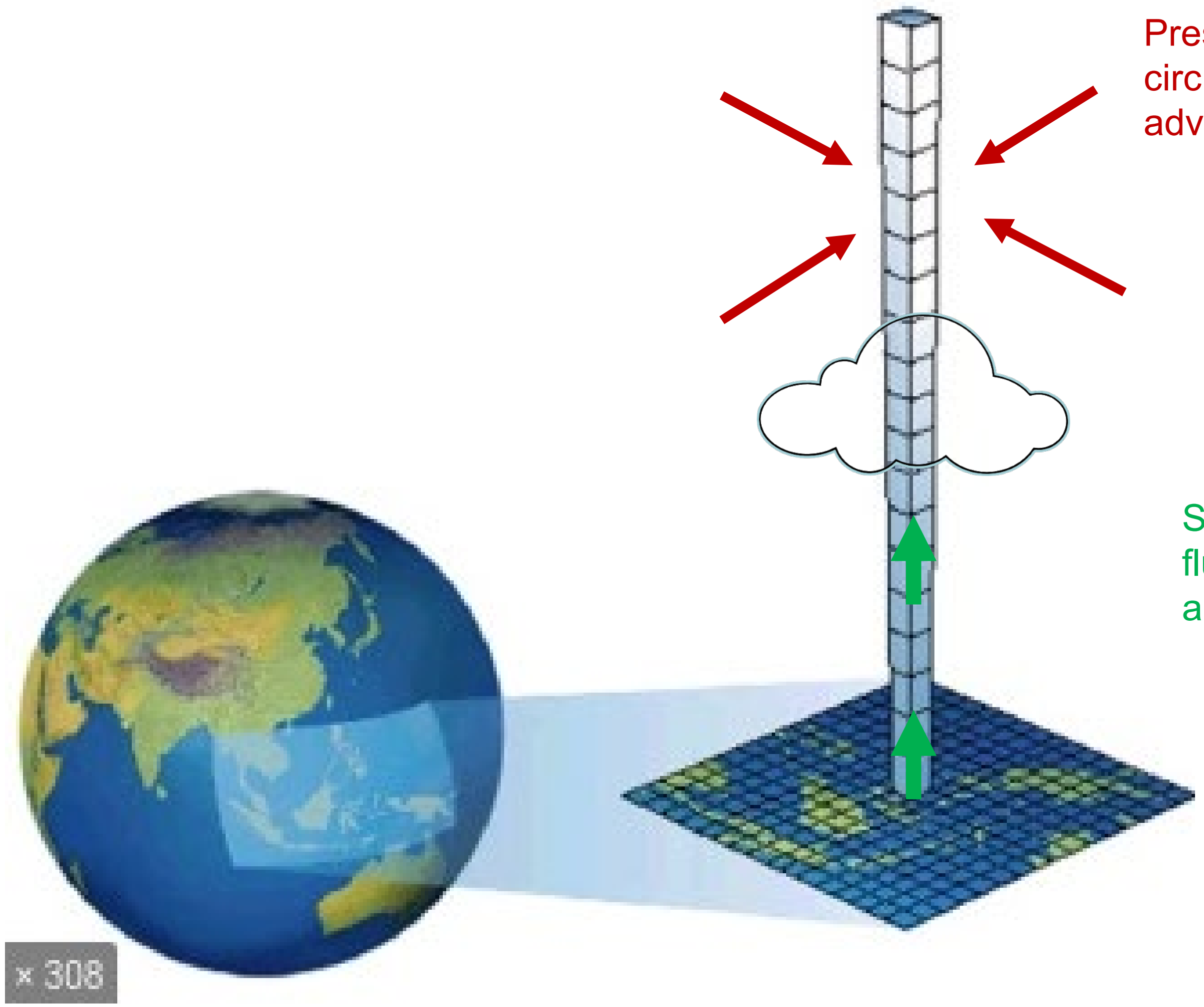
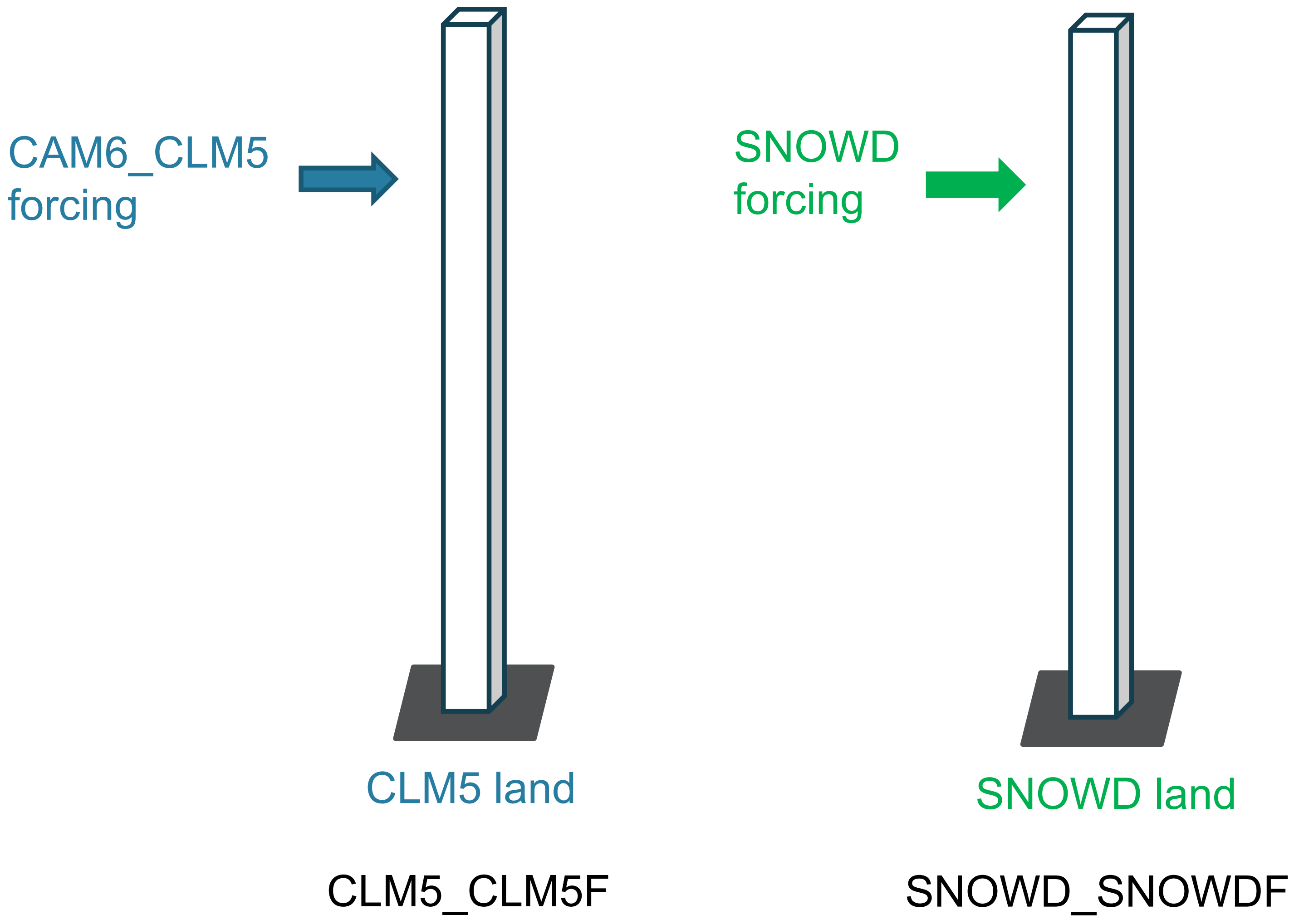


Prescribe the atmospheric circulation and associated advection terms

SCAM solves for the surface fluxes, the column physics and the vertical advection

Single Column Model Experiments



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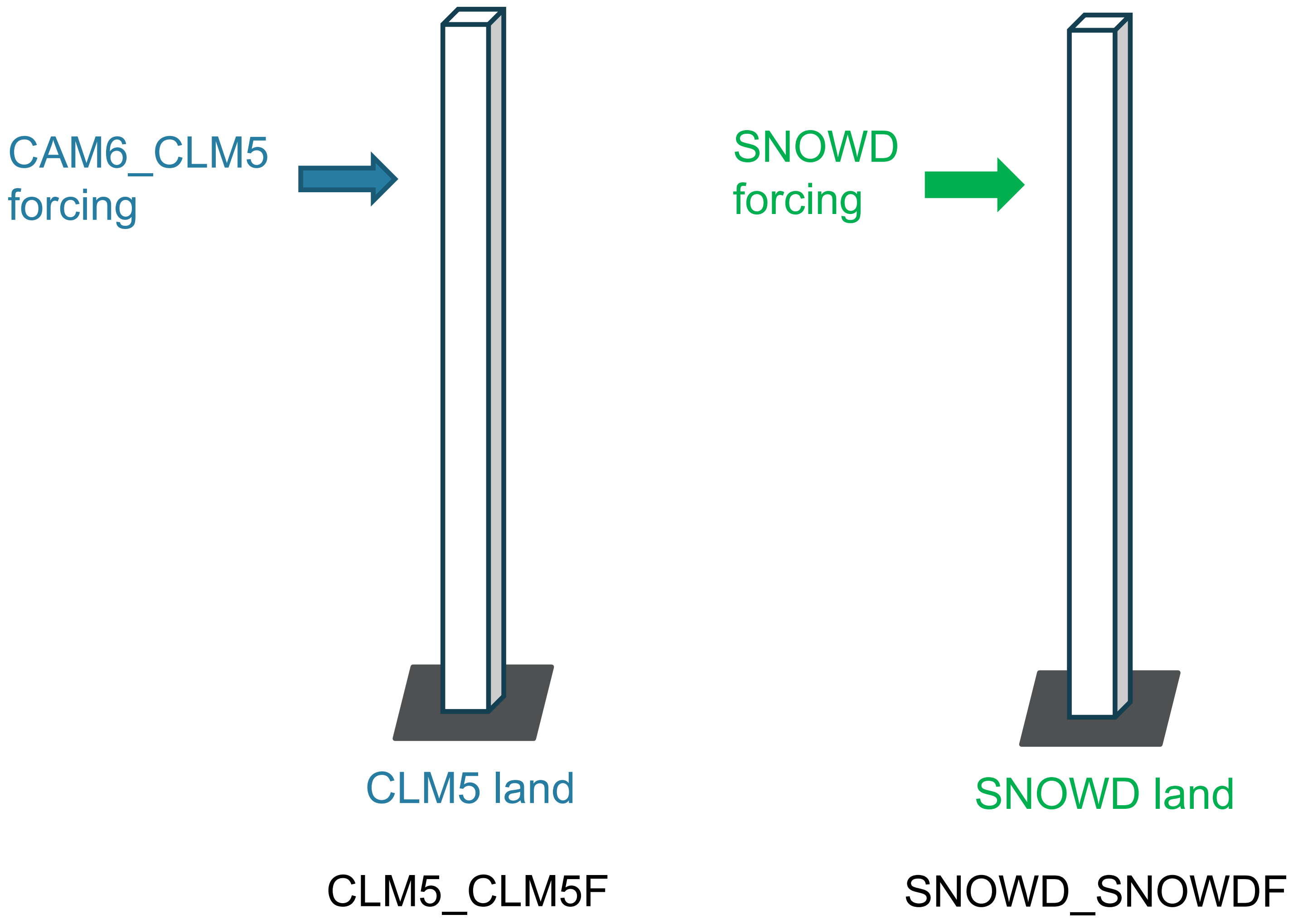


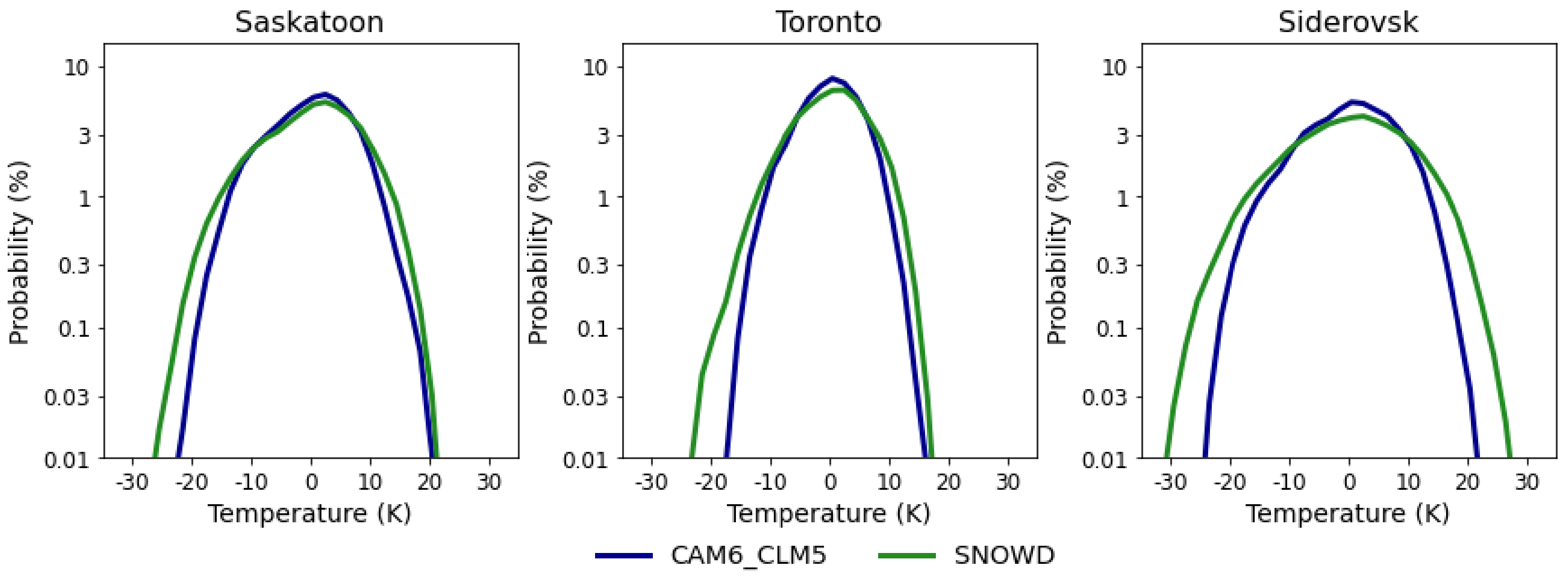
2x 36 year simulations (1979-2014)

Circulation from our CAM experiments

Three locations:Saskatoon, Toronto, Siderovsk

Can we reproduce the change in T2m variability in SCAM?

FULL CAM



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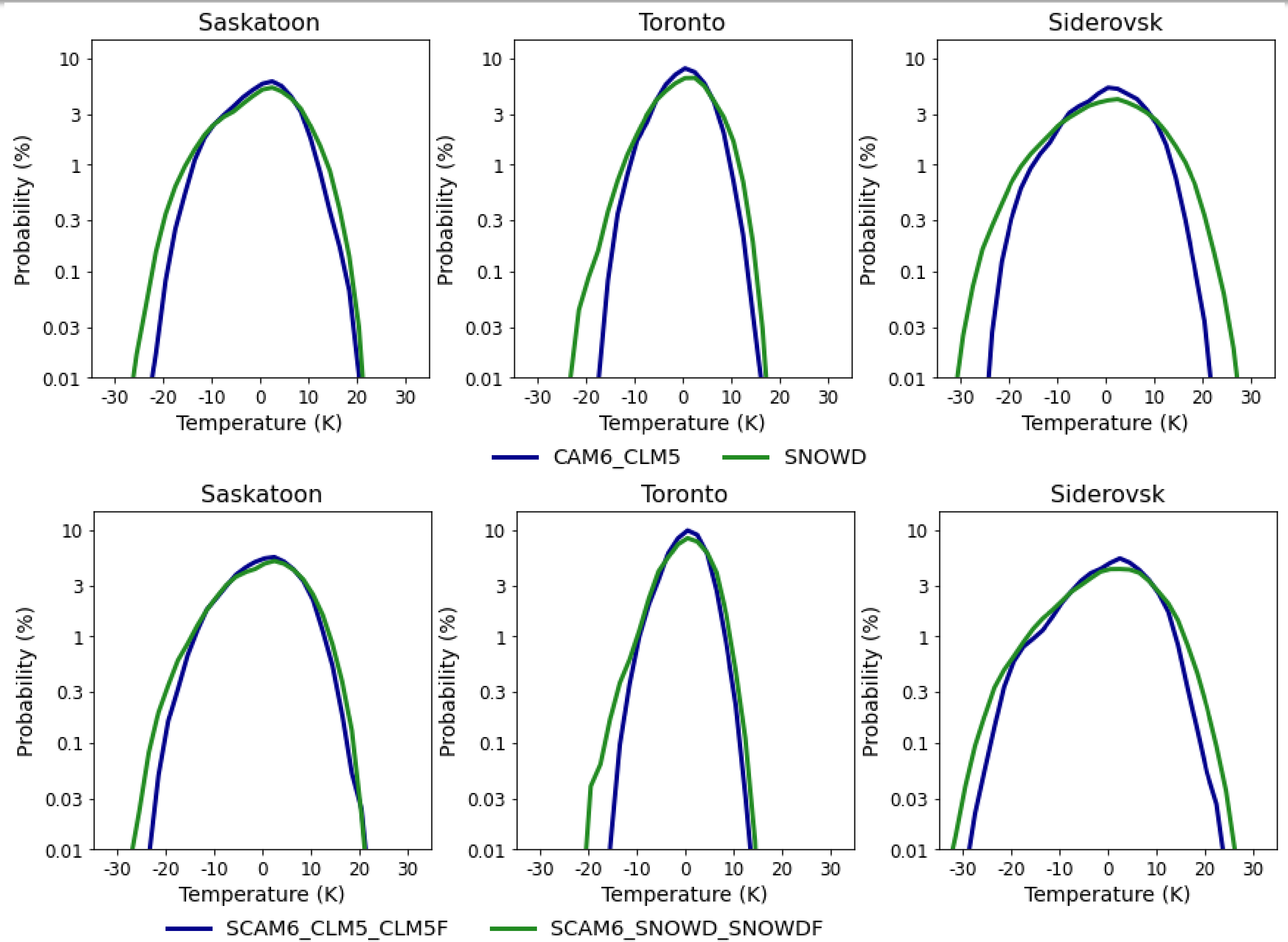

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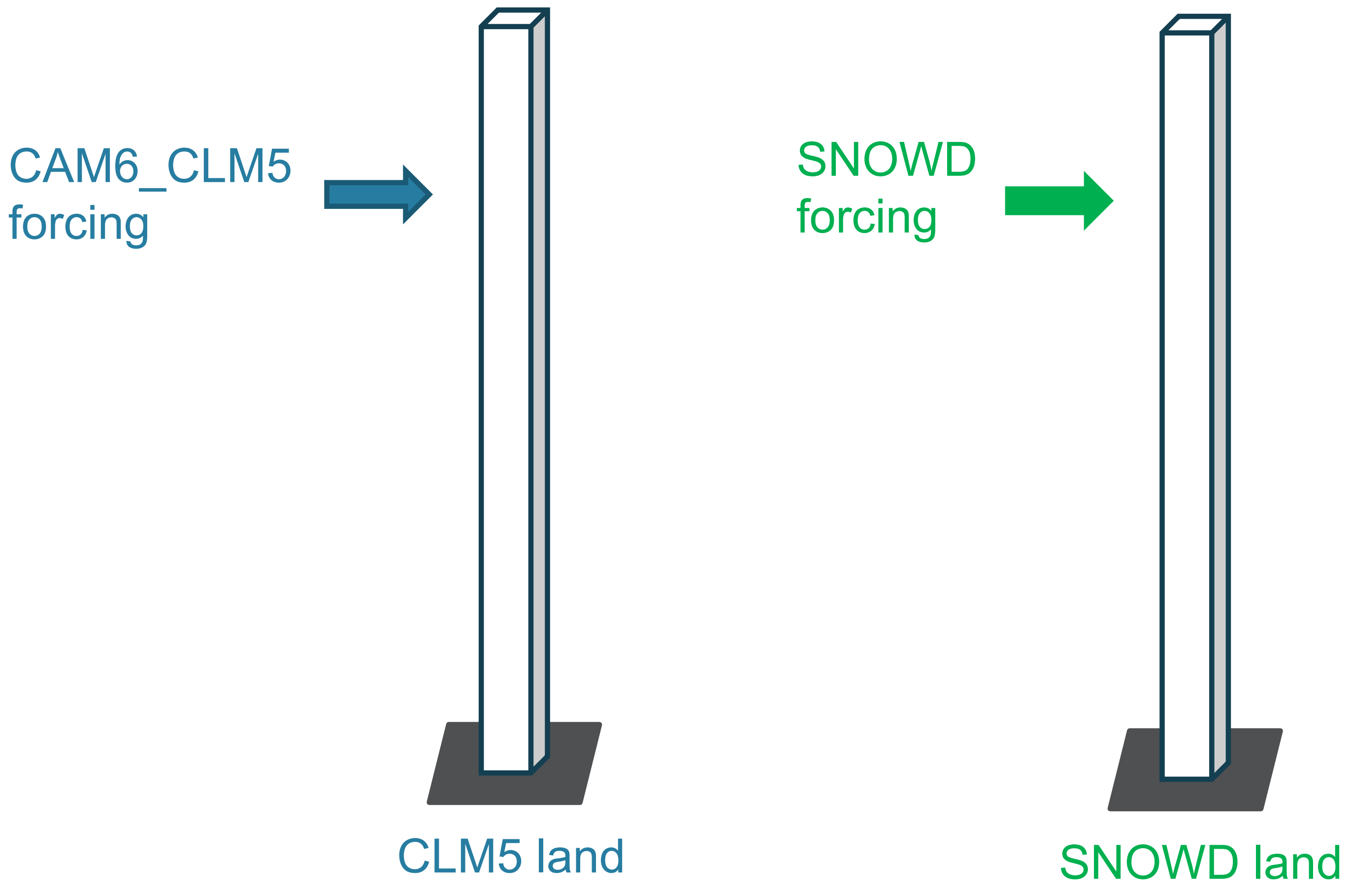
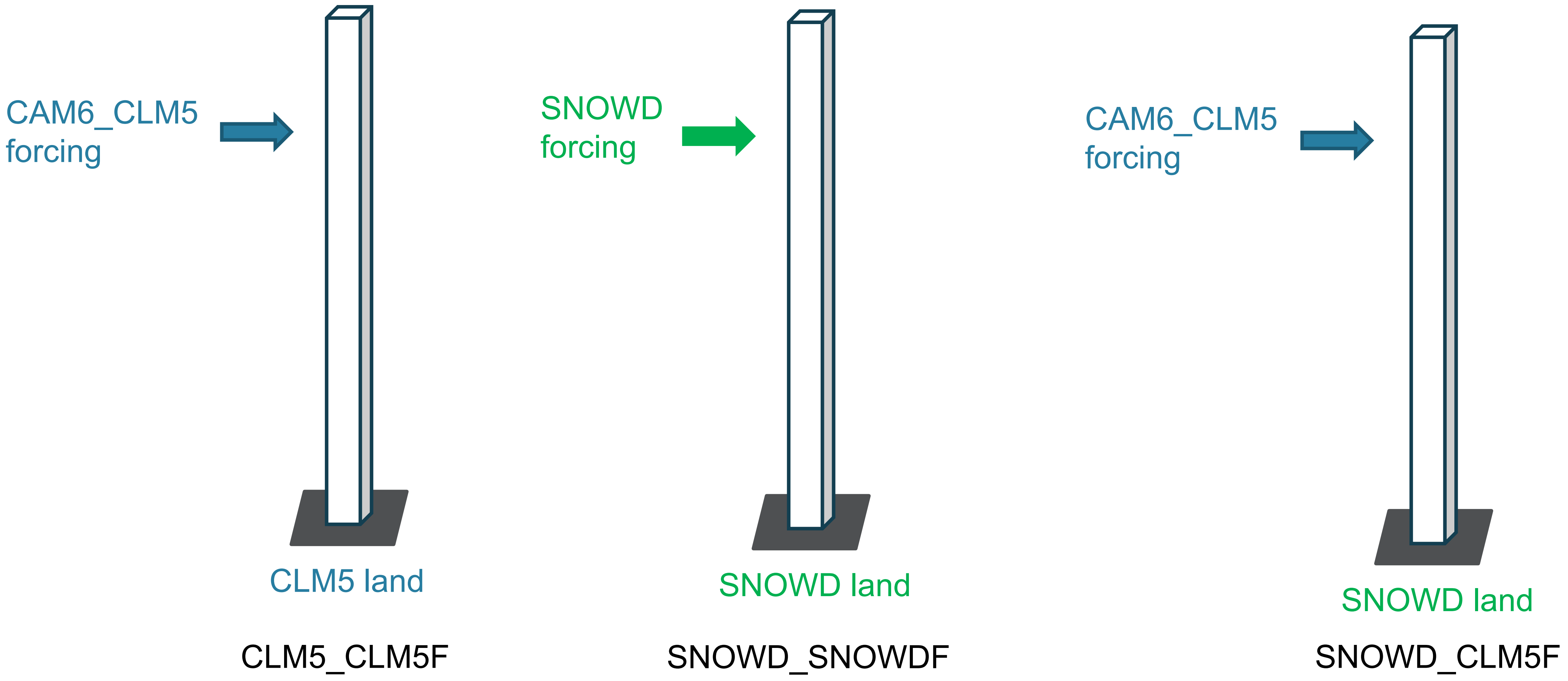


CLM5_CLM5F

SNOWD_SNOWDF

Single Column Model Experiments



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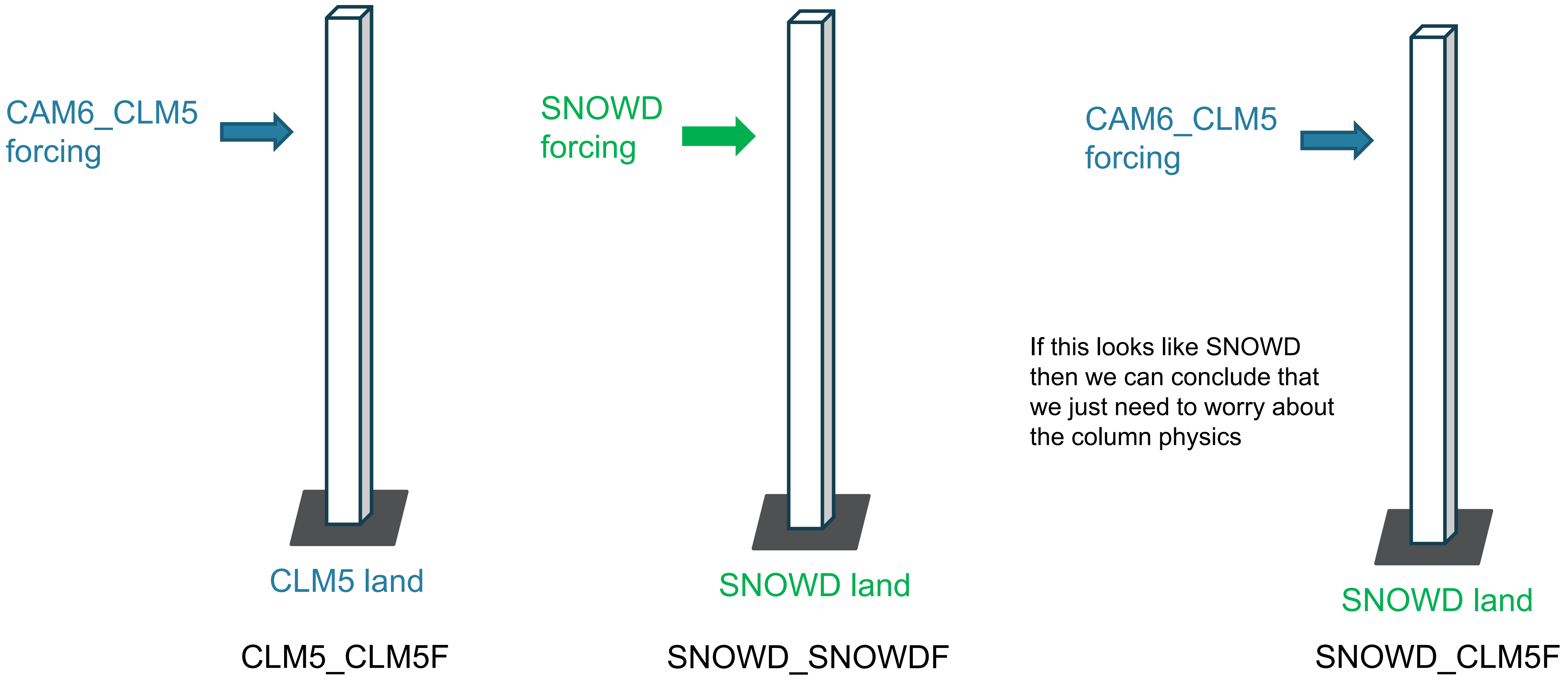
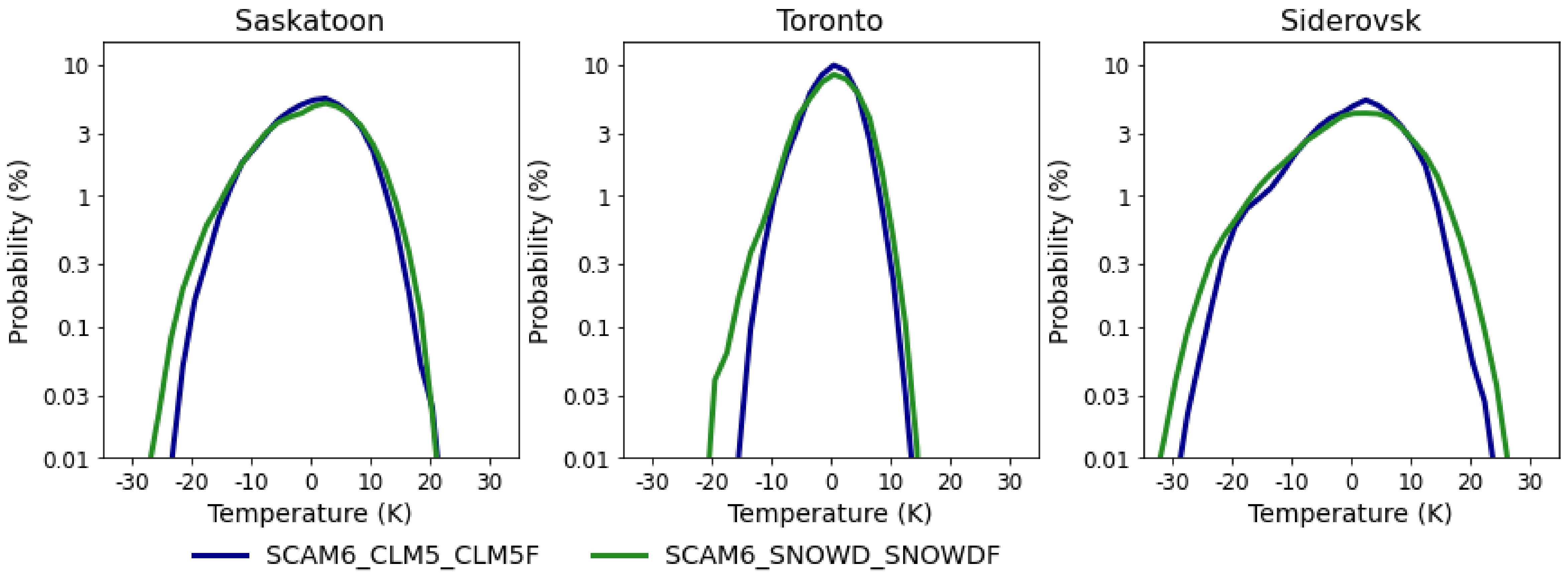


Is the SCAM change in variability reproduced through local processes alone?



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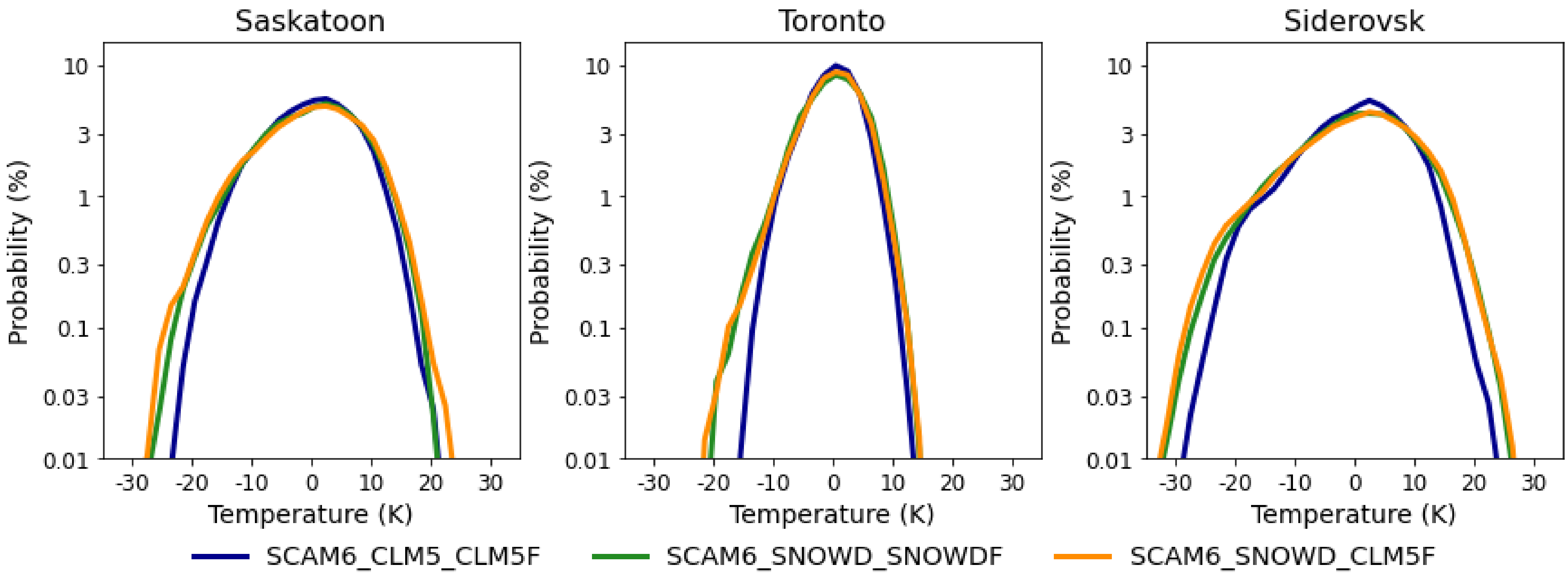

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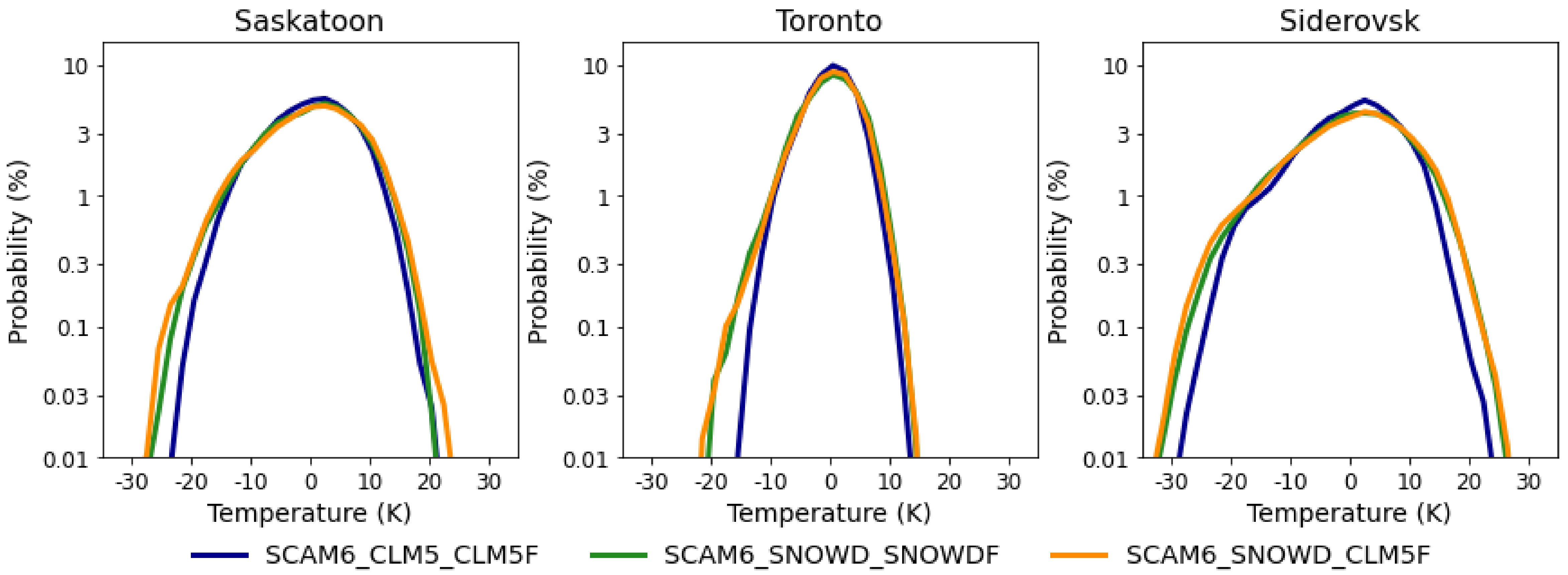
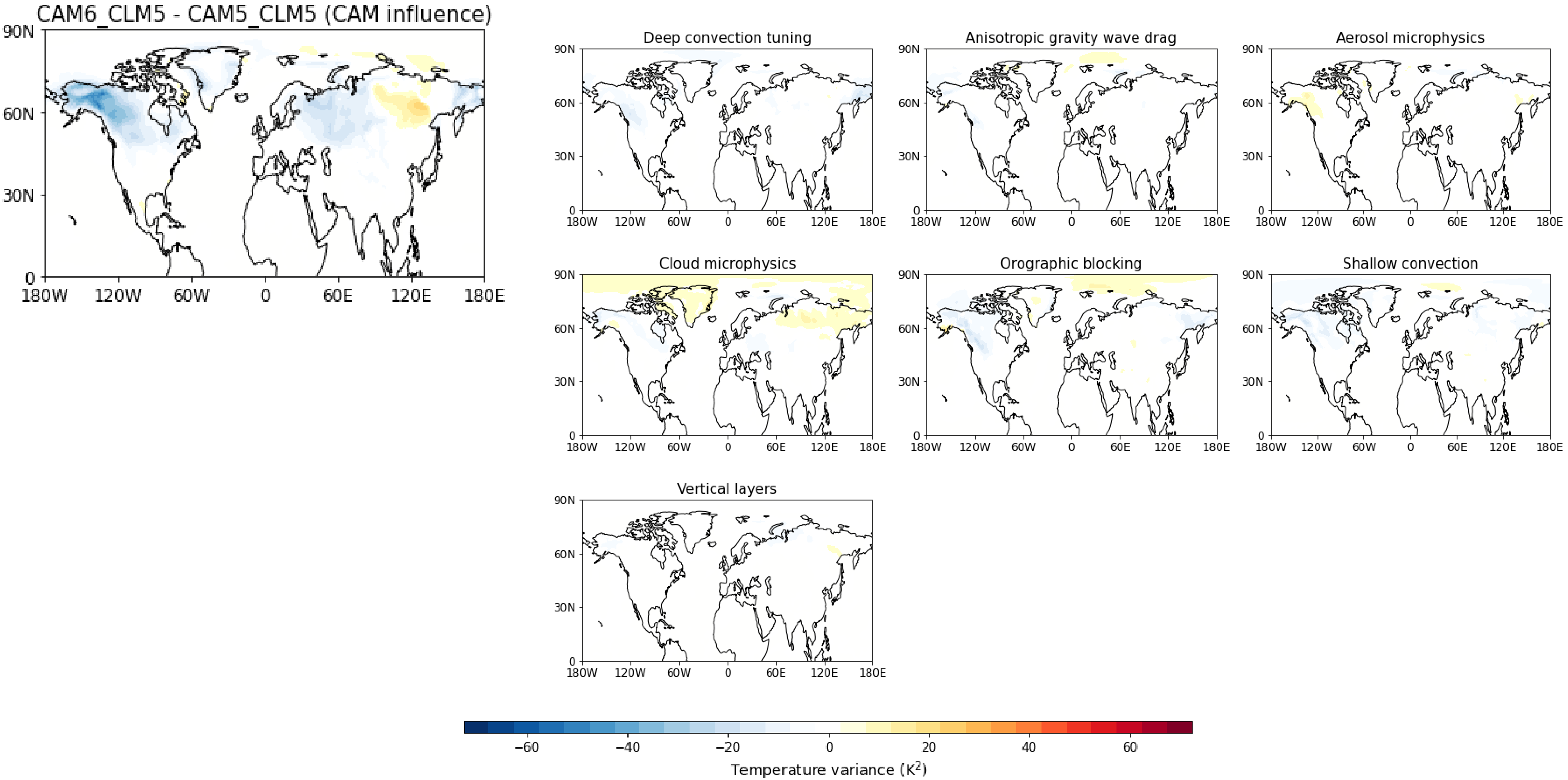


We need to focus on understanding how the local column physics is affecting the temperature variability when the snow density and densification is changed.

The Atmosphere model influence



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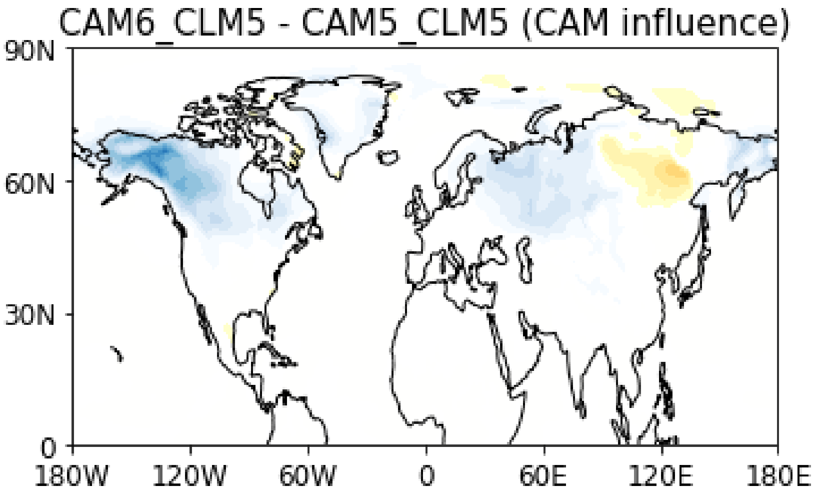
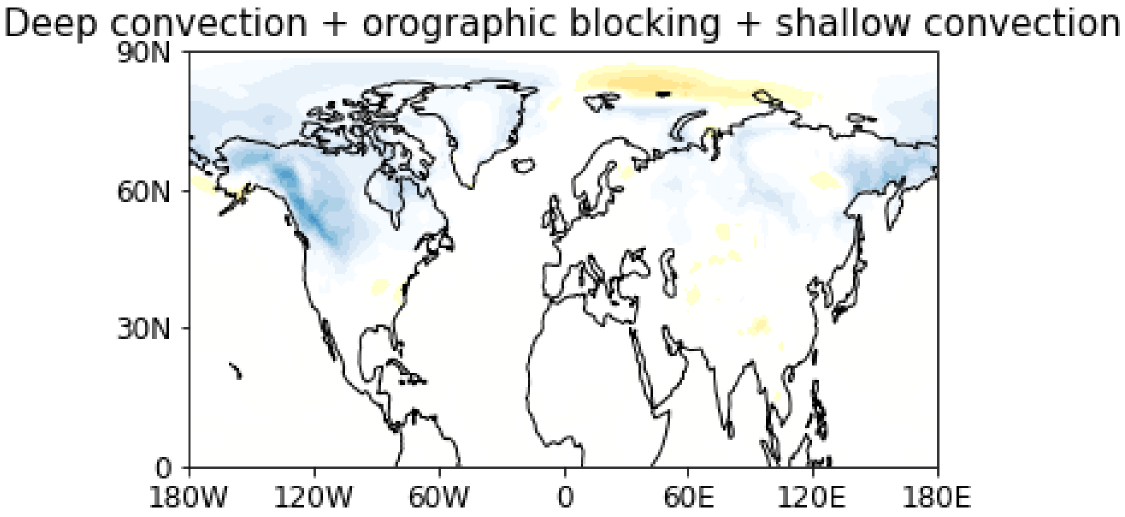
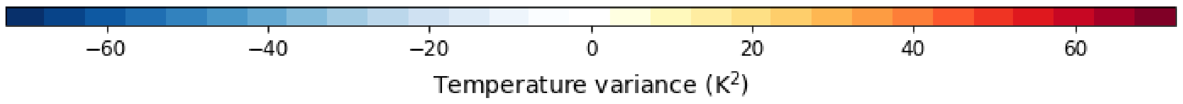
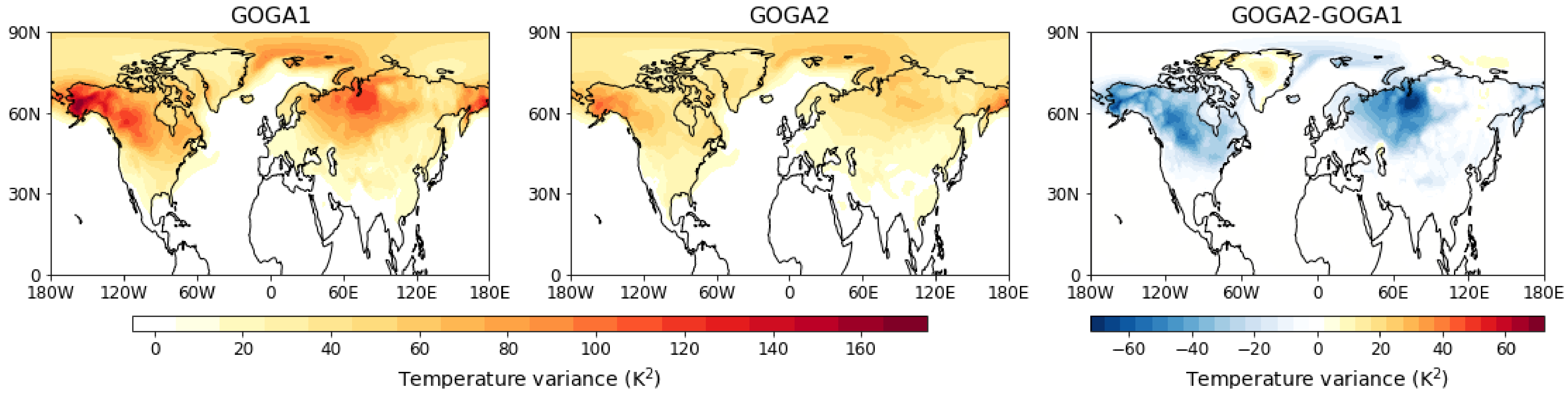
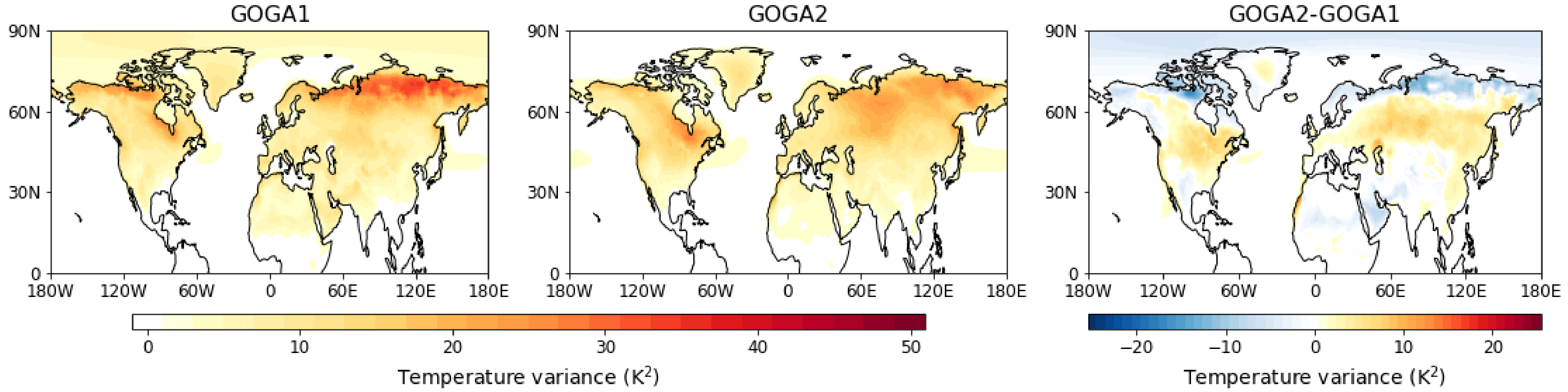







GOGA1
GOGA2
GOGA2-GOGA1
90N
60N
30N
0
180W 120W 60W 0 60E 120E 180E
0 20 40 60 80 100 120 140 160
Temperature variance (K^2)
−60 −40 −20 0 20 40 60
Temperature variance (K^2)

JJA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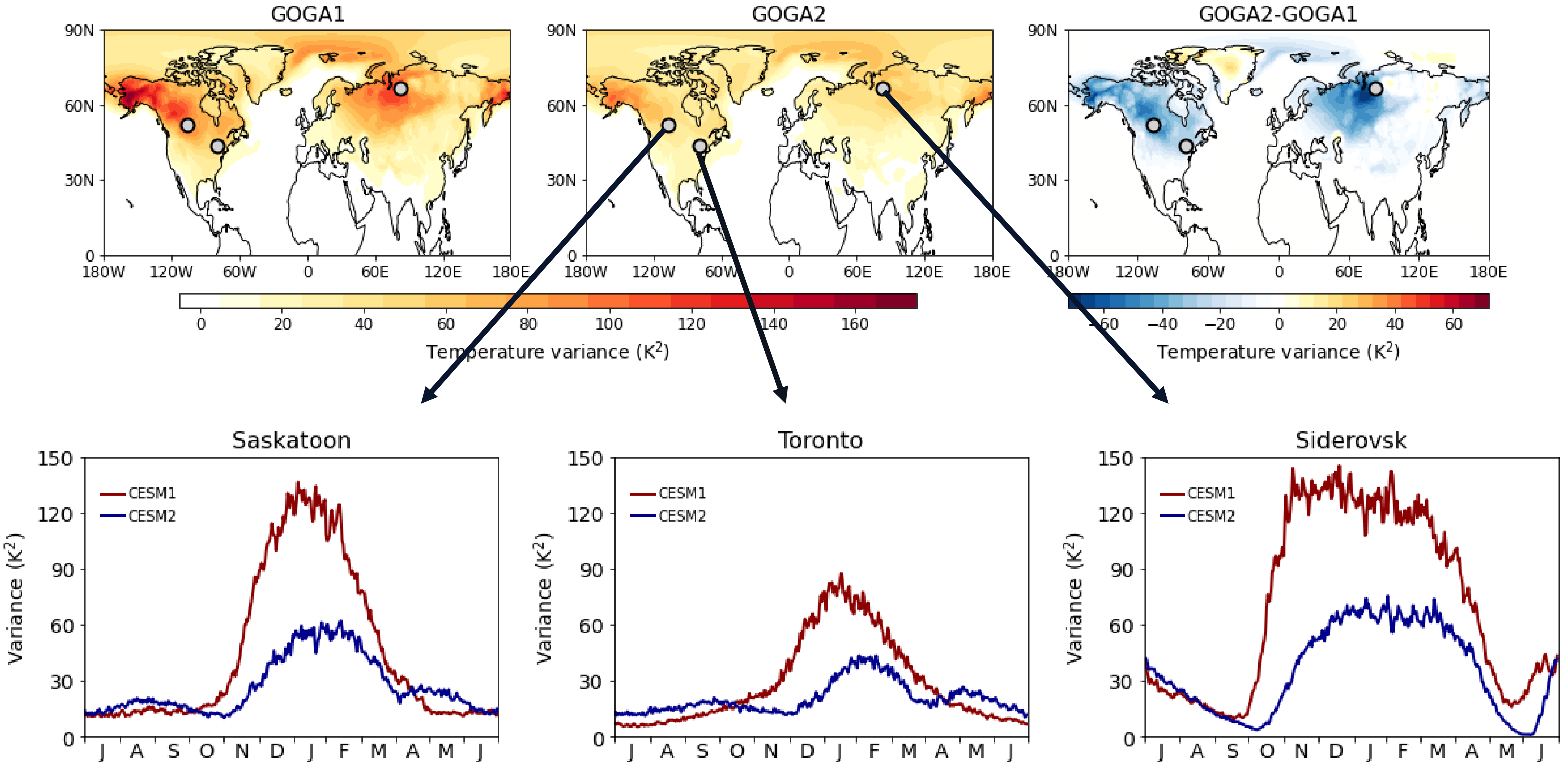
GOGA1
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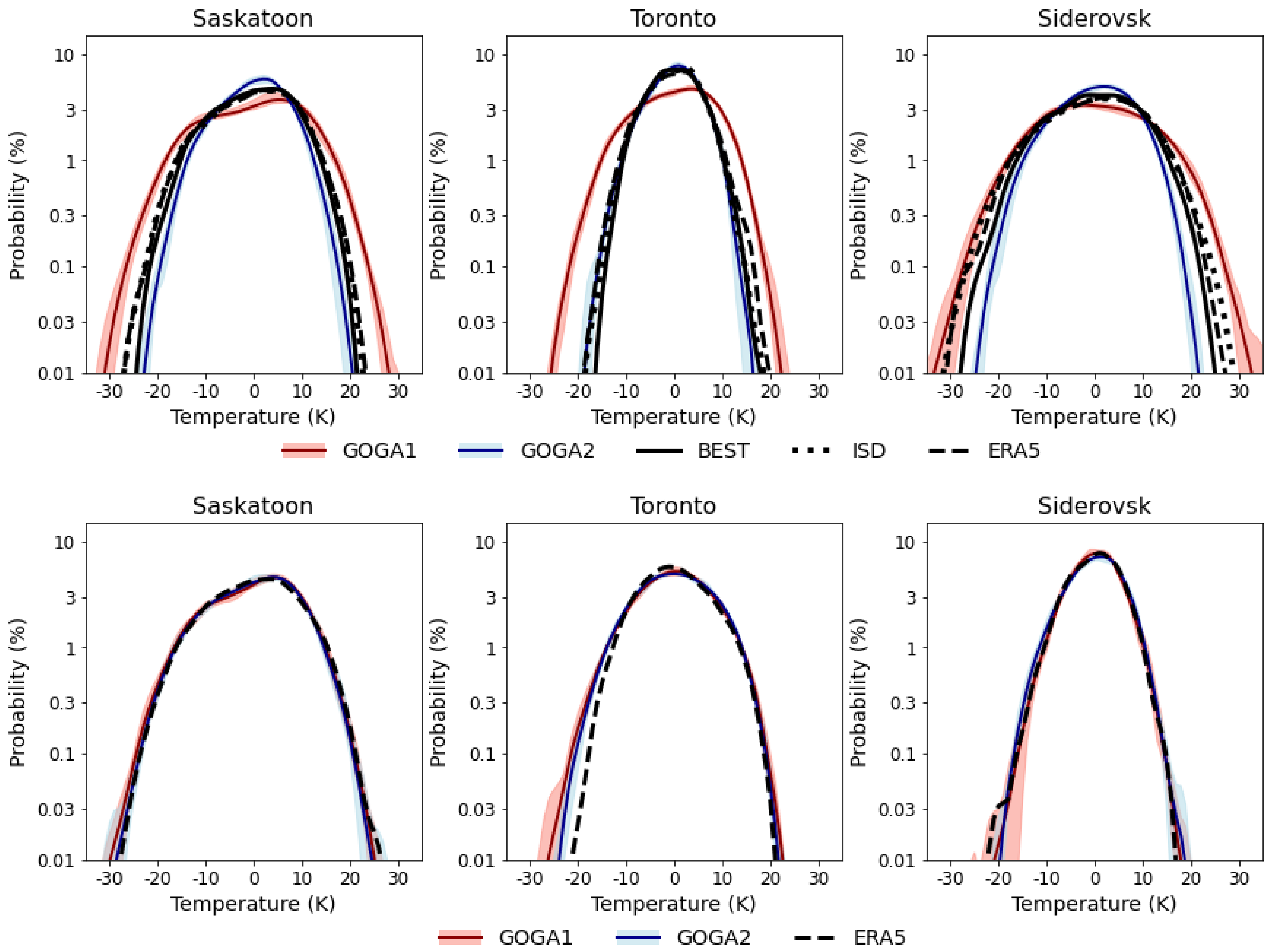
90N
60N
30N
0
180W
120W
60W
0
60E
120E
180E
Temperature variance (K²)
Saskatoon
Toronto
Siderovsk
CESM1
CESM2
Variance (K²)
J A S O N D J F M A M J

Temperature variability at 850hPa haven't really changed

T2m PDFs

T850 PDFs

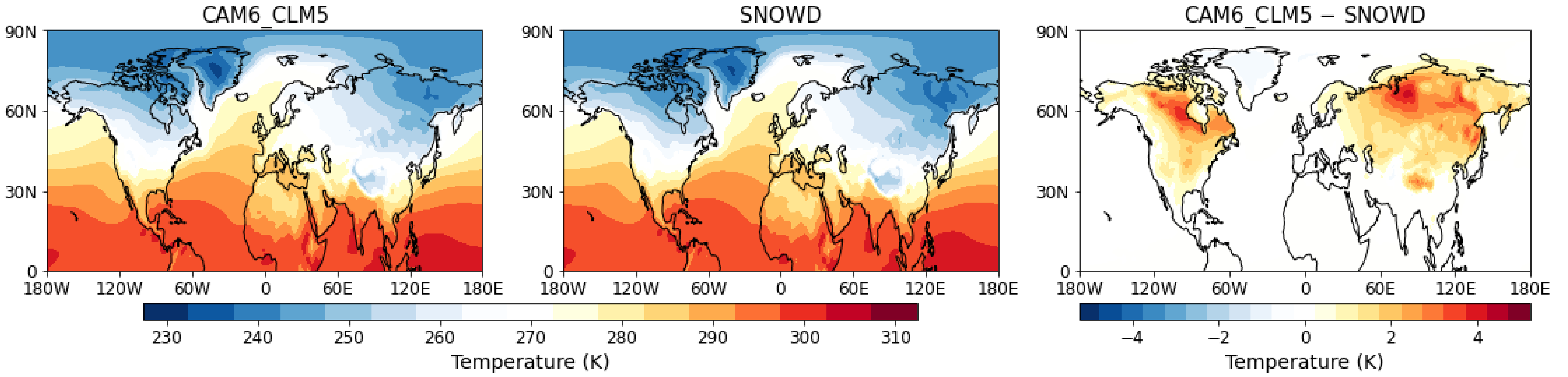


Change in variance over the course of the daily cycle

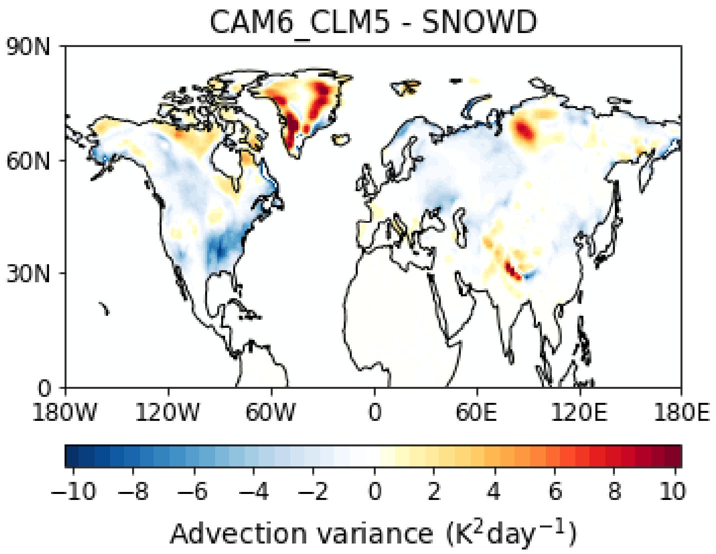
?????????

Local or non -local influences?

DJF surface temperature climatology



Change in variance across climatological temperature gradients on the lowest atmospheric model level i.e., $-\vec{v}.\nabla\overline{T}$



Local or non -local influences?

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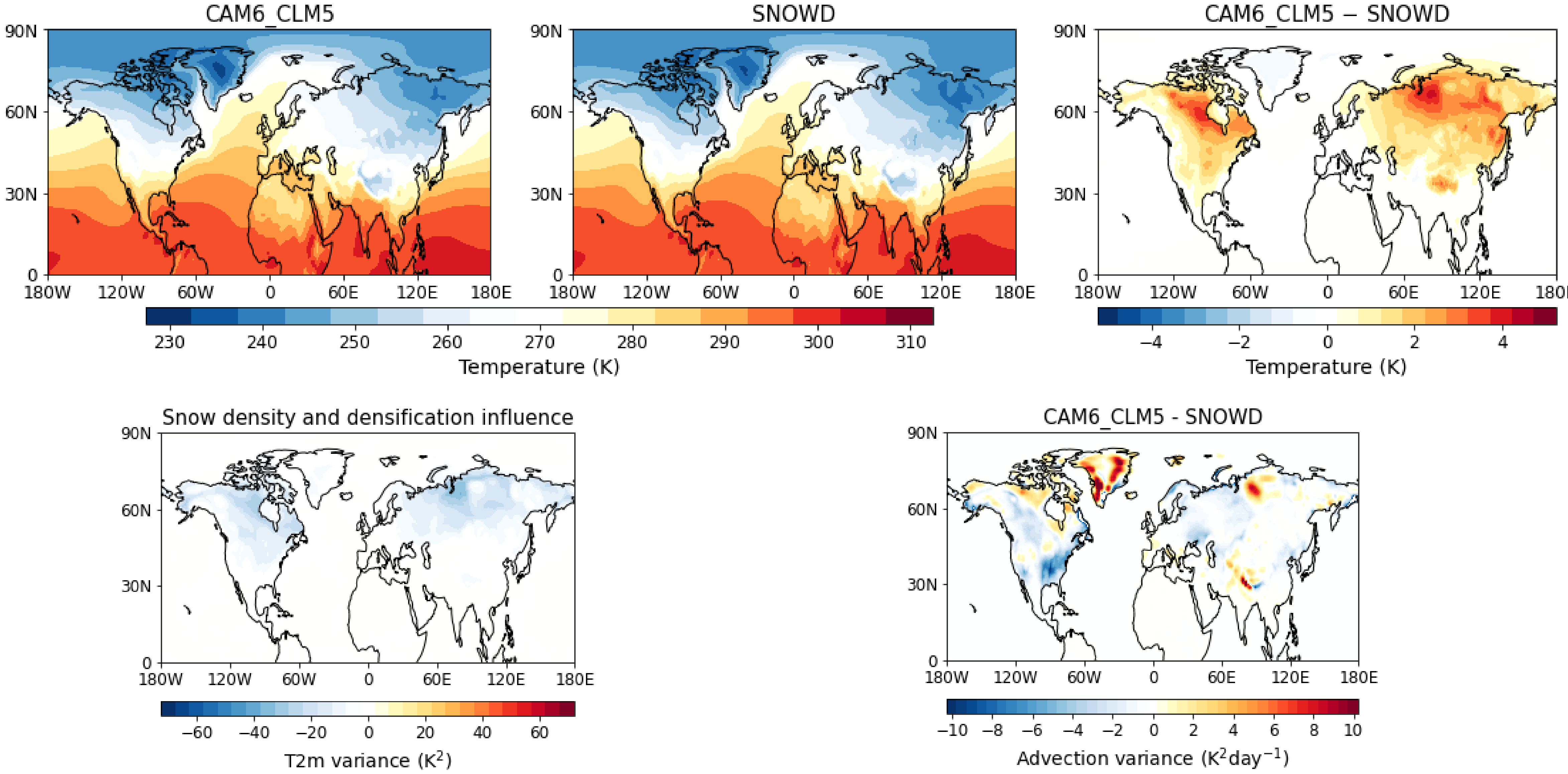

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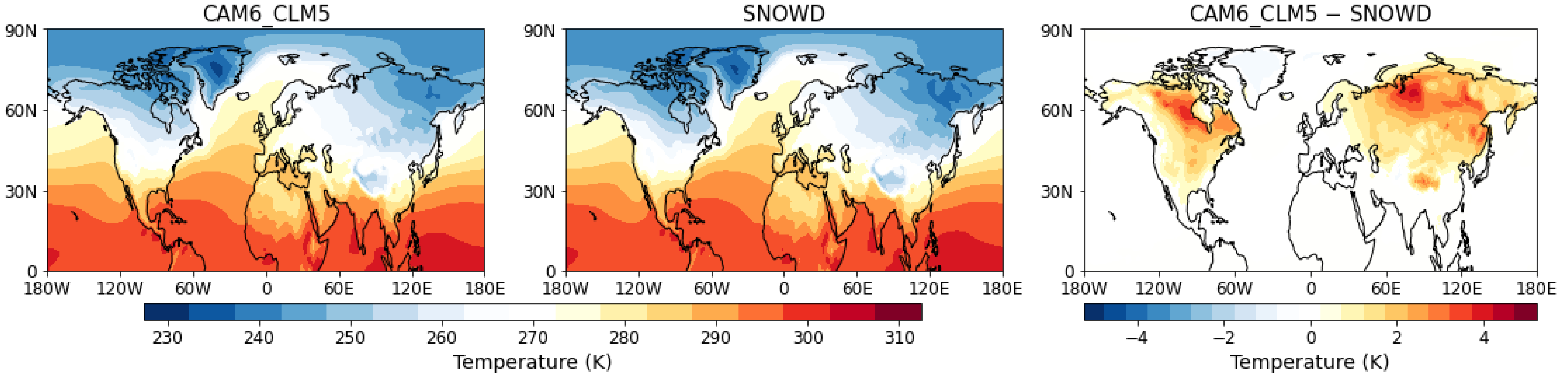
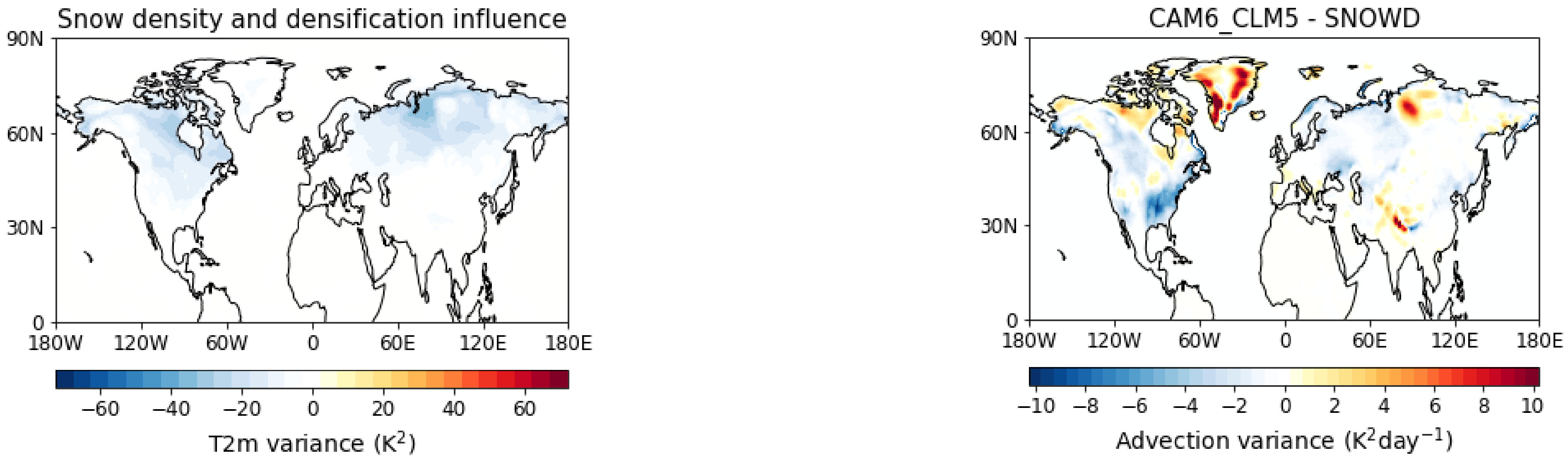
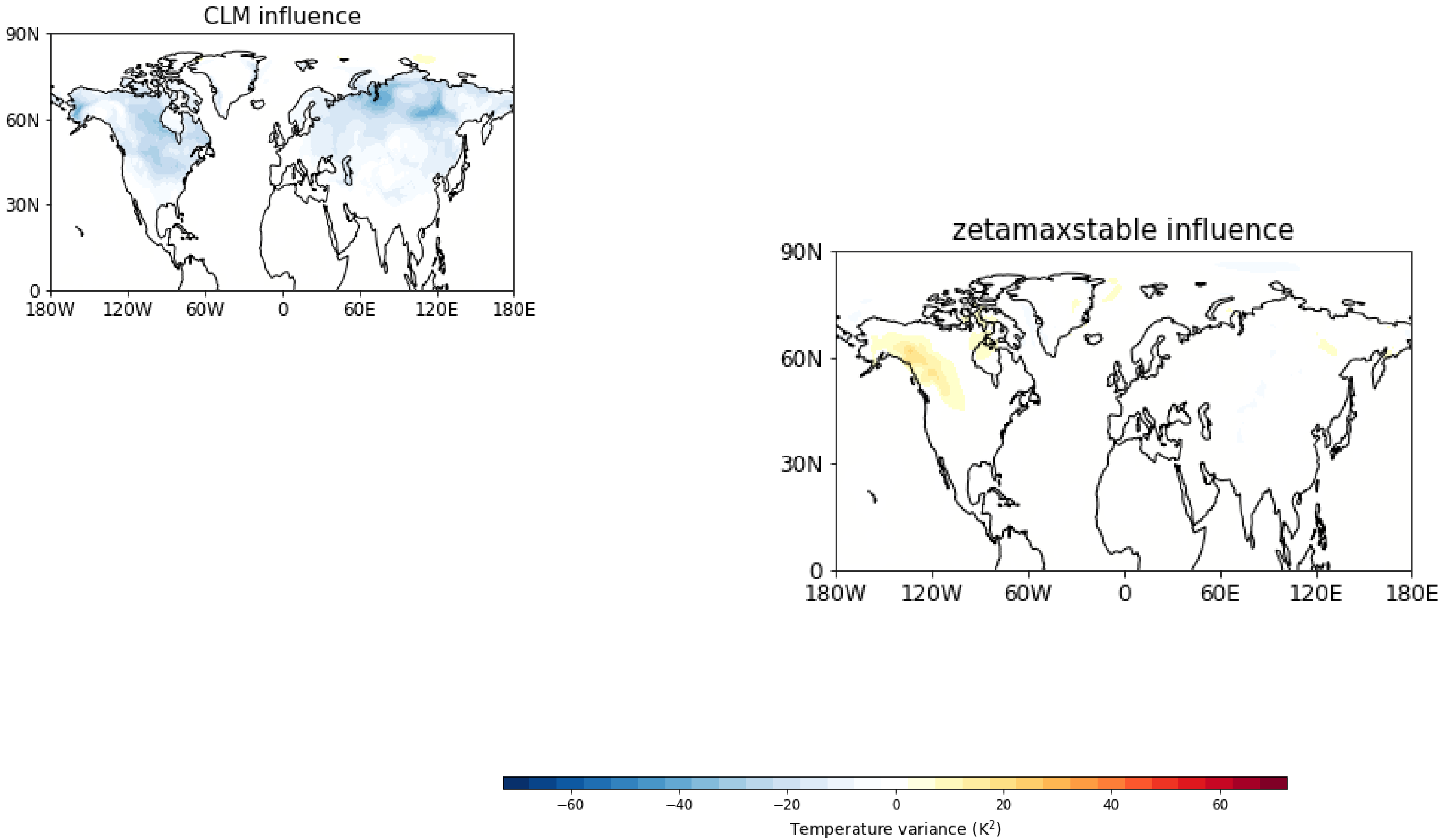




The land model influence



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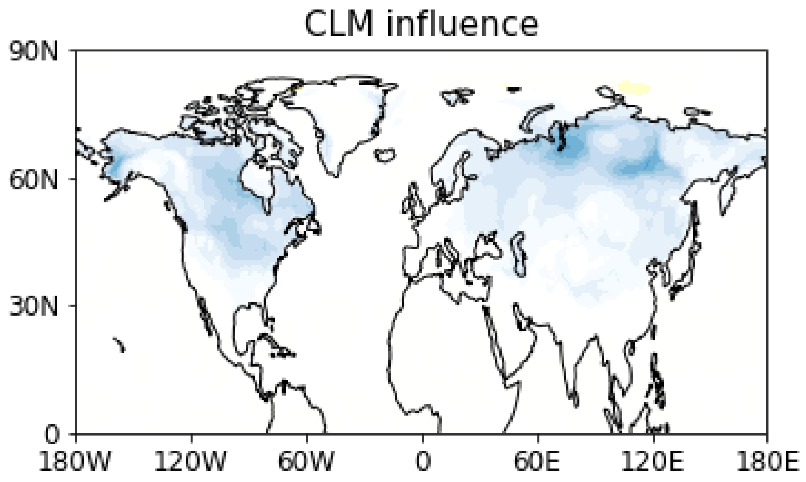
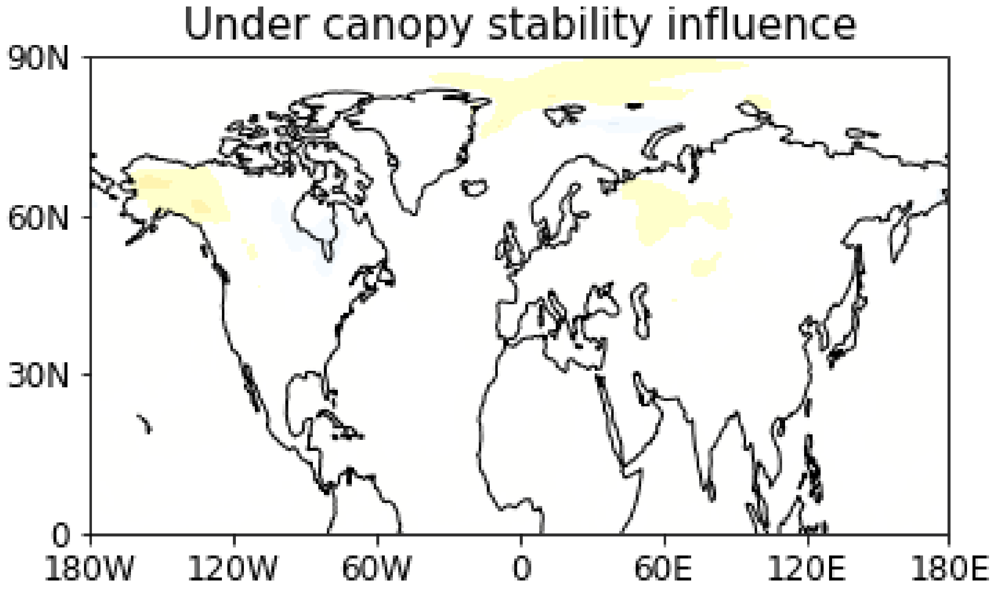
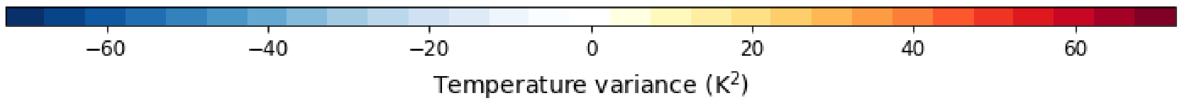
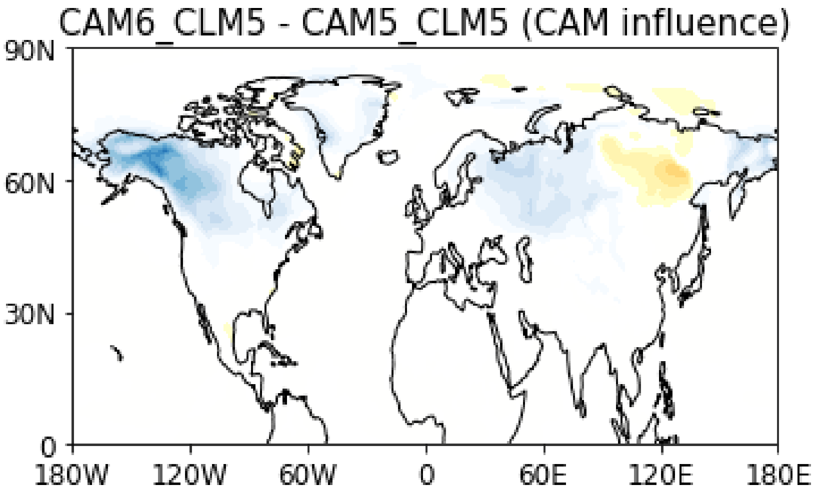
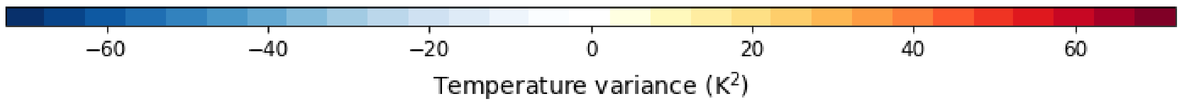


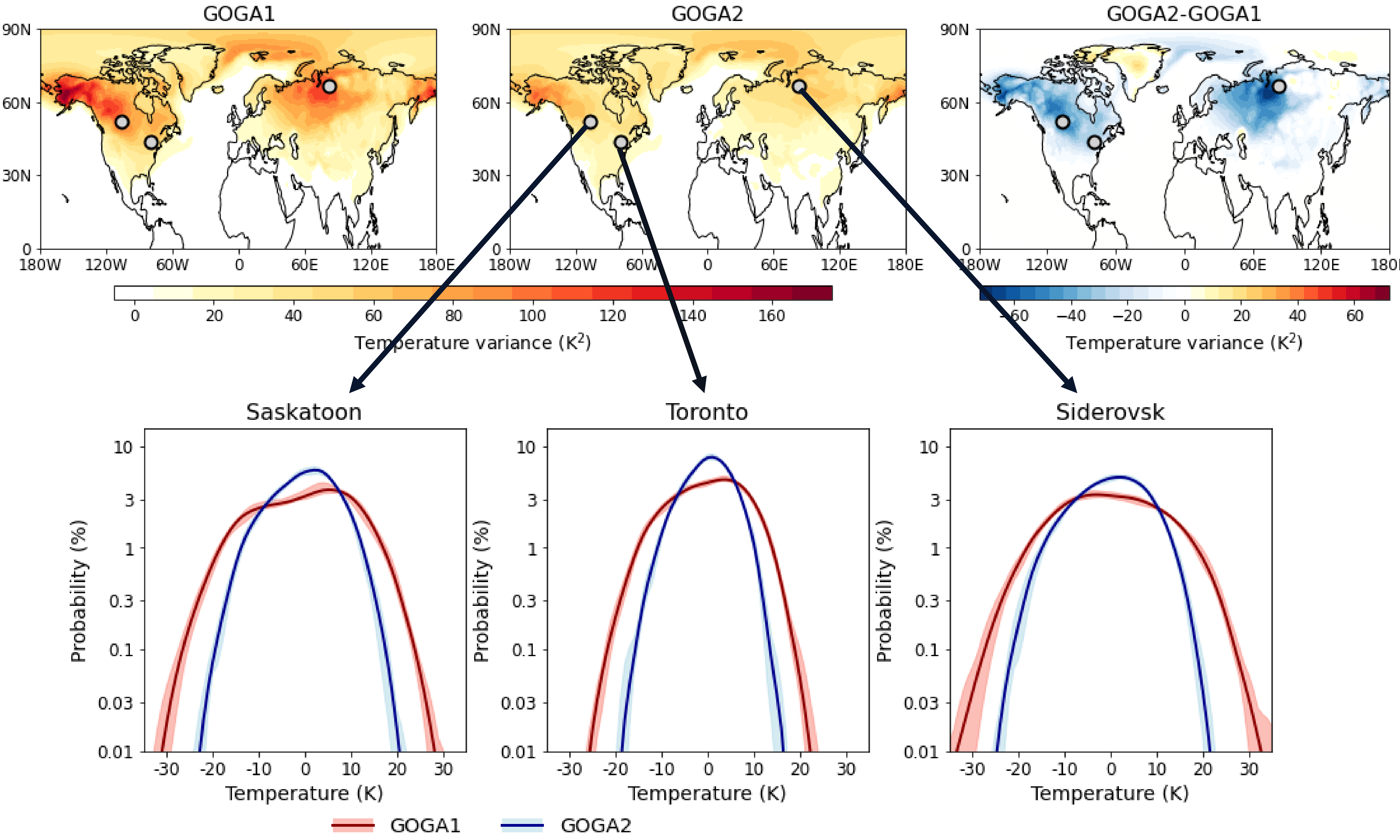


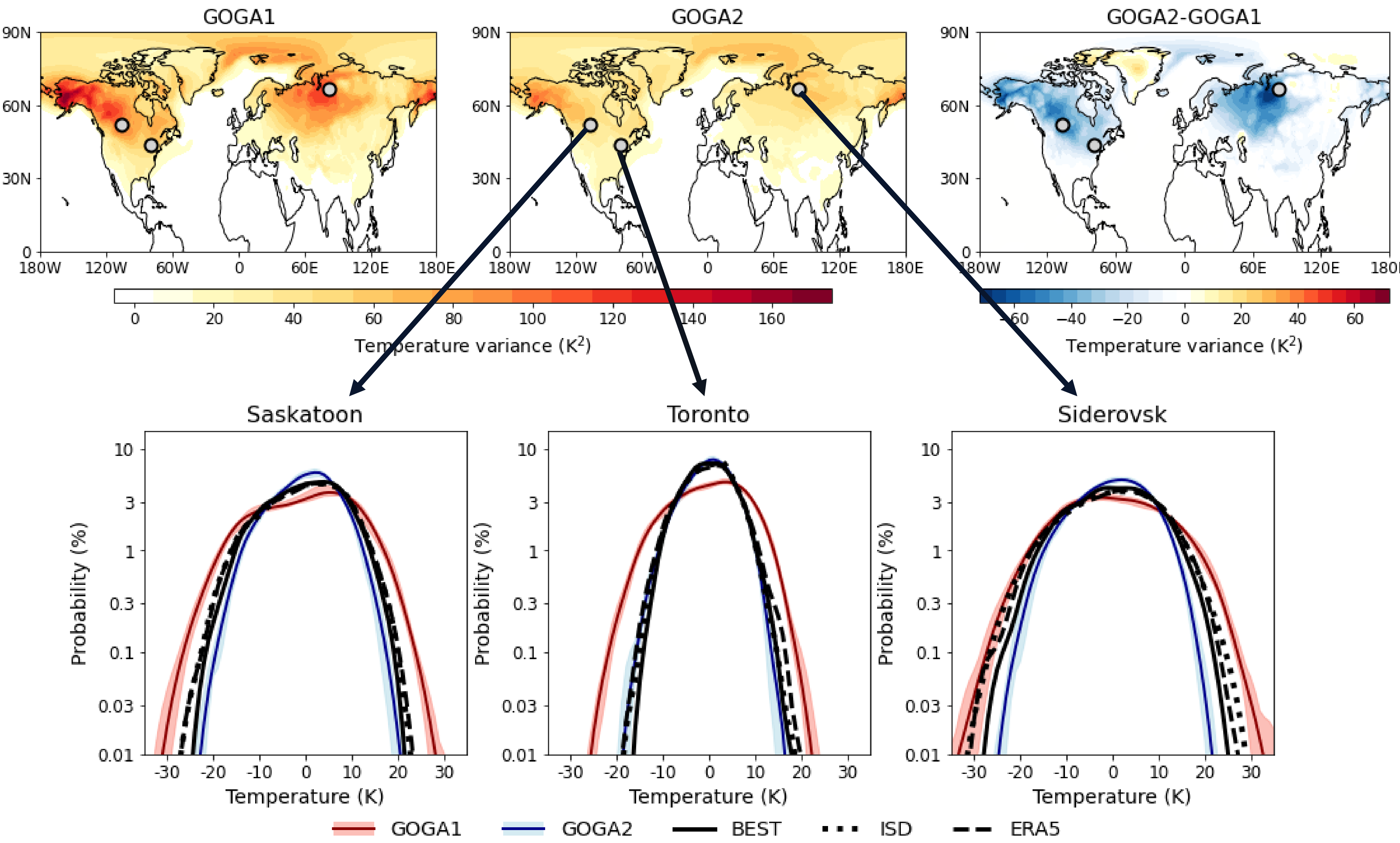


The Atmosphere model influence






GOGA1
GOGA2
GOGA2-GOGA1
90N
60N
30N
0
180W
120W
60W
0
60E
120E
180E
0
20
40
60
80
100
120
140
160
Temperature variance (K^2)
−60
−40
−20
0
20
40
60
Temperature variance (K^2)
Saskatoon
Toronto
Siderovsk
Probability (%)
10
3
1
0.3
0.1
0.03
0.01
-30
-20
-10
0
10
20
30
Temperature (K)
GOGA1
GOGA2


GOGA1
GOGA2
GOGA2-GOGA1
90N
60N
30N
0
180W
120W
60W
0
60E
120E
180E
0
20
40
60
80
100
120
140
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Temperature variance (K^2)
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Probability (%)
10
3
1
0.3
0.1
0.03
0.01
-30
-20
-10
0
10
20
30
Temperature (K)
GOGA1
GOGA2
BEST
ISD
ERA5