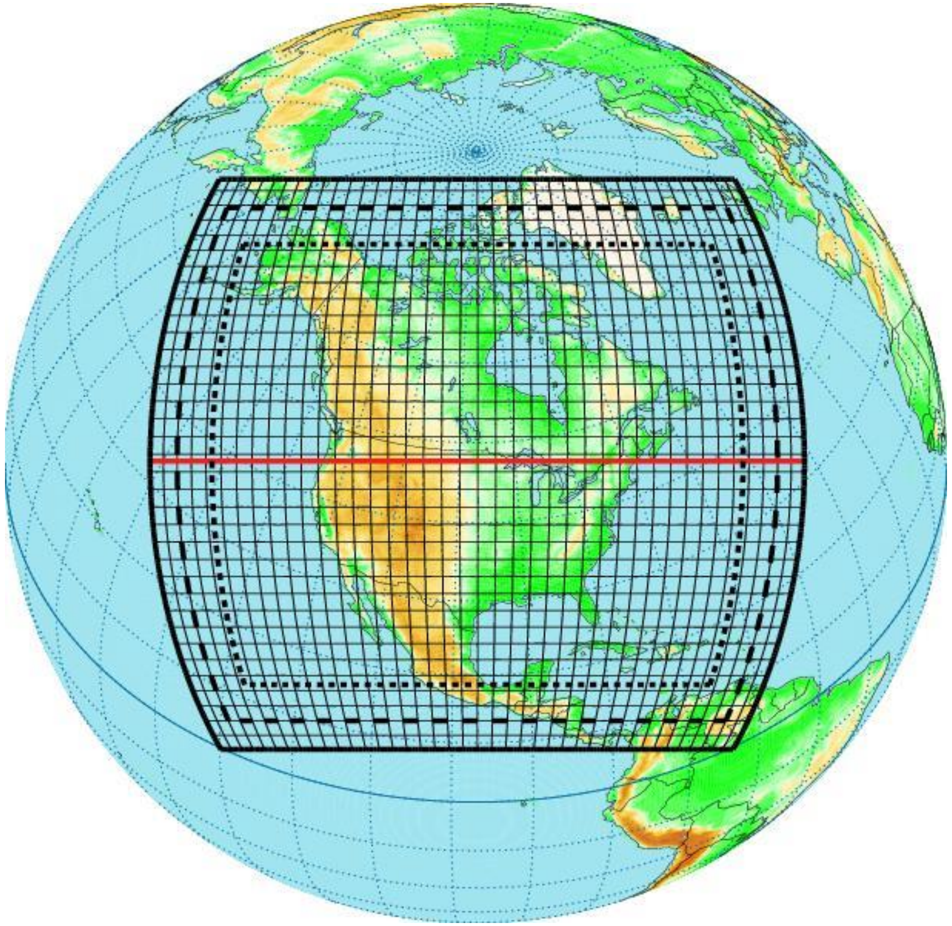
Environment and Climate Change Canada
Environnement et Changement climatique Canada

The Canadian Regional Climate Model (CanRCM5)



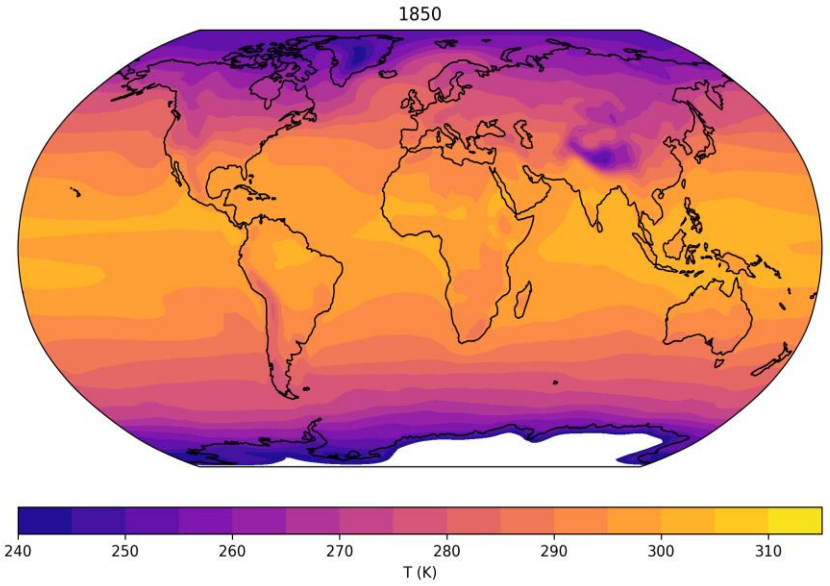
Carsten Abraham, John Scinocca, and Slava Kharin

Canada

Climate projections

- Climate models investigate the **average behaviour** of many weather realizations and results should not depend on initial conditions
- Climate models are supposed to produce **independent realizations of weather** which requires a large number of ensemble members to obtain robust answer
- Climate models require **external forcings** (land-surface properties, atmospheric composition, solar irradiance)

SSP245



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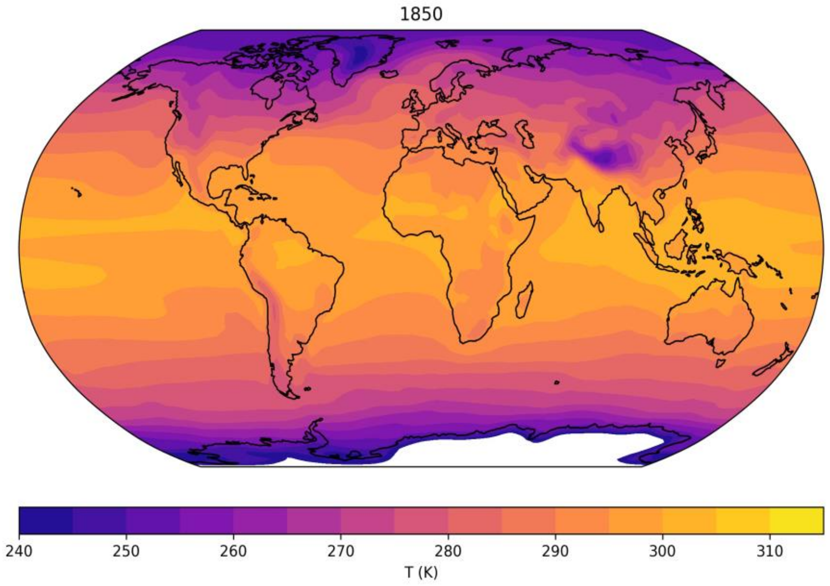

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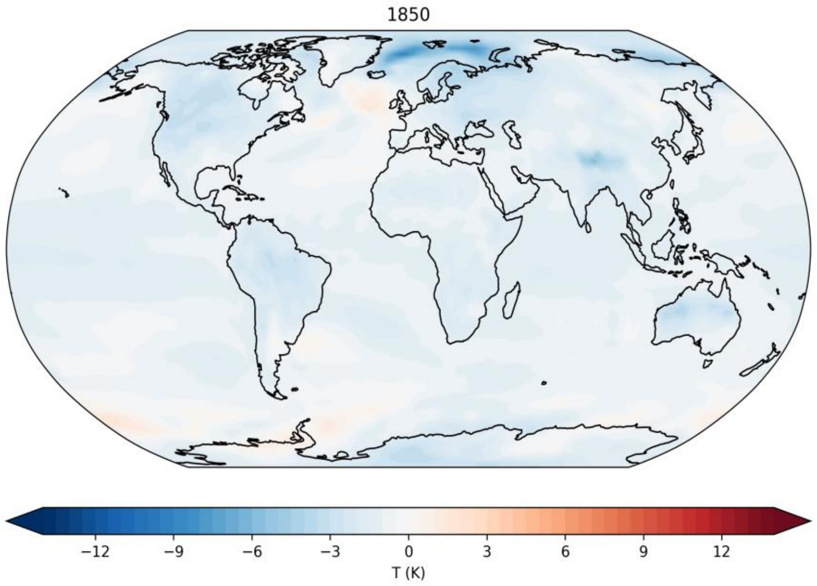

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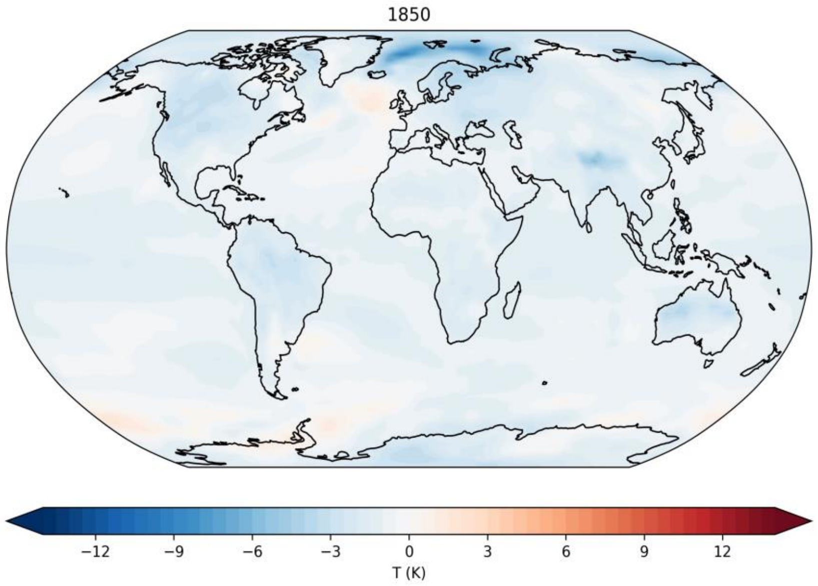

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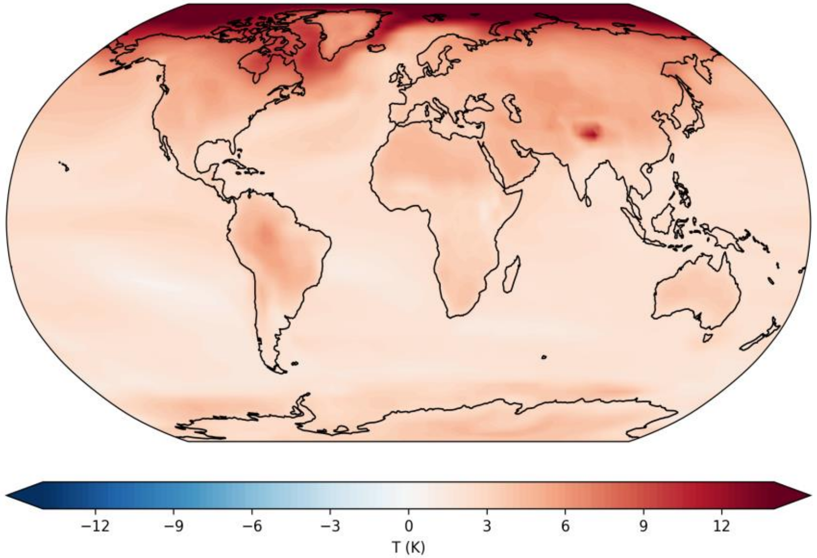

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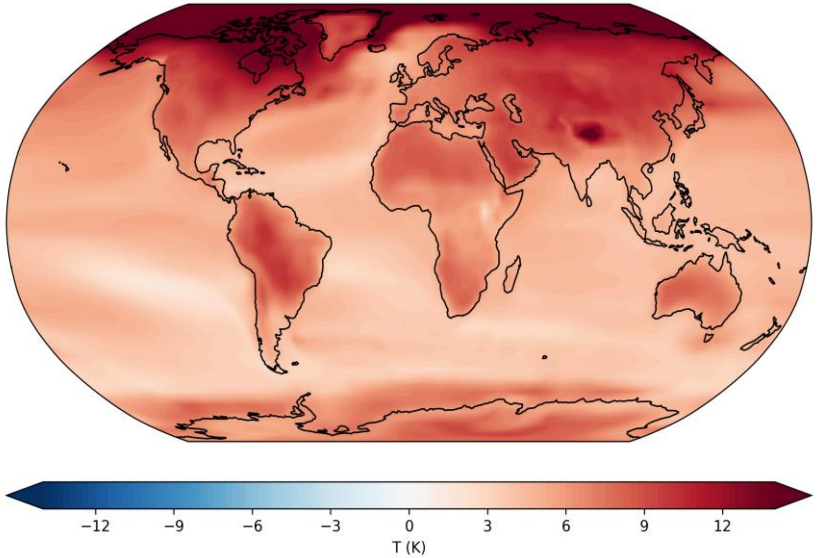
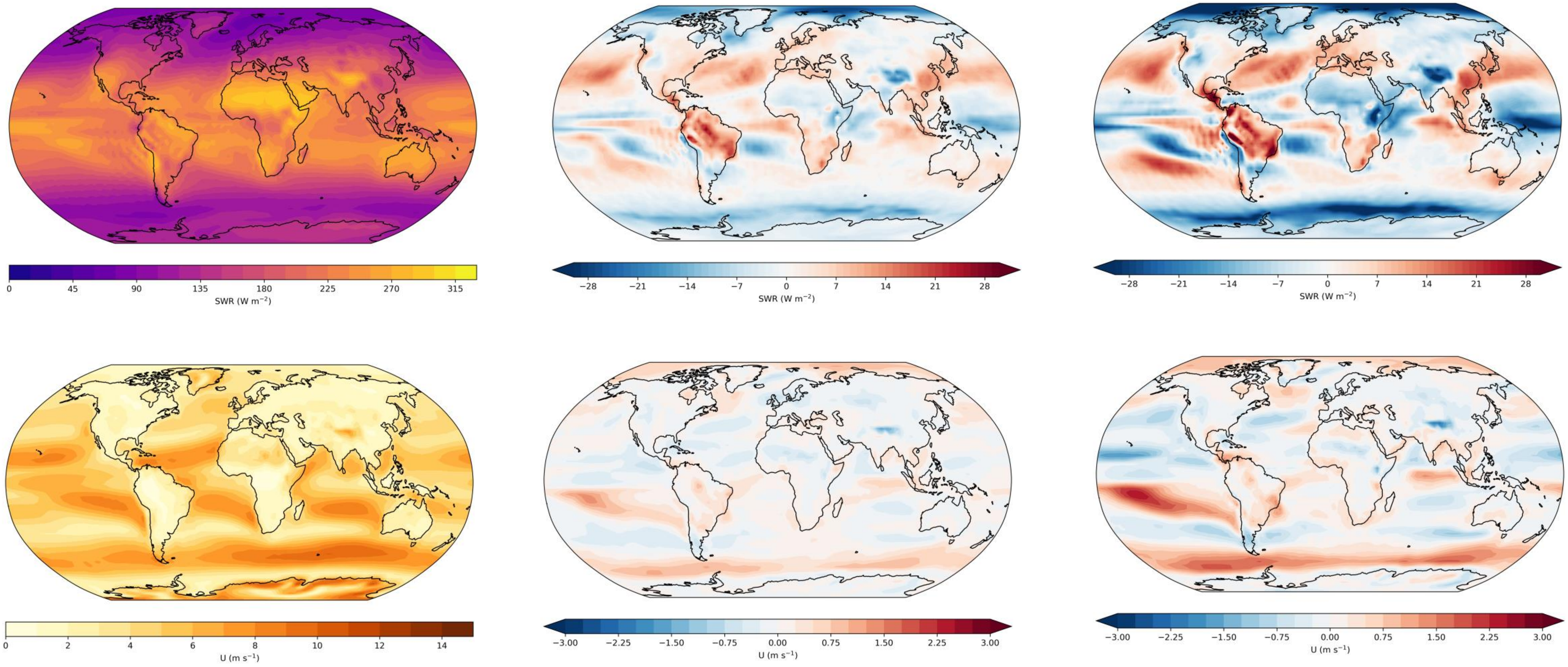


Changes to winds and surface solar flux

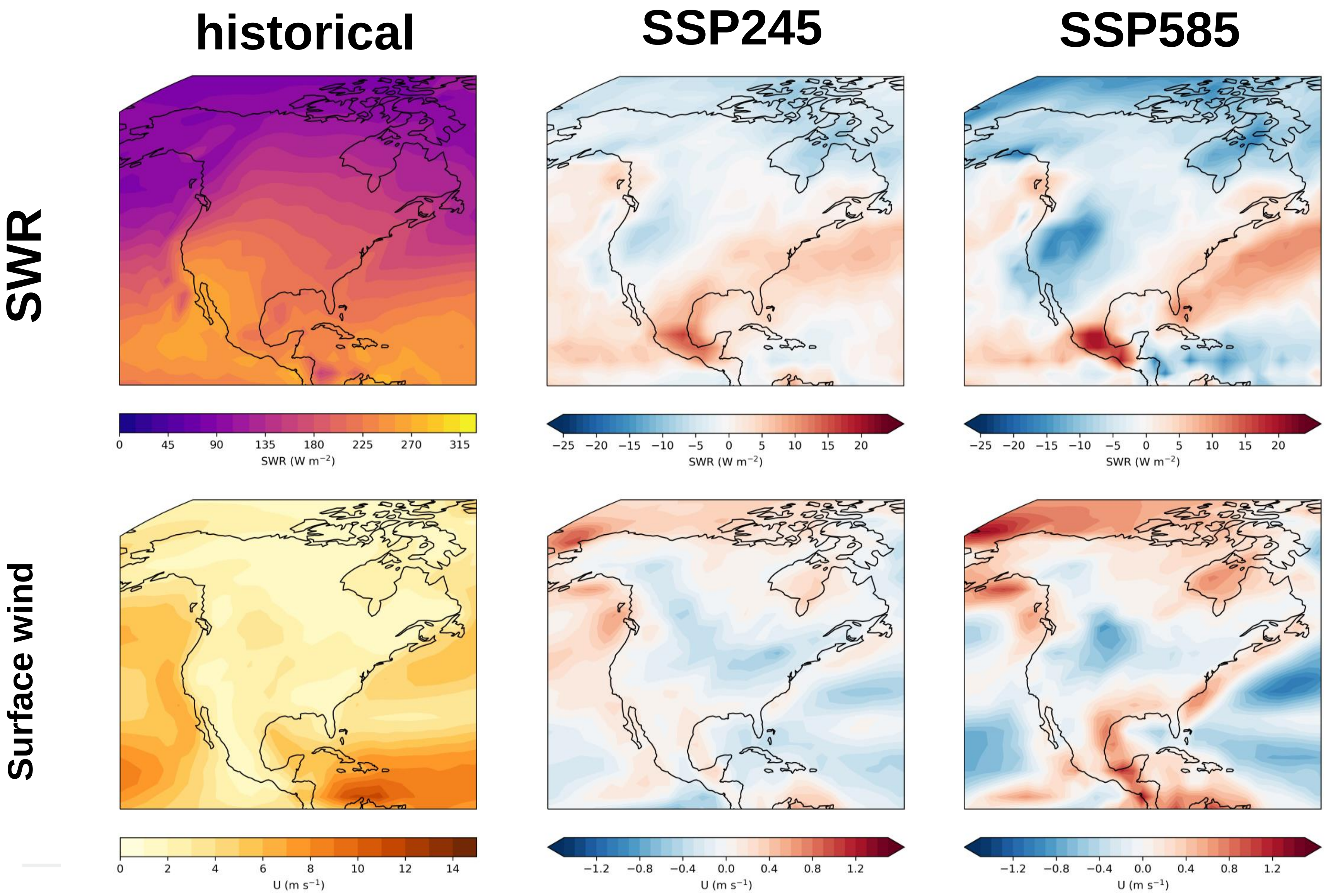
historical | **SSP245** | **SSP585**

SWR

Surface wind



Climate projections



The operational version of the Canadian Earth System Model (CanESM5) has currently a spatial resolution of about 300 km. This resolution does not suffice for assessments and applications on regional scales.

How to obtain more spatial resolution?

Enhance resolution of the ESM

The Problem:

- ESMs have typically grid boxes of 100s of km
- ESMs are required to run 1000s of simulations each ranging typically centuries
- The resolution of an ESM is limited by those requirements and the computing resources

Statistical downscaling

- Derive **statistical relationships** between observed scales and the resolved ESM scales using functional relationships, regression models, or neural networks

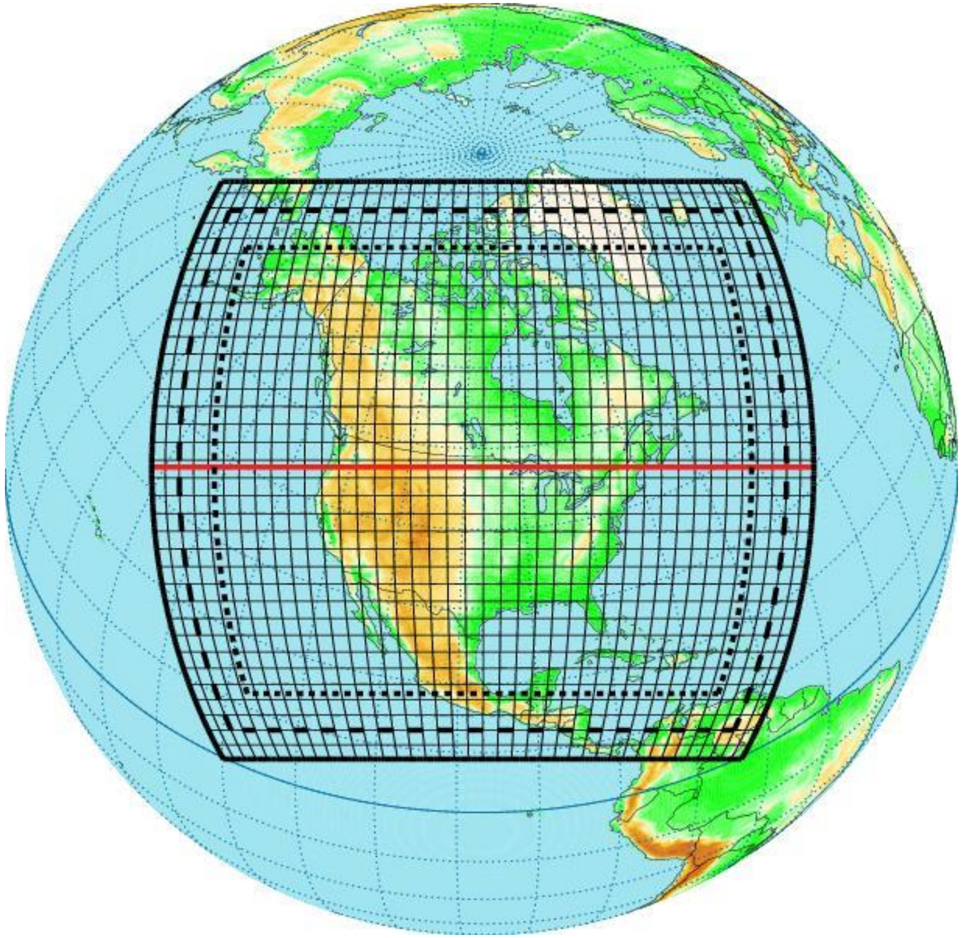
Assumption:
Statistical relationships hold for conditions they are **not trained for or have not been observed yet**

Dynamical downscaling

- Using a limited area **regional** general circulation model and run it at a higher resolution than the ESM

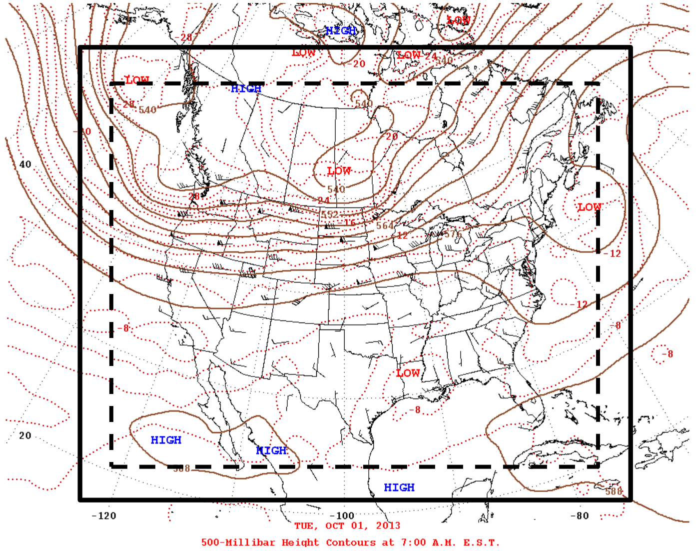
Assumption:
The regional climate model provides the **same solution** that the global model at that resolution would have produced

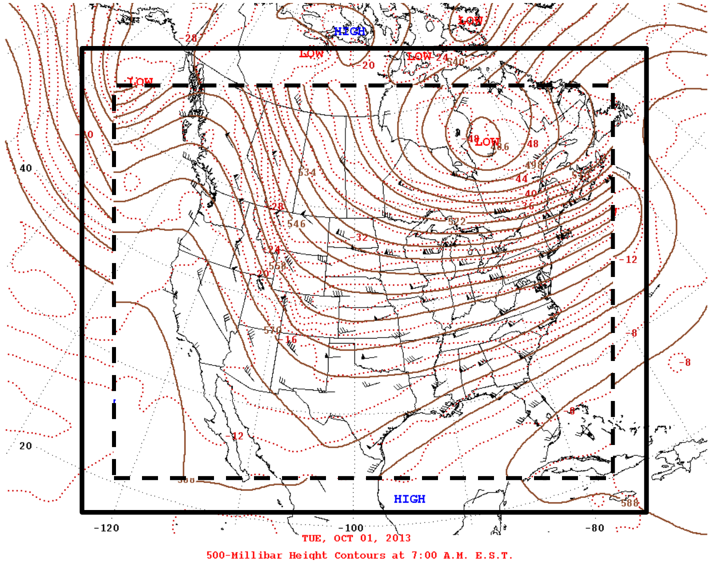
The Canadian Regional Cliamte Model (CanRCM)



- CanRCM uses a **One-way-nesting**
- Boundary conditions are updated **every 6 hours** from CanESM simulations
- CanRCM uses the same physics package as CanESM
  - Close relationship between the models allow a high degree of physical consistency between the two models and boundary driving data are directly available
- Main domain: **North-America**
- Resolution: **25 km**

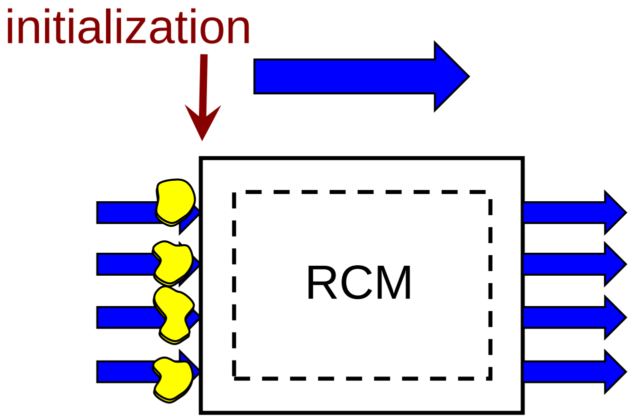
The problem with one-way nesting



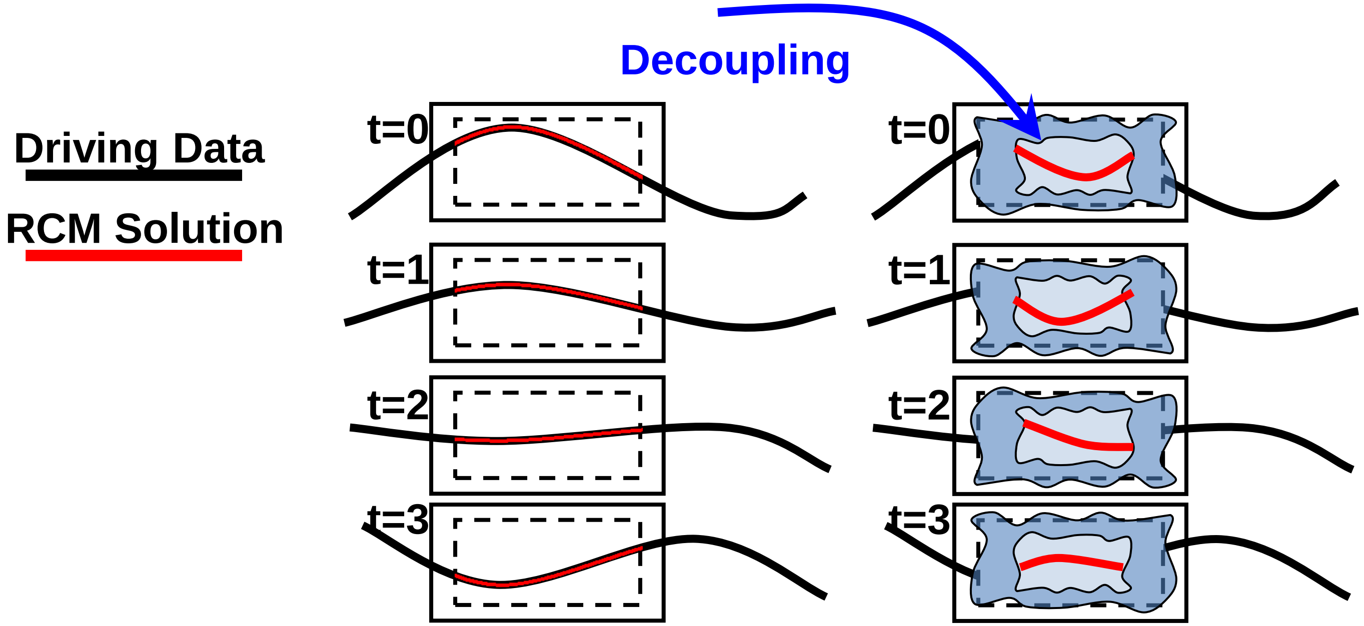


- RCMs have a lack of control exerted by the lateral boundaries and the internal variability of the RCM solution
- Two intractable issues emerge:
  1. "Chaotic Divergence"
     - the tendency of the interior RCM solution to diverge from the weather realization imposed on its lateral boundaries due to the nonlinearity of its governing equations
  2. "Upscale Influence"
     - the tendency of better resolved, small-scale features, in the RCM to influence or alter the larger-scale flow in its interior

Chaotic divergence and upscale influence

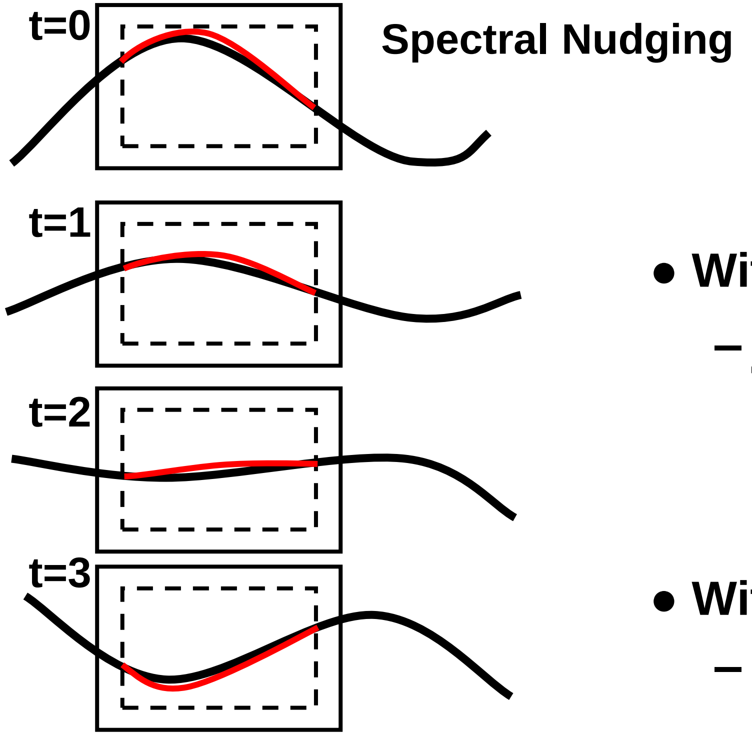


- Once an air parcel enters the RCM domain, the clock starts ticking on chaotic divergence due to nonlinearity
- the lifetime of an air parcel (time between being swept in and then out of the domain) determines how long chaotic divergence due to nonlinearity can occur (boundary control).
  1. small domains diverge less (less “free” time)
  2. mid-latitude wintertime domains diverge less than summertime



- RCM weather becomes disconnected, or decoupled from weather specified at the boundaries as small-scale resolved features influence the large-scale flow, causing artifacts
- atmospheric teleconnections can break down
- breaks the initial assumption that the solution of the ESM and RCM are the same and RCM climate becomes inconsistent with the ESM

Constraining the RCM large-scale



- CanRCM applies spectral nudging on large-scales which forces the largest spatial scales of the RCM to follow the driving ESM data within the RCM domain

- **With Spectral Nudging:**
  - **<u>chaotic divergence</u> is controlled but <u>upscale influence</u> is suppressed**

    Pro: control of artifacts associated with decoupling

    Con: retain correctable biases in large-scale flow

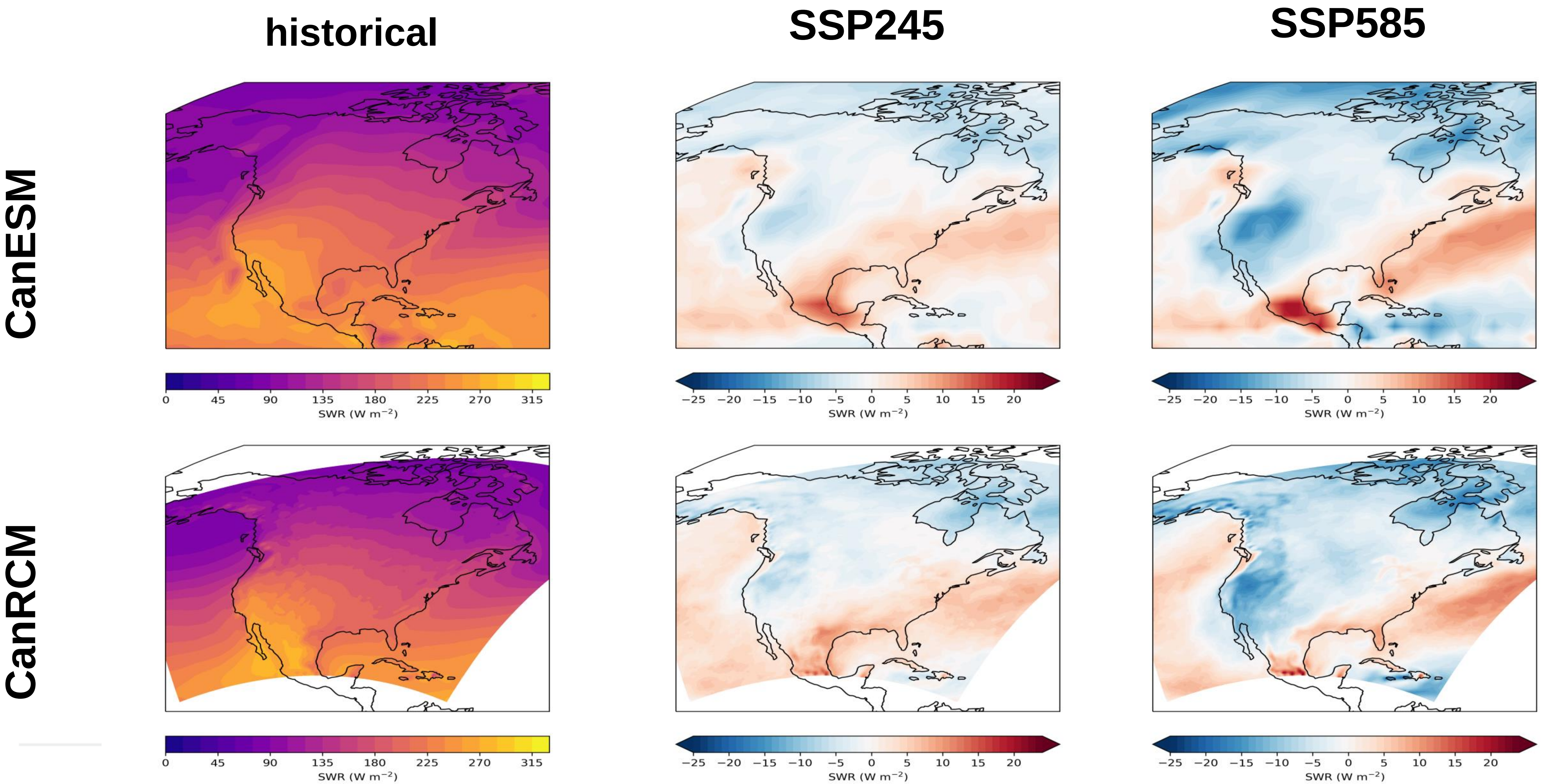
- **Without Spectral Nudging:**
  - **<u>chaotic divergence</u> and <u>upscale influence</u> are not suppressed**

    Pro: potentially remove correctable biases in large-scale flow

    Con: no control of artifacts associated with decoupling

Due to <u>chaotic divergence</u> and <u>upscale influence</u>, downscaled RCM climate change responses will always contain some amount of artifacts

CanRCM5 climate change response



CanRCM5 climate change response

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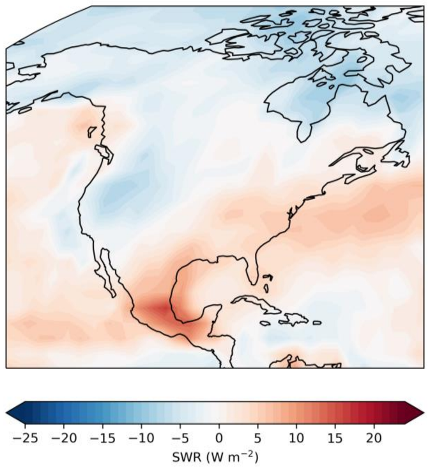
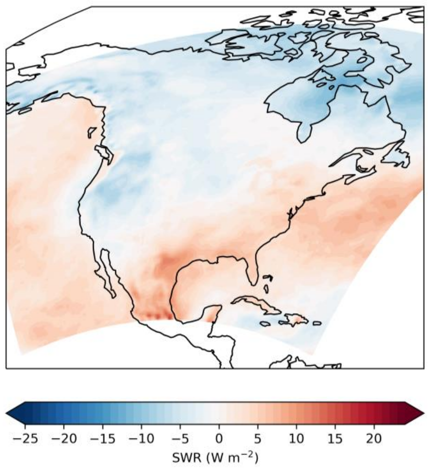
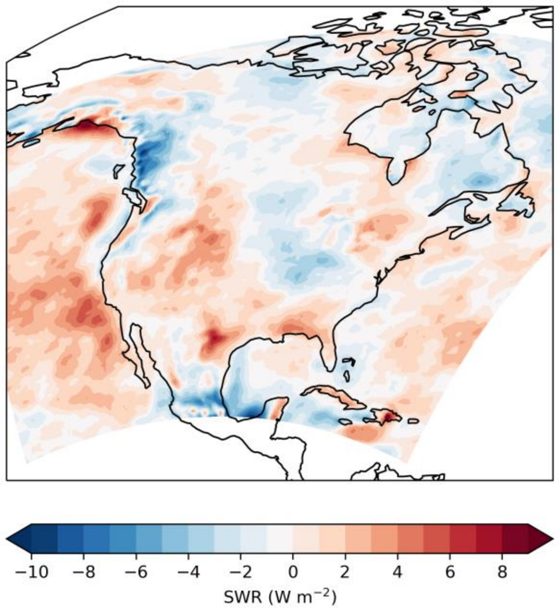
CanESM



CanRCM



CanRCM-CanESM



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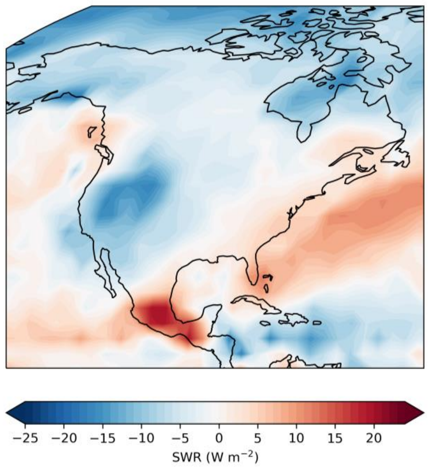

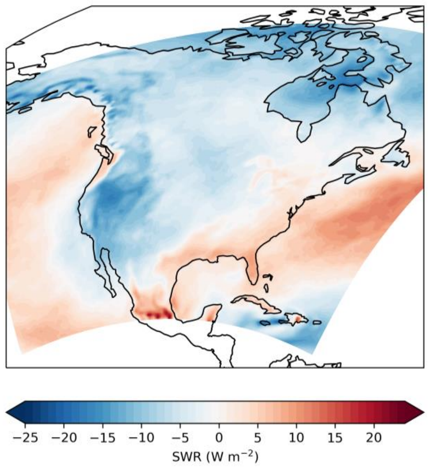

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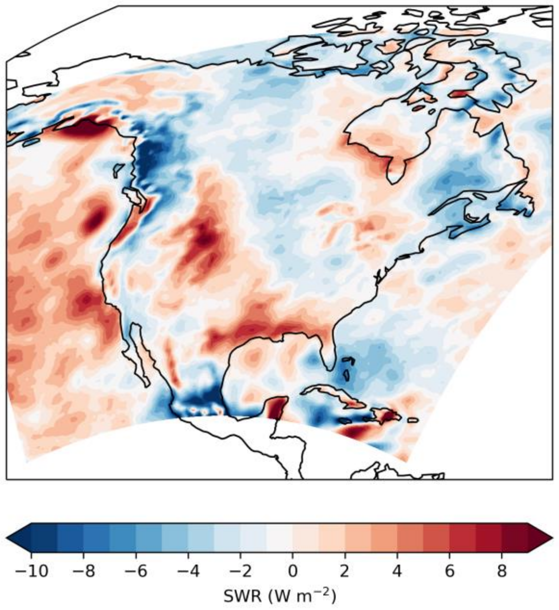

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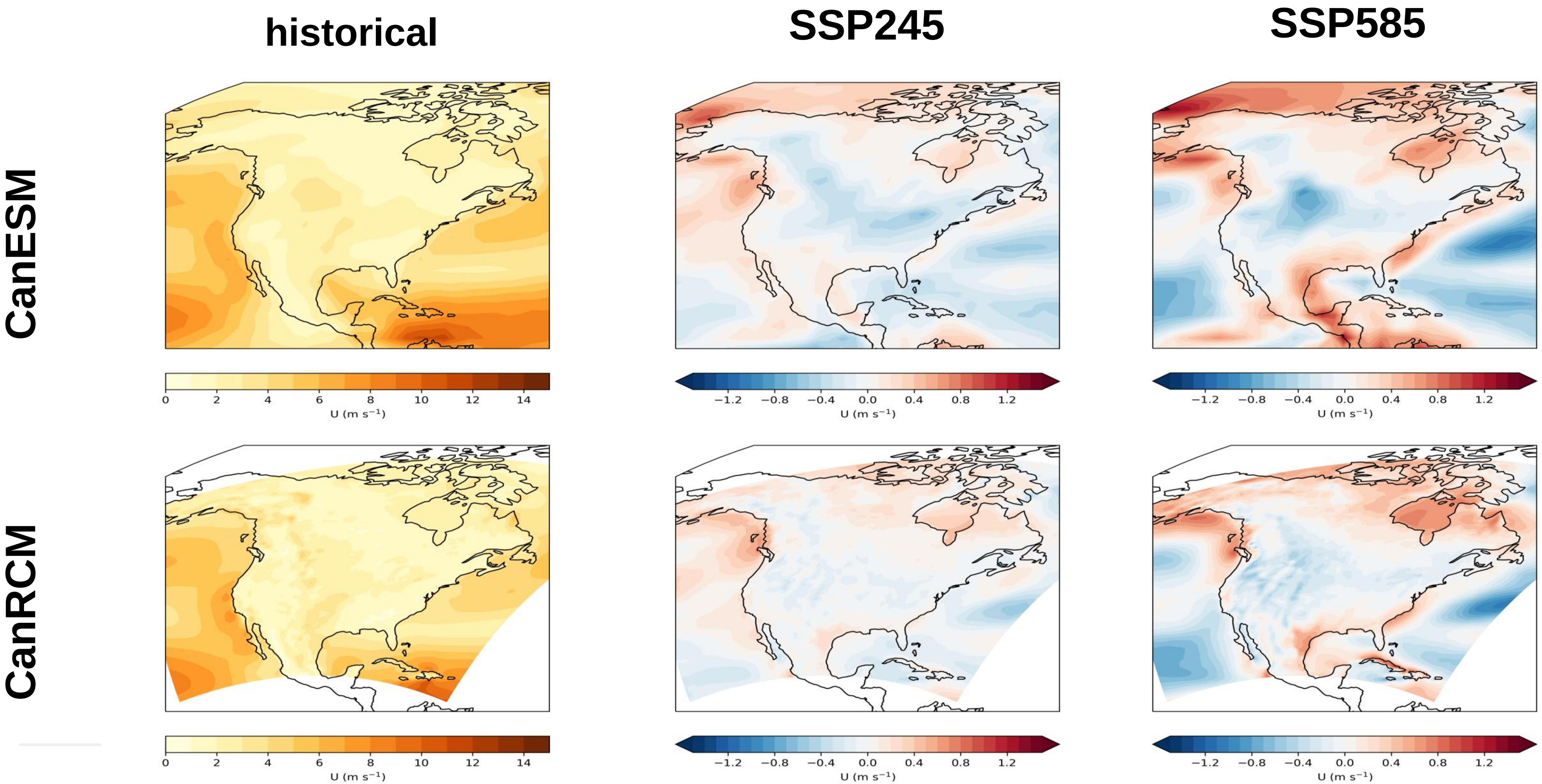

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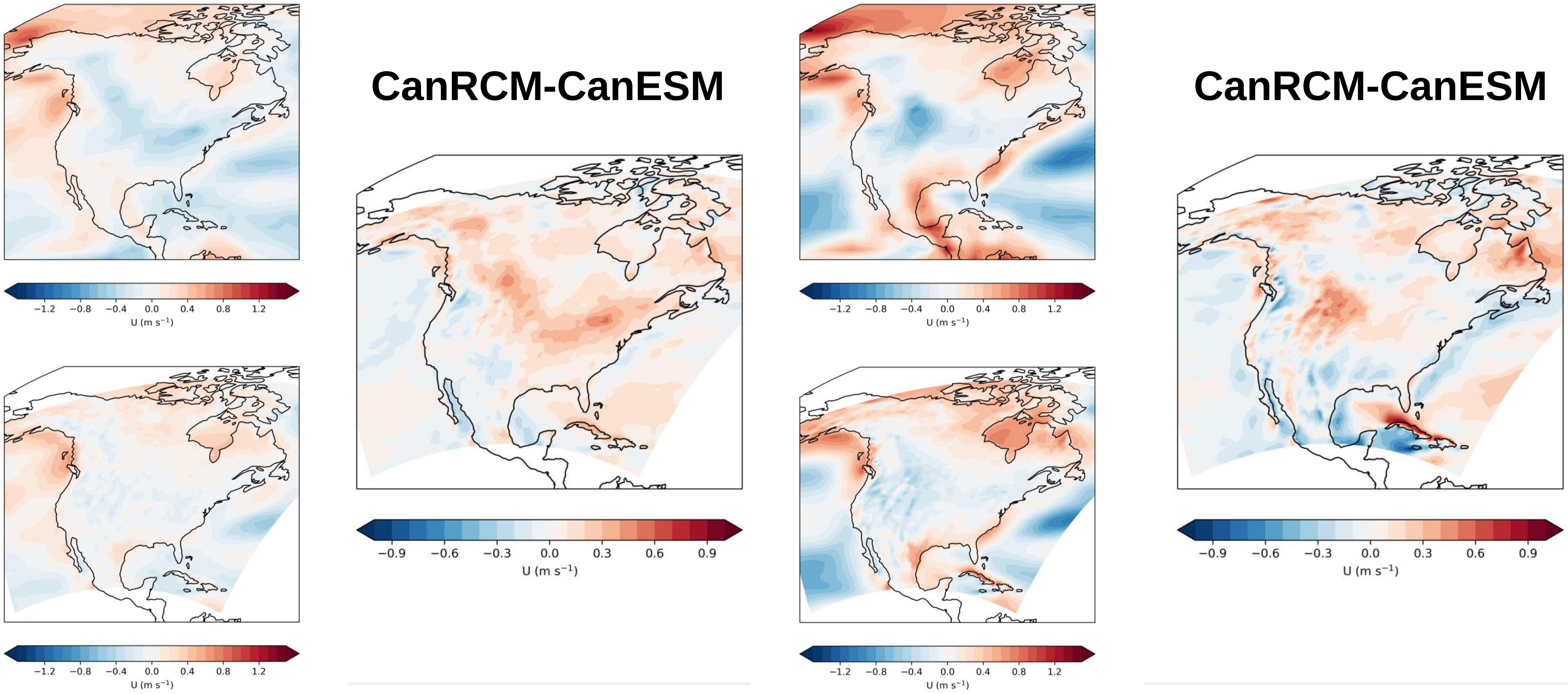
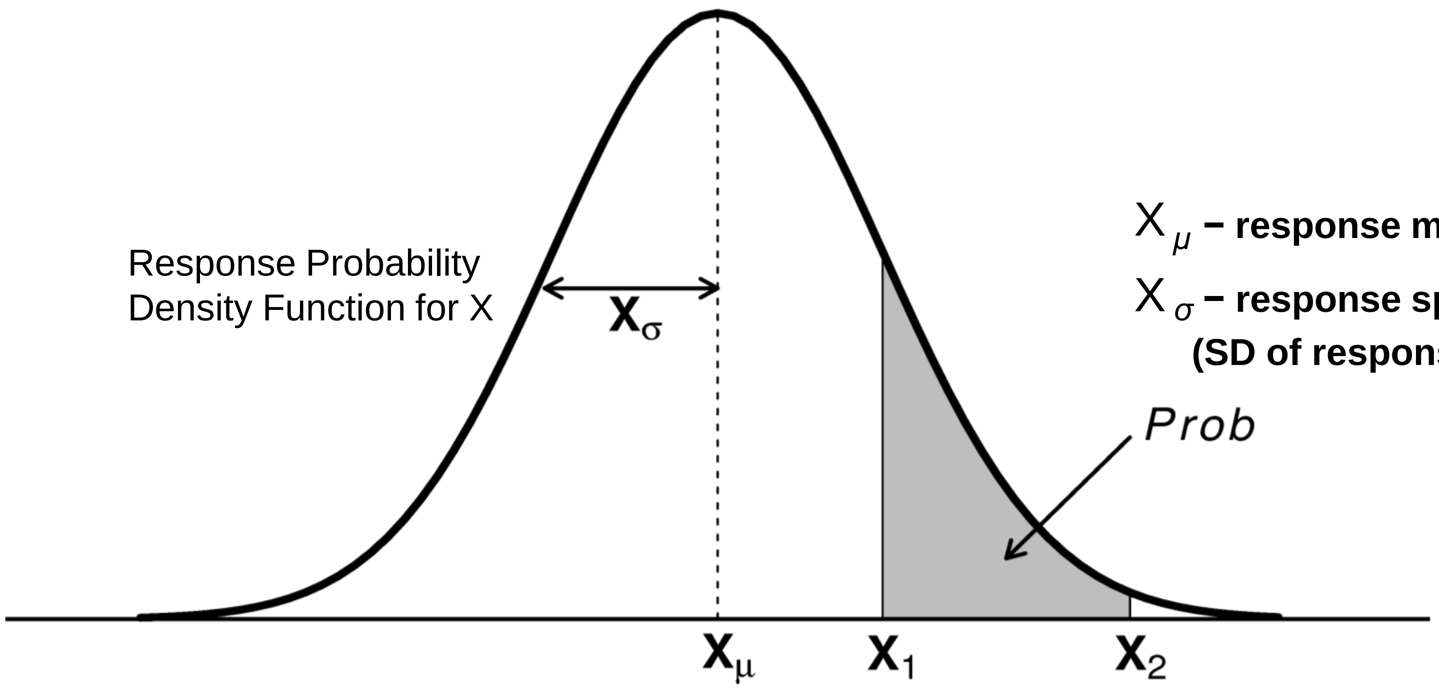


Quantify added value from RCM simulations

- Since the RCM produces its own "climate" appreciable differences can be quantified to identify added value from the RCM
  - Appreciable differences are a necessary (but not sufficient) condition to identify added value



X_μ – **response mean**

X_σ – **response spread (SD of response PDF)**

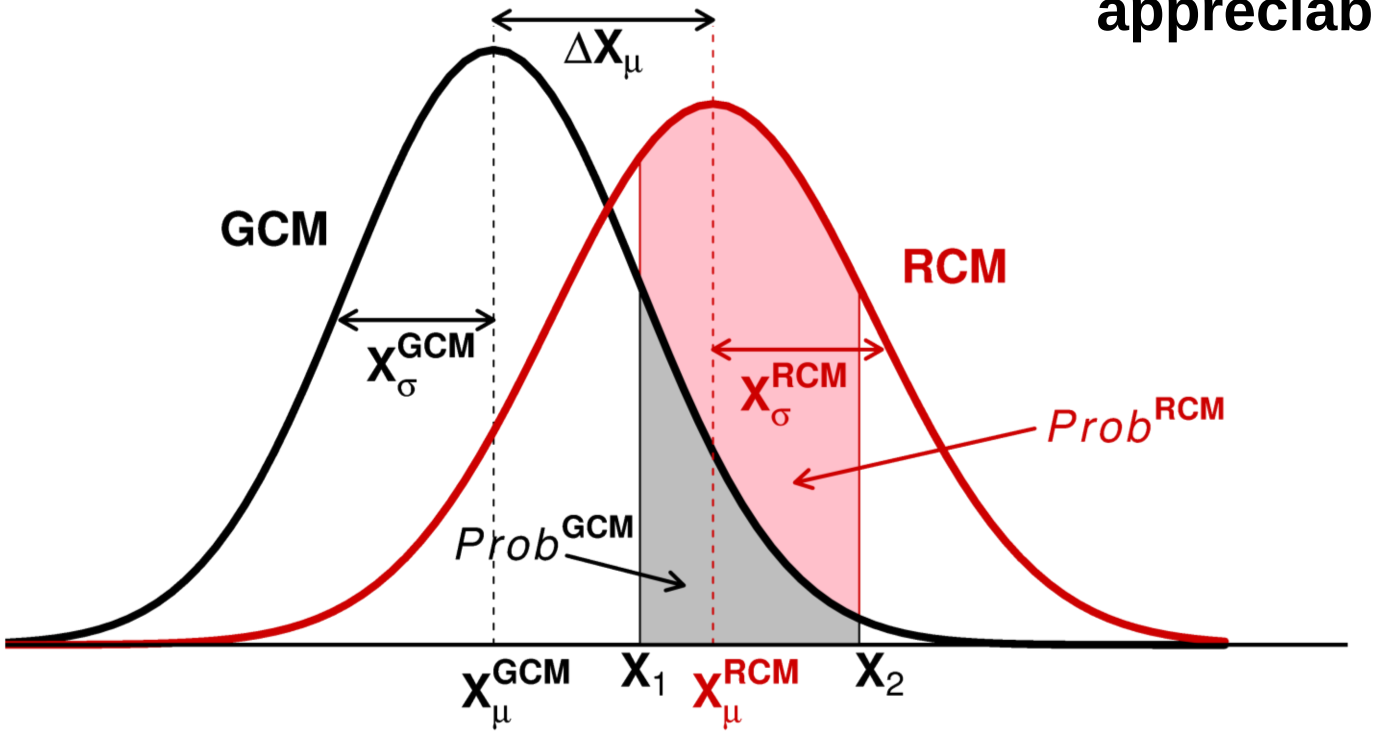
- Climate projection are used to understand the response distribution of some quantity X (Temperature) to a change in an external forcing of the system (atmospheric CO_2 concentration)

Quantify added value from RCM simulations

- Given a probability distribution response of X, *Prob*^{GCM}, from a GCM climate-change exp., does RCM downscaling suggest a <u>substantively</u> different value

$$\Delta Prob = Prob^{RCM} - Prob^{GCM}$$

Δ*Prob* must be larger than some specified threshold to be considered appreciable



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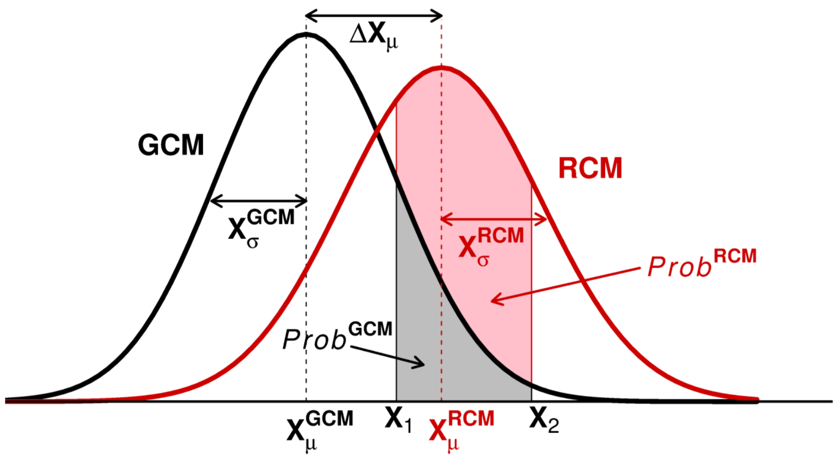
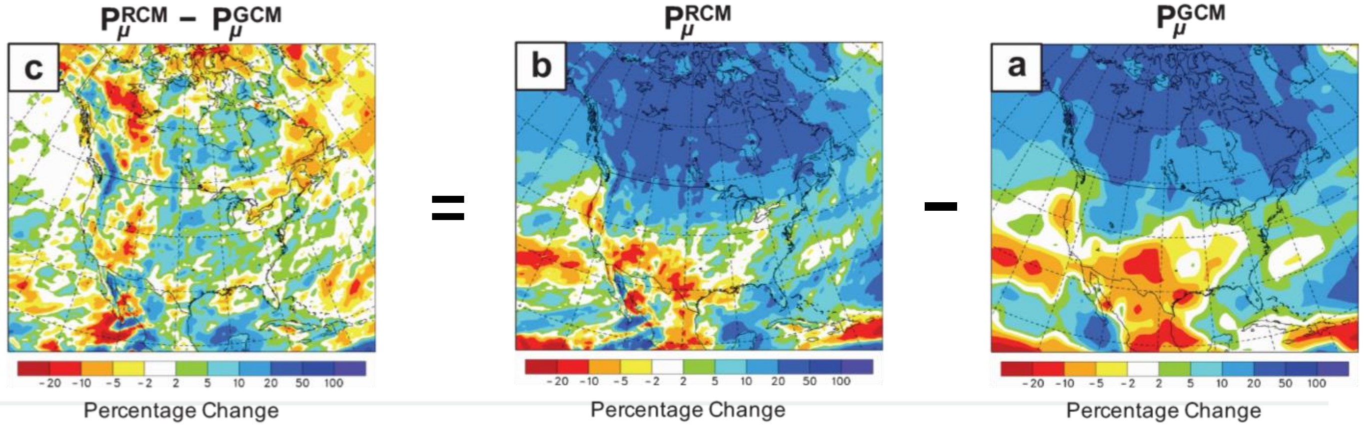


Δ*Prob* must be larger than some specified threshold to be considered appreciable

The most straightforward quantity to look at is the mean response:

$\Delta X_\mu = X_\mu^{RCM} - X_\mu^{GCM}$ $\longrightarrow$ **difference in response means**



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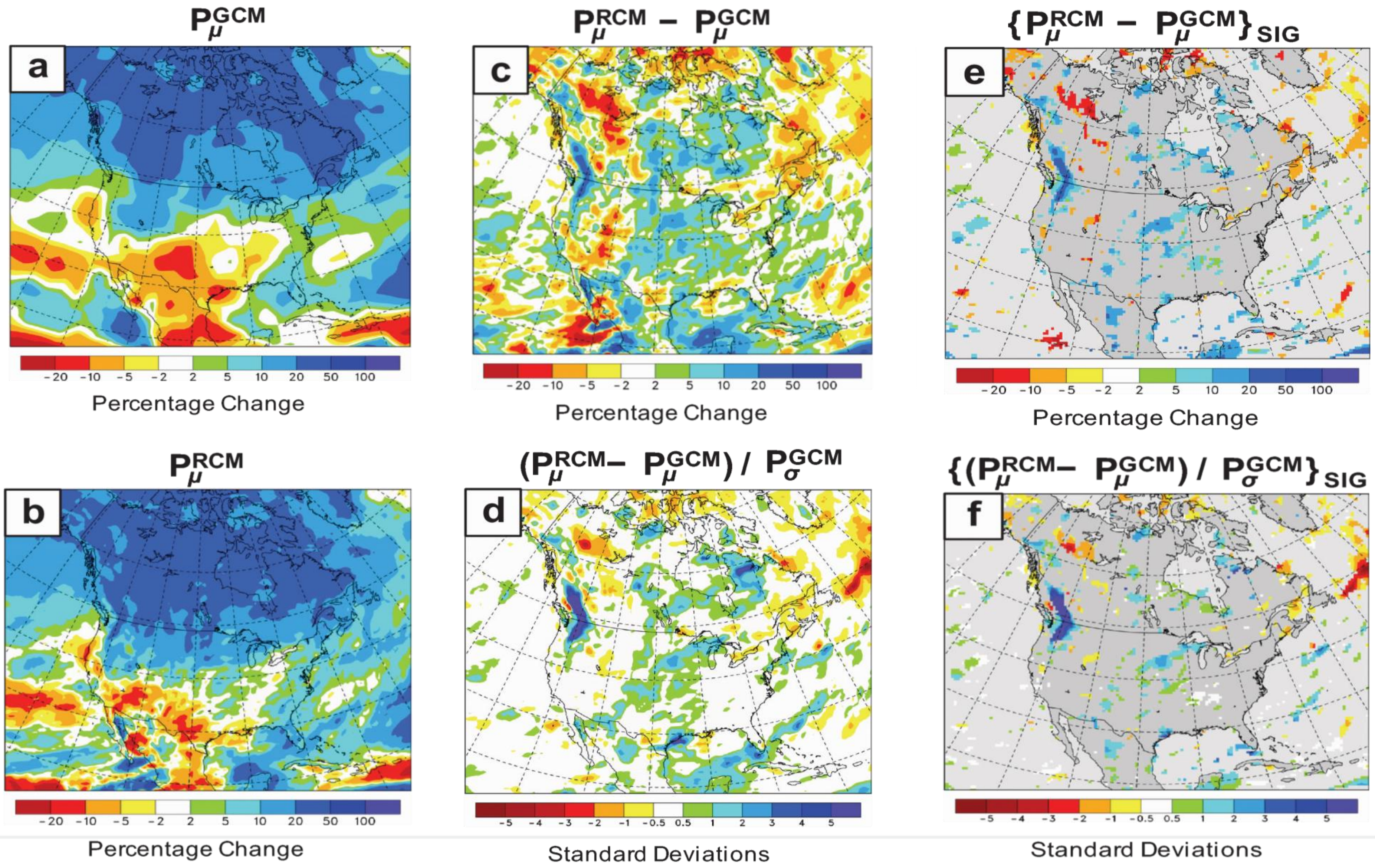
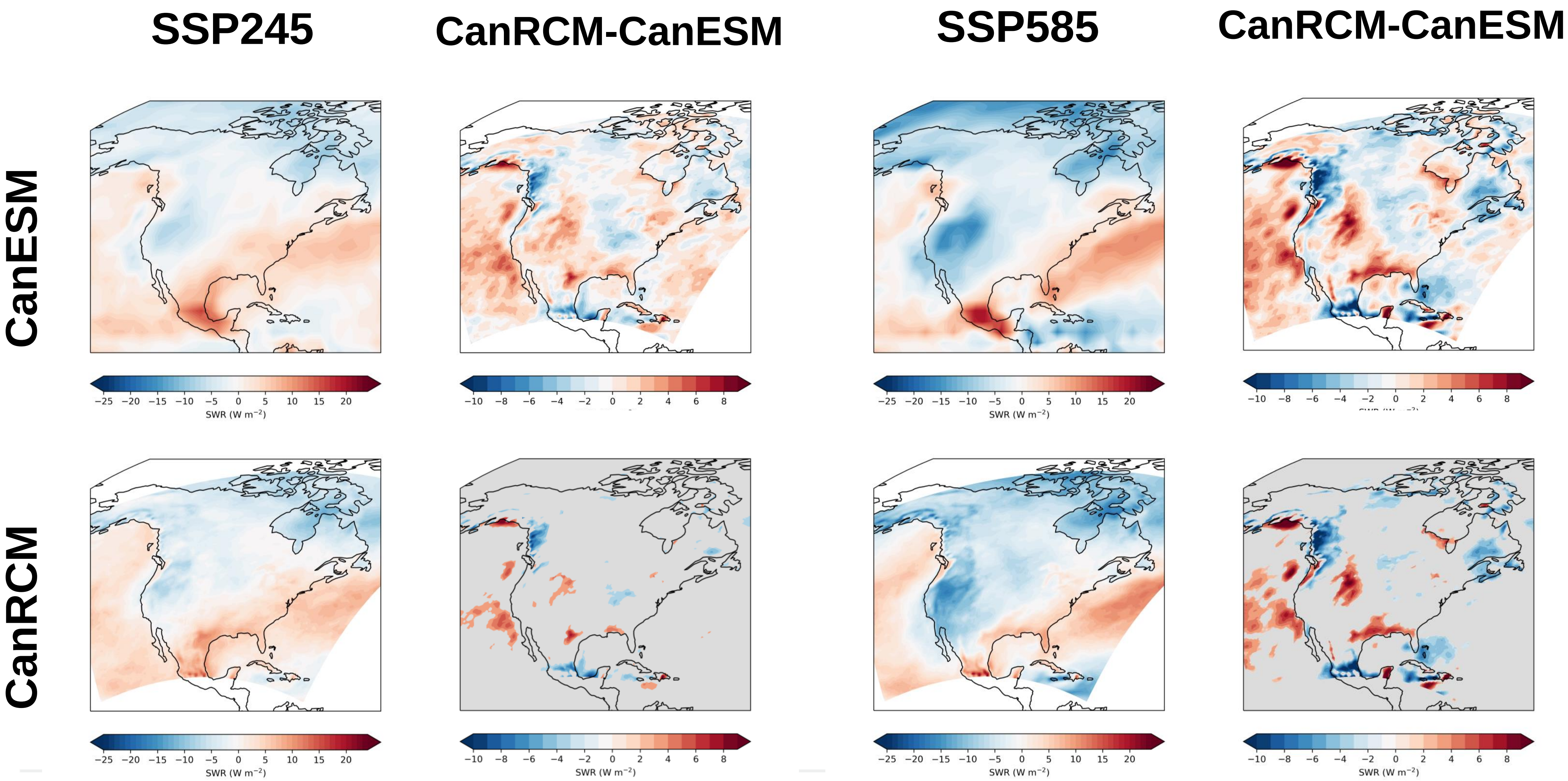


← Statistically significant at the 5% significance level.

~16% areal fraction significant

CanRCM5 climate change response



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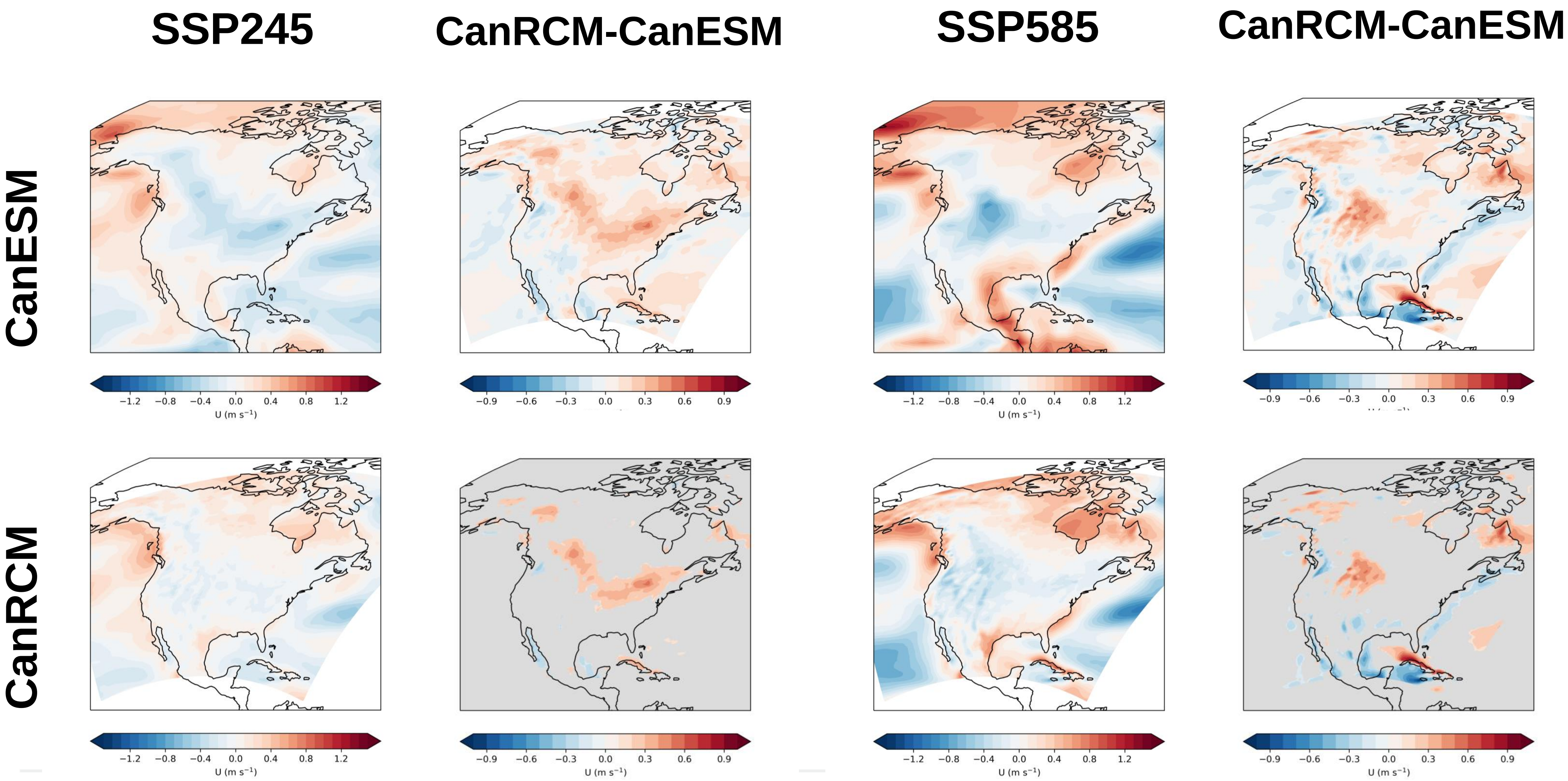
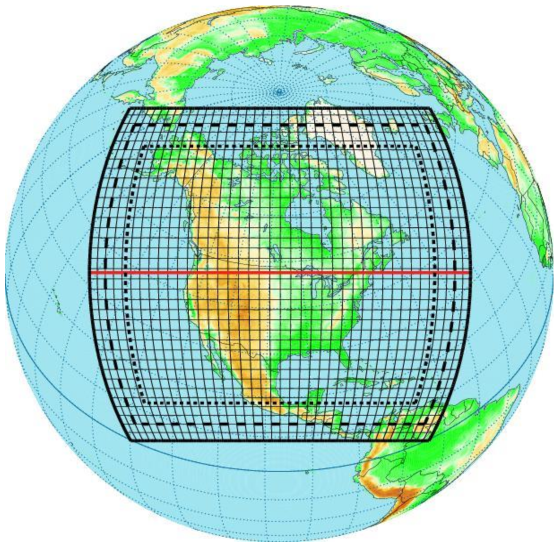


Takeaways

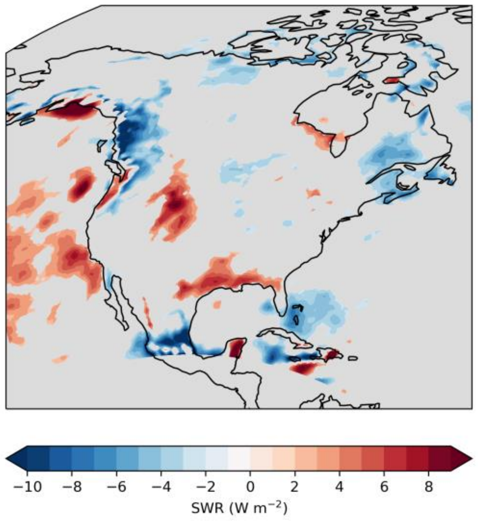


The Canadian Regional Climate Model (CanRCM) is a physically-consistent nested local area model within the Canadian Earth System Model

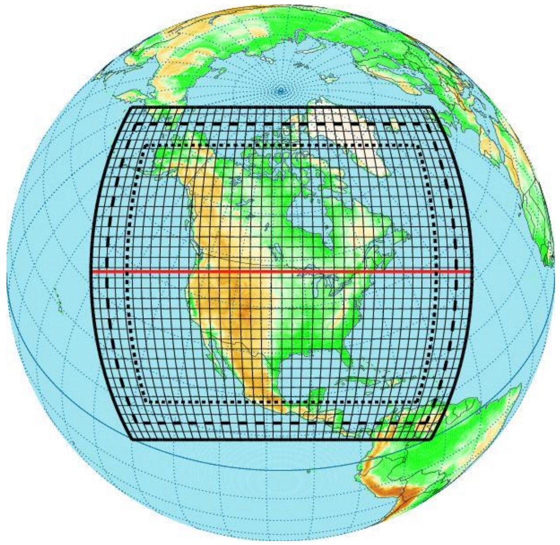
- CanRCM’s large scale is nudged towards its parent model CanESM

Regional climate models have to some extent their own climate:

- Careful evaluation required to what extend grid cells have potentially added value from higher resolution



Development toward CanRCM6



- Higher spatial resolution (10 km)
- Higher vertical resolution (88 levels)
- Coupled regional climate model (regional ocean model will be coupled)
- New physics package (deep convection, radiative transfer code, cloud microphysics, turbulence, land-surface module)
- Bias corrected large-scale flow

Bias-correcting the large-scale

Each frozen version of any climate model (i.e. fixed numerics, resolution, physical parameterizations and their tunings) has biases to real-world realization

tendency of prognostic variable (U,V,T,q)

model advection, physics, external forcing

Free model: $$\frac{\partial X}{\partial t} = G(X)$$

Bias-correcting the large-scale

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Derived “Bias Correction” to the model

Procedure: 1. apply a simple relaxational adjustment to u,v,T,q to constrain the model to be “close” to reanalysis (e.g. ERA-5)

$$\frac{\partial X}{\partial t} = G(X) - \frac{1}{\tau} F(X - X_R)$$

τ – relaxational timescale (24hrs)

$F(\bullet)$ – low-pass spatial filter (~ scales larger than T21)

X_R – reanalysis reference state (ERA-5) 6hr sampling

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$$\frac{\partial X}{\partial t} = G(X) - \frac{1}{\tau} F(X - X_R)$$

2. Store nudging tendencies every 6hrs from the simulations

3. average these tendencies by calendar date and time to obtain mean seasonal cycle of bias correction <BC>

4. Rerun the model with bias correction <BC>

Validation for the use of climate projections

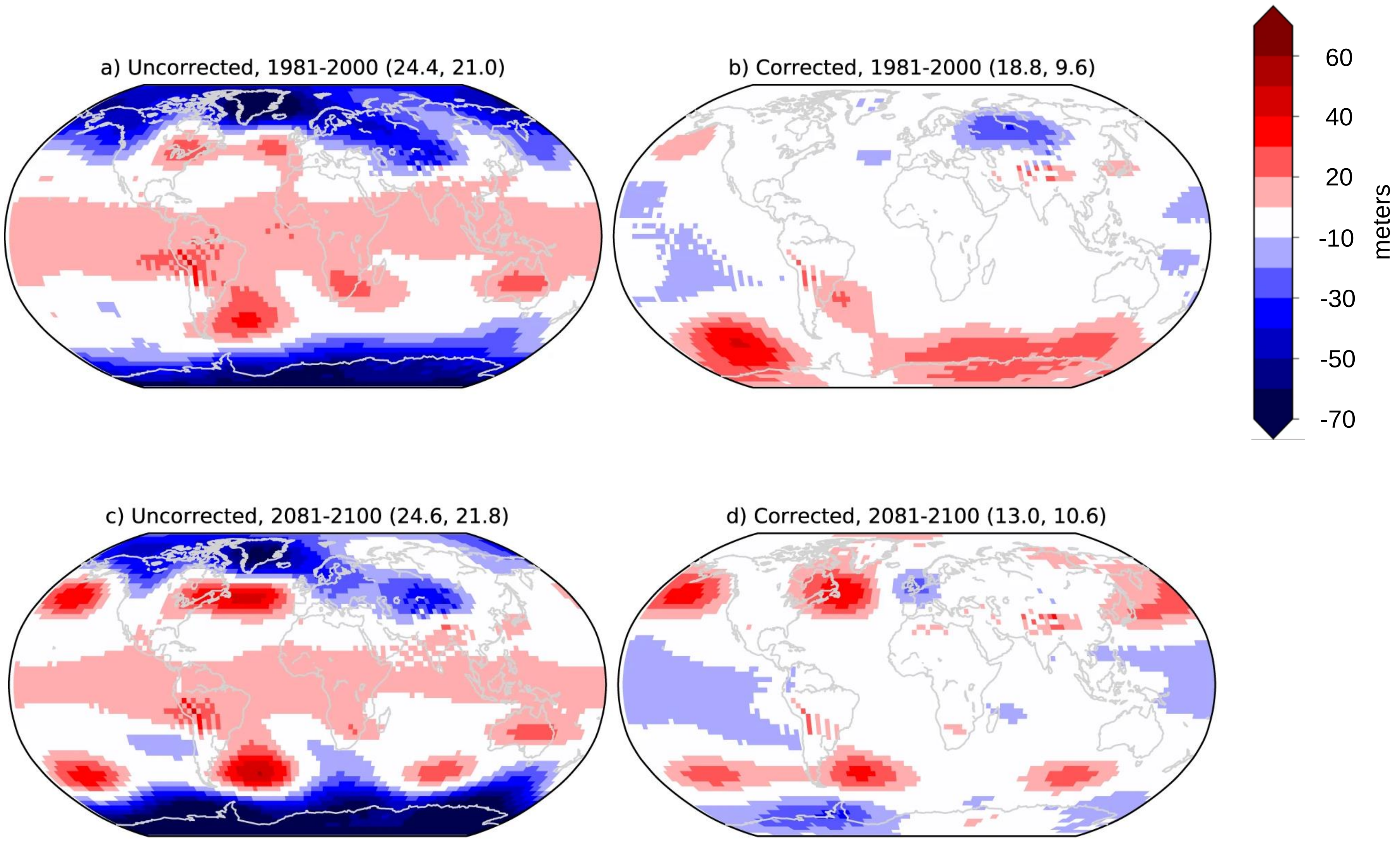
In the absence of observations on climate-projection timescales use a different climate model, model B, as the "pseudo observations" for model A

$$\frac{\partial X}{\partial t} = G(X) - \frac{1}{\tau} F(X - X_R)$$

$$\frac{\partial X}{\partial t} = G(X) + \langle BC \rangle$$

– bias correct model A basic state to better match model B that provides pseudo obs

Validation for the use of climate projections



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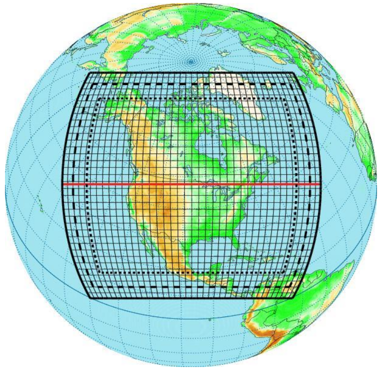

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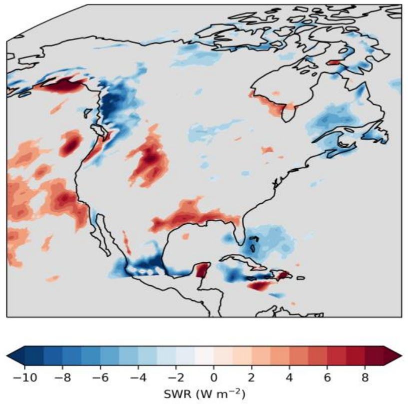

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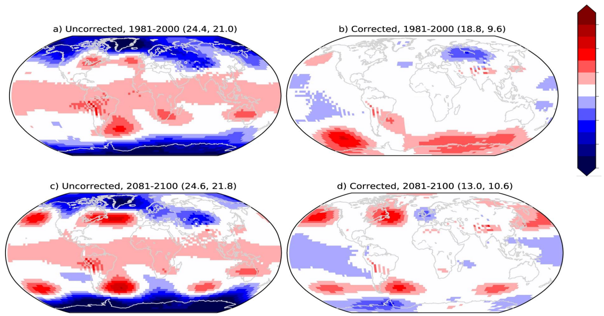

Model states will be bias corrected in the next CanRCM version. Bias correction terms can be applied in future climate projections and lead to better skill