Evaluating Scale-Dependent Bias in the Community Earth System Model's Representation of the Mean Diurnal Cycle of Precipitation over South America

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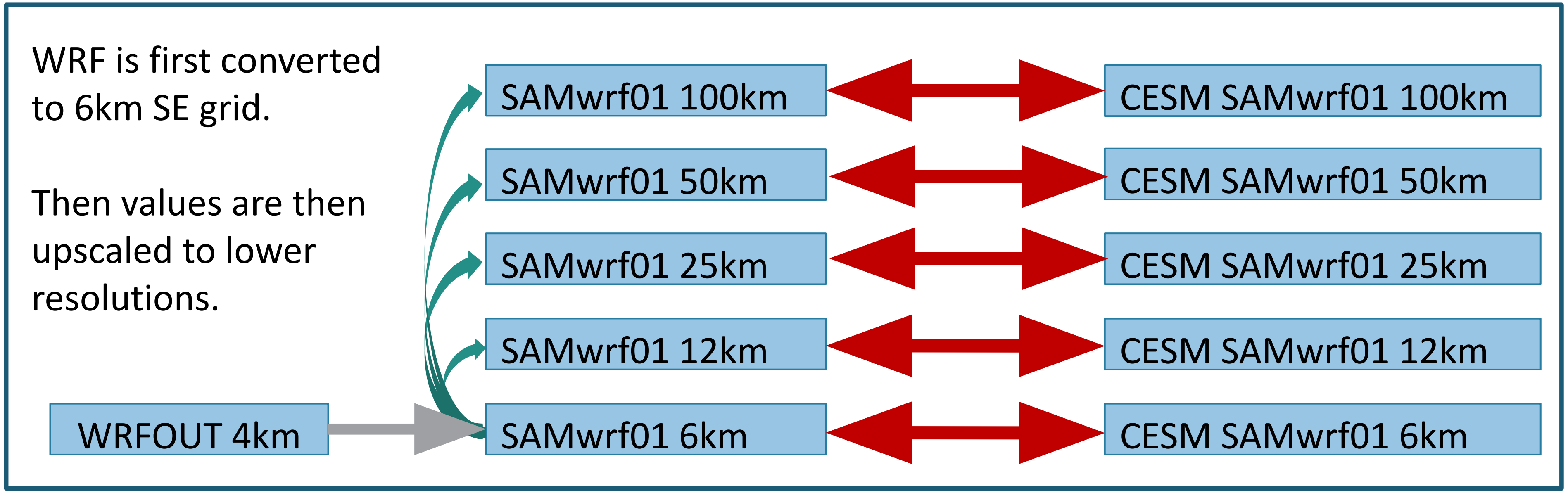
Introduction

- High-resolution modeling at convection resolving scales has emerged as a useful tool to advance our understanding of Earth's climate.

- For simulations on climate time scales, requiring ensembles of simulations, high-resolution models are not practical and we must still rely on lower resolution climate models.

- Our goal is to use the results of these high resolution simulations to improve CESM's usefulness as a hydrological model, to improve it's usefulness for long term planning under future climate scenarios.

Analogous to the 'Grey-Zone' case study approach, we run coincident CESM simulations on a hierarchy of horizontal and vertical resolutions and compare the results with contemporaneous output from WRF.



WRF Simulations

- Collaborative effort focused on the water and energy cycle of South America
- Three 1-year WRF simulations for each phase of ENSO.

3 Phases of ENSO	
June 2010 - May 2011	La Nina
June 2015 – May 2016	El Nino
June 2018 – May 2019	ENSO Neutral

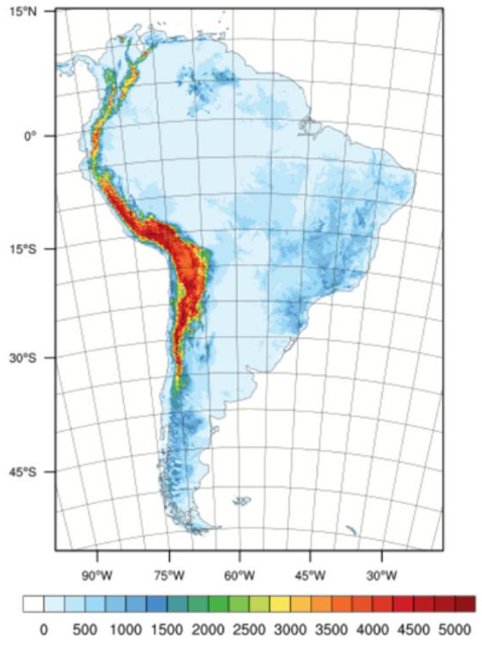
WRF Model Version 4.1.5

1472x2028 horizontal grid

60 Vertical levels , 10hPa top.

ERA5 Boundary conditions

4km WRF Domain



More Information Available:

South American Affinity Group (SAAG)

https://ral.ucar.edu/projects/south-america

Major sub-grid parameterizations:
Thompson microphysics
Yonsei Univ PBL
Noah-MP land surface model
RRTMG radiative transfer model

CESM Configurations

Using a refinement region aligned with the WRF domain a hierarchy of regional grids were created from 100km to 6km resolution.

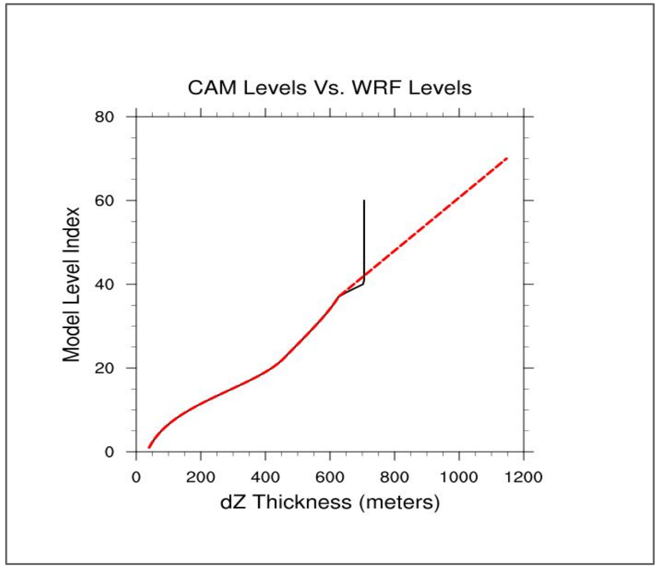
Each grid has a global base resolution of 100km

For each horizontal grid, there are 2 vertical resolutions:

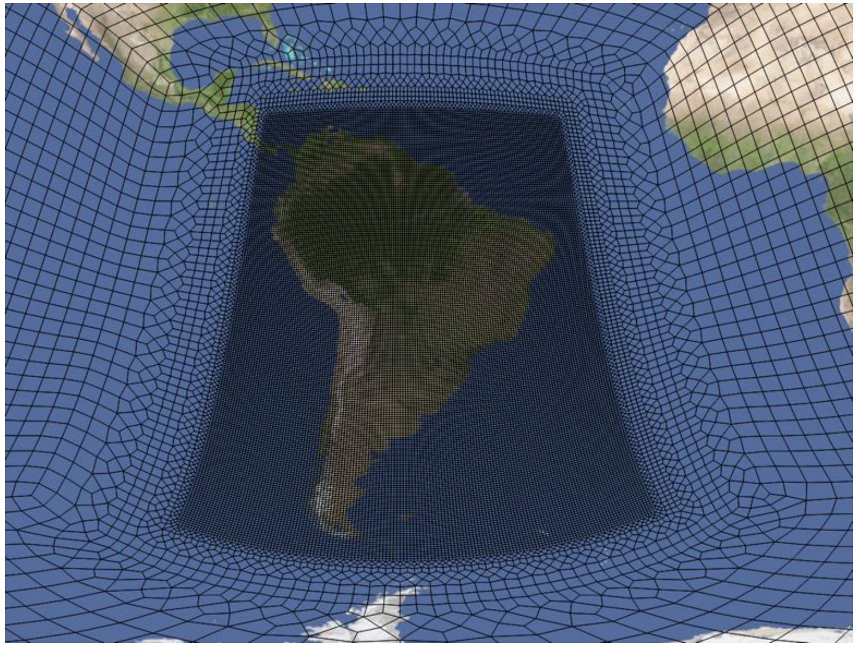
- 32 level configuration, the CAM default
- 70 layer configuration, for which the lowest 38 levels are nominally aligned with the WRF levels and the remaining levels are stretched to maintain the default CAM model top.

For consistency with the WRF regional model, boundary conditions outside and along the perimeter are imposed with strong nudging to ERA5.

The resulting datasets are a huge resource (~400Tb) for research and model development.



12 km (ne240) Refinement



SE Refined resolution	Nominal Grid resolution	Horizontal Grid points
ne30	100km	48,602
ne60	50km	64,766
ne120	25km	116,534
ne240	12km	337,503
ne480	6km	1,167,113

The Mean Diurnal Cycle

- Represents a dominant contribution to overall variability
- Errors in the diurnal cycle provide a measure of how well fundamental processes are represented.
- This mode exists in the intersection between the chaotic behavior of the weather regime and longer-larger scale variability.

It is essential that a focused effort be made to improve the representation of the mean diurnal cycle. (e.g. Getting the phase of precipitation to agree with OBS)

With hourly outputs, the datasets we have generated are a huge resource.
Here we start out small with an examination/assessment of results for a single month of data.

The results shown here:

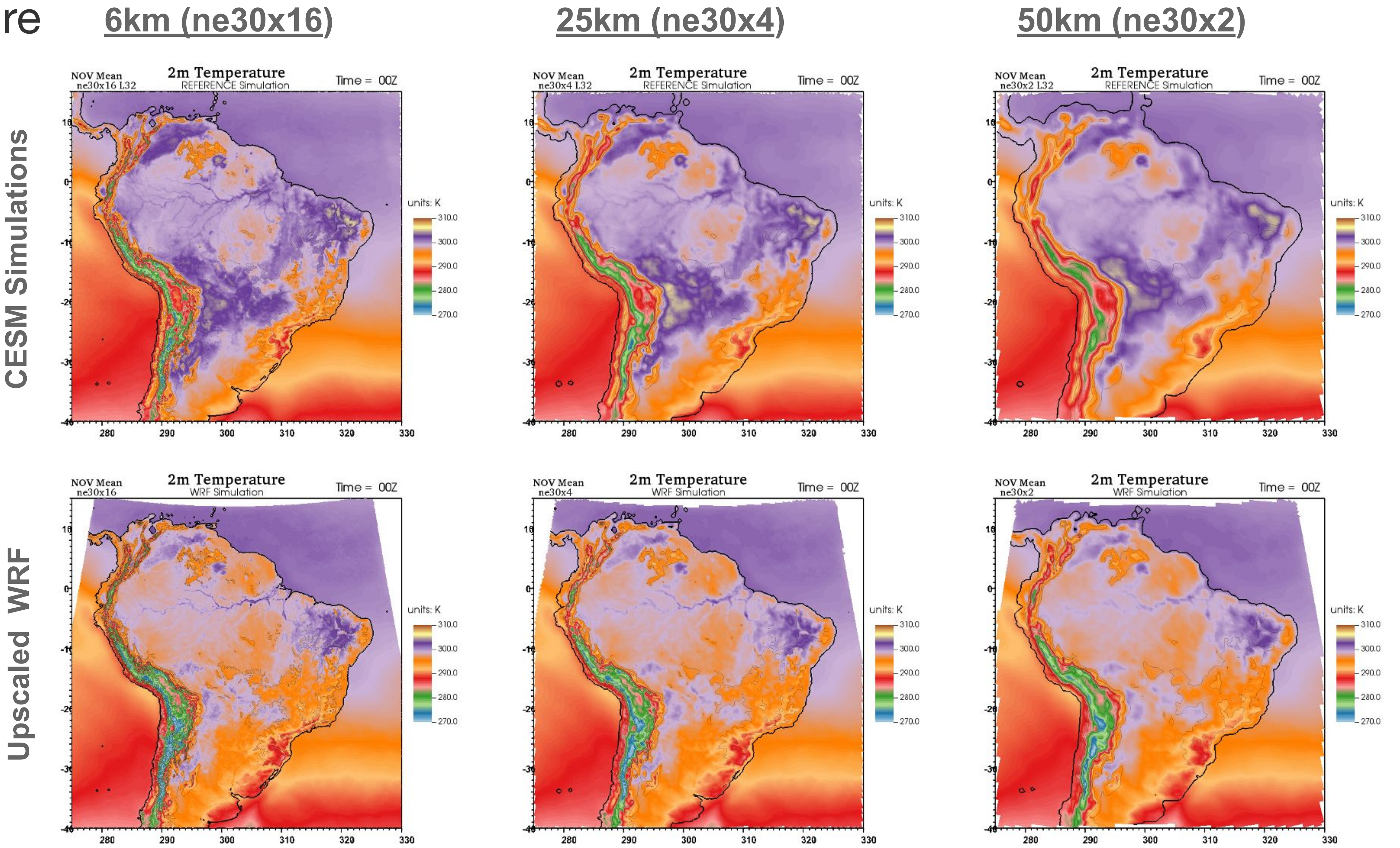
Time:	The mean diurnal cycle for **November 2010**
Variables:	**Precipitation**, **2m Temperature**, and **2m Water vapor**
Horizontal Resolutions:	Only representative horizontal resolutions **6km (ne30x16)**, **25km (ne30x4)**, and **50km (ne30x2)** . The behavior at the other 2 resolutions can be inferred from these.
Vertical Resolutions:	Results only shown for **L32**. The L70 results are similar to the L32 results, but with a larger amplitude errors/bias.

2m Temperature

Note:

The warm temperature bias between WRF and CESM at all scales.

The larger diurnal variation in temperatures in CESM



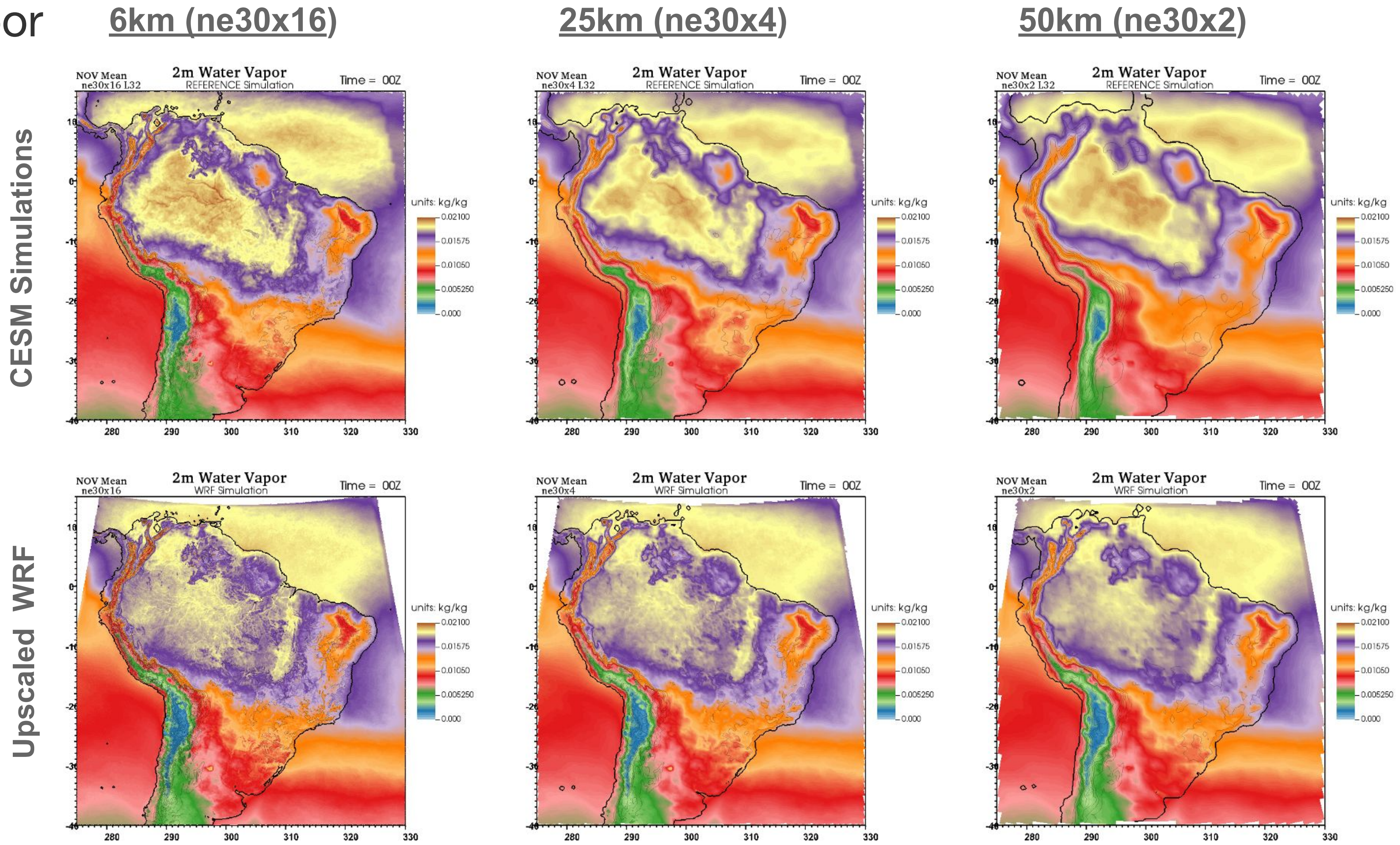
2m Water Vapor

Note:

The significant persistent bias in water vapor associated with the Amazon river.

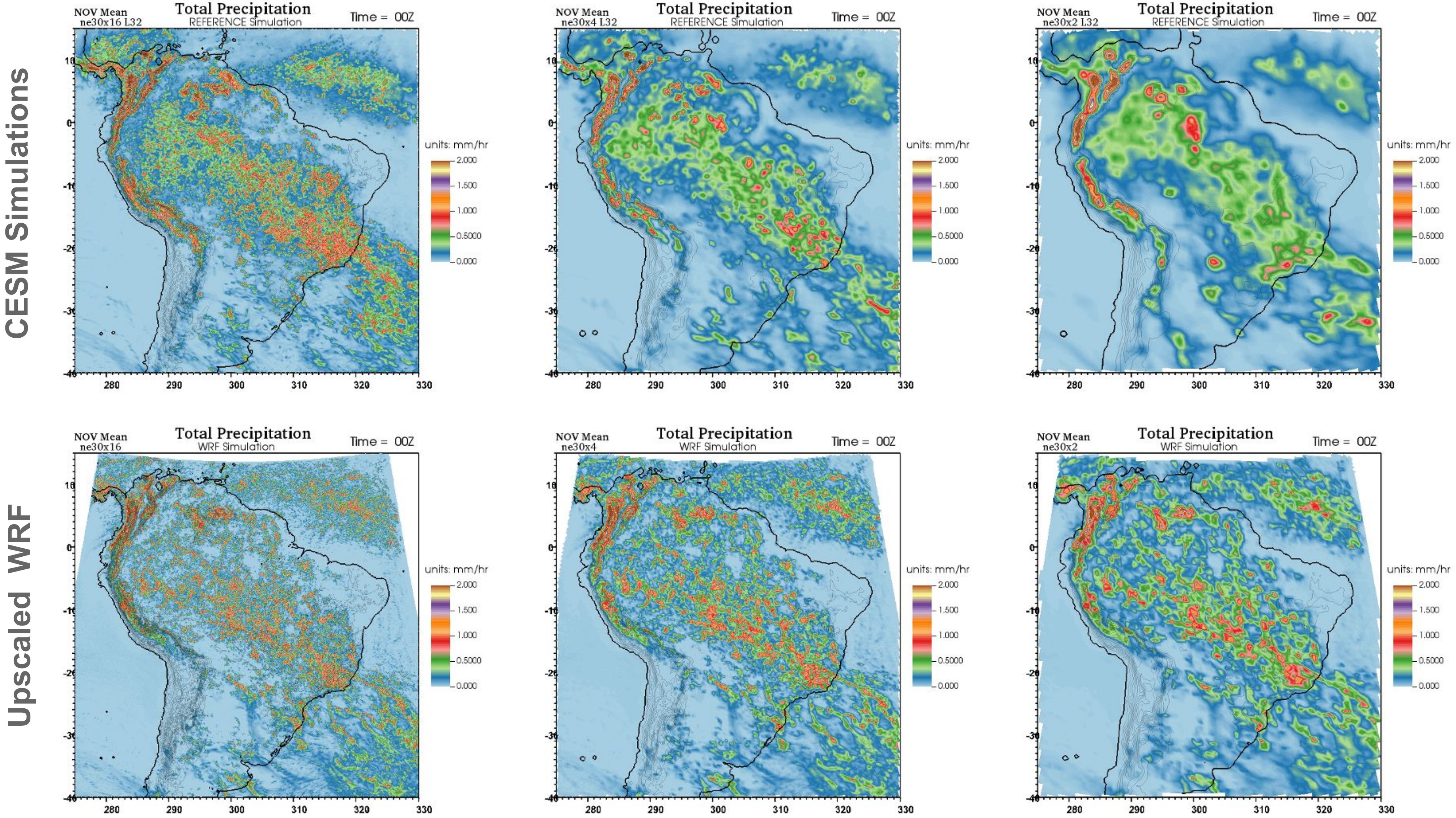
The double impulse of water vapor is substantially larger.

The uptake and transport of water vapor in the Amazon basin is much too strong in CESM compared to WRF.



Precipitation

6km (ne30x16) | **25km (ne30x4)** | **50km (ne30x2)**



Note:

Scale of WRF precipitation compared to CESM, even at 6km.

Dry no-precipitation ‘halo’ along the Andes in CESM

Persistent precipitation over Andes.

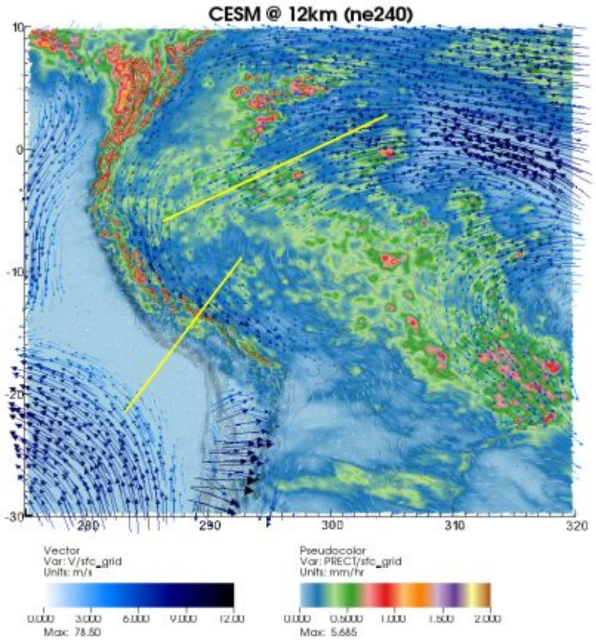
Propagation differences South of ~ 25S.

November Mean Profiles

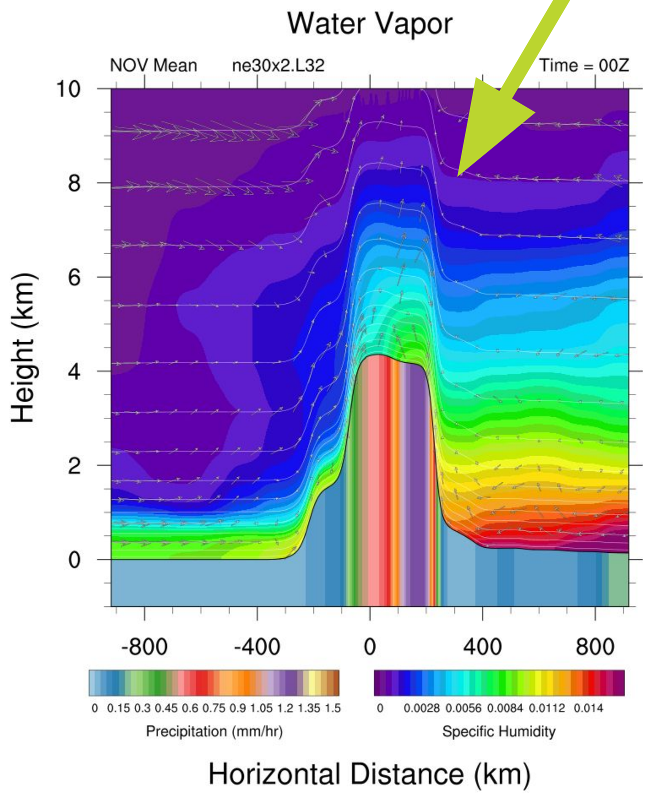
The panels show the cross sections of water vapor across the Andes ridge.

(indicated by the yellow line below)

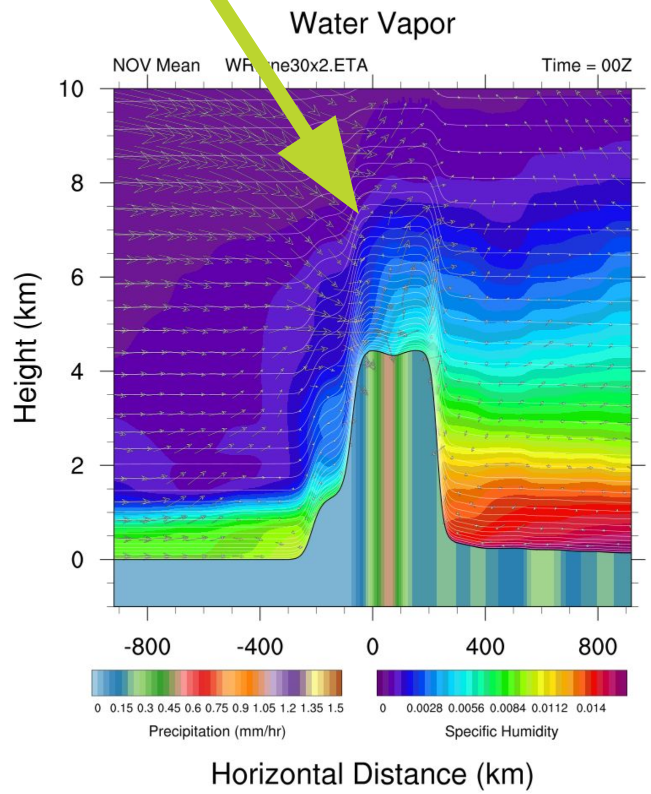
The CESM profile compared to the WRF result indicates anomalous water vapor over the ridge with contours roughly aligned along model levels.



CESM



WRF



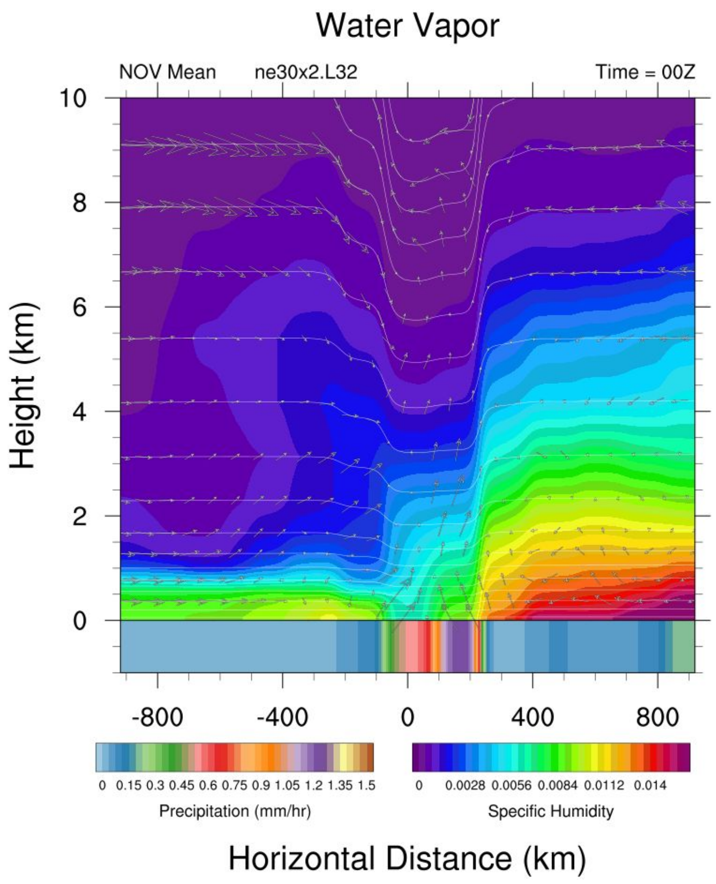
November Mean Profiles

Removing the topography provides a better view of how WRF maintains a sharp gradient along model levels.

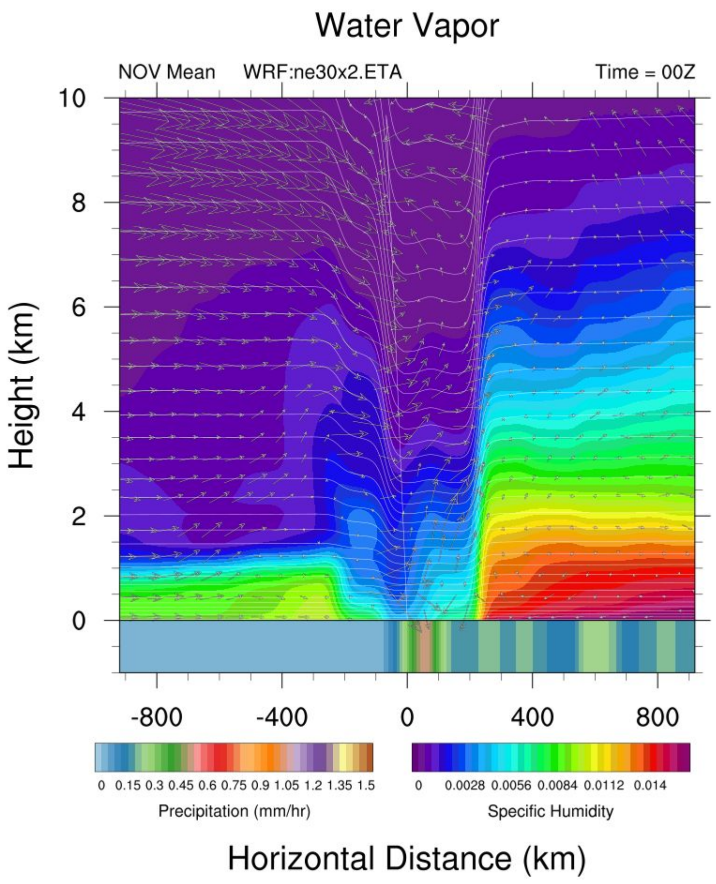
Whereas, for CESM, the gradient is smoothed out substantially.

At 6km (ne30x16) CESM better maintains a sharp gradient, but there is still leakage leading to anomalous precipitation (not shown).

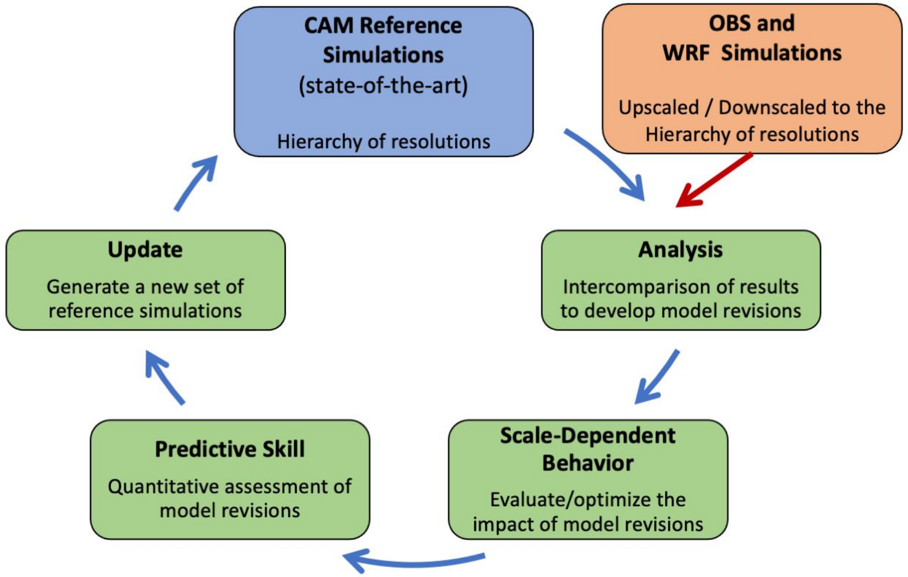
CESM



WRF



Multi-Resolution Model Development



Fundamental Goal:
Improve CAM simulations running at climate resolutions for extended periods of time.

Specifically:
- Demonstrate an improvement in the fidelity of results across scales (i.e. The Grey Zone).
- Demonstrate a quantitative improvement in predictive skill

To utilize hierarchical model simulations to systematically improve climate simulations, we envision a workflow of the form:

Evaluation/Analysis:
Intercomparison of hierarchical models results and OBS to develop a modification or a new parameterization.

Implementation/Testing:
Short term restart simulations to verify installation and tune/optimize modifications.

Validation: Scale-Dependent Bias
Assessment (quantitative) of simulations at a hierarchy of resolutions to determine the impact the modifications have on scale-dependent bias.

Validation: Predictive Skill
Assessment (quantitative) of the impact the modifications have on predictive skill (e.g. S2S suite of tests)

Update:
For modifications demonstrate improvement in scale-dependent bias and predictive skill, generate new improved state-of-the-art results.

Iterate:

Diurnal Mean Results

From the Diurnal comparisons we observe:

- An excess in water uptake from the surface and the Amazon river.
- A warm bias in the 2m temperatures
- A bias in the strength of the trade winds over the Amazon (not shown)
- A large bias in precipitation associated with the topography

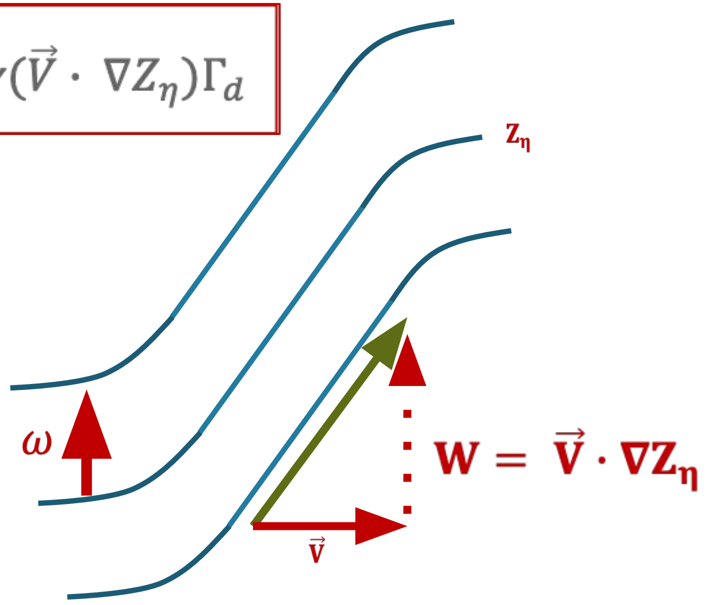
While the CESM results better resemble those of WRF as horizontal resolution increases, these fundamental differences are generally uniform across scales.

Here we focus on the well-known problem of **orographic precipitation.**

Analysis of the results indicate a discrepancy in which the governing equations are not adequately representing tangential (vertical) motions along the surface boundary.

$$\frac{\partial T}{\partial t} = -\gamma(\vec{V} \cdot \nabla Z_{\eta})\Gamma_d$$

An empirical correction was derived and a justification for a corrective parameterization could be developed. BUT.... Other diagnostic tests suggest that the problem may originate in the Spectral Element Dycore.



<u>AVOID</u>: Developing a parameterization that masks an underlying deficiency in the dycore equations.

Review of the Governing Equations

Revisiting the development of the governing equations for possible discrepancies.

Wet/dry surface heights are NOT the same.

(1) Replace Hydrostatic Balance with Hydrodynamic Balance

Replace the assumption that all vertical accelerations vanish with a requirement that only the accelerations normal to the model surface mush vanish

(wet) $$\left(\frac{\partial Z}{\partial \eta}\right)_m = -\frac{RT_v}{gP_m}\left(\frac{\partial p}{\partial \eta}\right)_m H_m(p, T_v, \vec{v}, \dot{\eta})$$

(dry) $$\left(\frac{\partial Z}{\partial \eta}\right)_d = -\frac{RT}{gP_d}\left(\frac{\partial p}{\partial \eta}\right)_d H_d(p, T, \vec{v}, \dot{\eta})$$

Hydrostatic Defect: depends on momentum, contains higher-order terms which become relevant at higher resolutions.

Implementing this balance in wet/dry equations revealed an inconsistency in the governing equations which implicitly assume that the moist and dry model surface heights are the same.

With moist surfaces taken as the model surface heights, the resulting dry hydrostatic deviation correction terms carry the effects of moisture in the dry equations.

(2) Add moisture advection terms to the Thermodynamic equation

(3) Correct numerical errors from ∇p

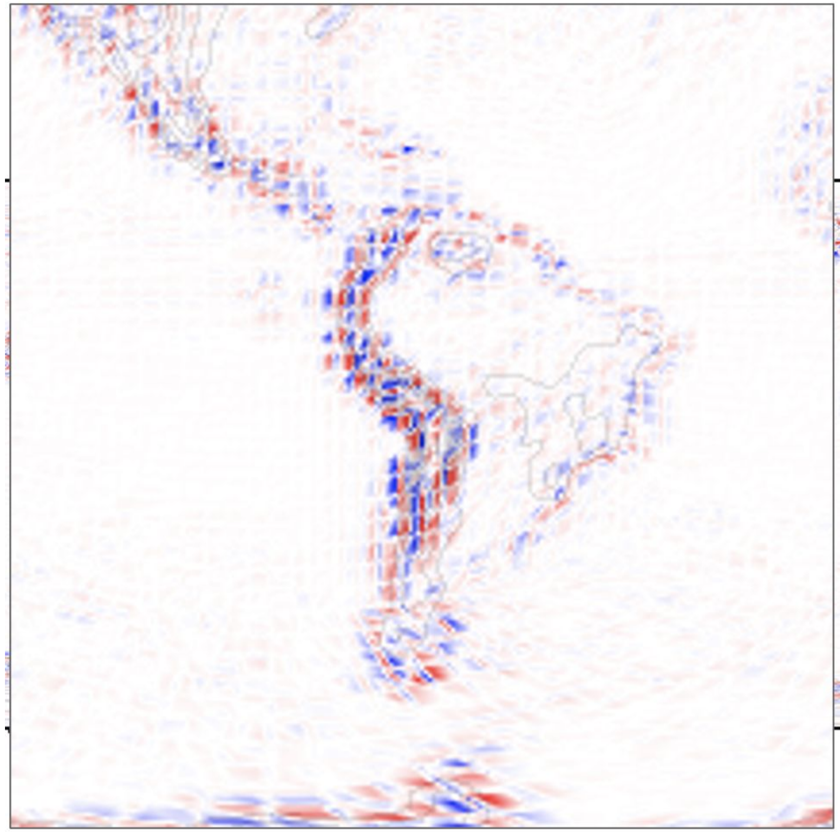
Review of the Governing Equations

(4) Hyper-viscosity damping in the Spectral Element dycore.

Not appropriate for low-order truncated polynomial basis functions!

Rather than acting to remove variations at the smallest grid scales, the operator results in bi-linear adjustments to the element mean values.

The current implementation of hyper-viscosity damping violates every single one of the conservation principles (Momentum, Energy, Mass).



Solution:

- Remove and replace the current damping with an alternate spectral damping which allows for the selective removal of grid-scale variability.
- Ensure that the form of applied damping does not violate the conservation principles that the governing equations are based on.

(5) Mathematical Inconsistency:

if $\left(\frac{\partial p}{\partial \eta}\right)_m = \left(1 + \sum q_i\right)\left(\frac{\partial p}{\partial \eta}\right)_d$ and $P_m = A(\eta)P_0 + B(\eta)(P_s)_m$, $\left(\frac{\partial p}{\partial \eta}\right)_m = \left(\frac{\partial A}{\partial \eta}\right)P_0 + \left(\frac{\partial B}{\partial \eta}\right)(P_s)_m$ then $P_d \neq A(\eta)P_0 + B(\eta)(P_s)_d$, $\left(\frac{\partial p}{\partial \eta}\right)_d \neq \left(\frac{\partial A}{\partial \eta}\right)P_0 + \left(\frac{\partial B}{\partial \eta}\right)(P_s)_d$

All terms with this form in the model are a source of errors!

Implementing DYCORE Modifications

These modifications to the DYCORE have been incrementally installed and tested using 2-month restart simulations from the beginning of October for the 50km 32-level grid. (i.e. 1 month spin-up of atmosphere for each mod)

There are many DOF, so this has required many low resolution test simulations.

Results from two recent tests are shown next:

Expt 1:	For this test, the modifications (1-3) have been installed but the hyper-viscosity damping has only been replaced in the energy and mass conservation equations. The association between the anomalous topographic precipitation and the hyper-viscosity can be observed by varying the strength of the damping. For this test, it’s effect is reduced by lowering it’s strength to a minimal value.
Expt 2:	Same as Expt 1, but with the tracer hyper-viscosity damping replaced with an alternate spectral damping.

Revised DYCORE Results

WRF | **DYCORE MOD** | **REFERENCE**

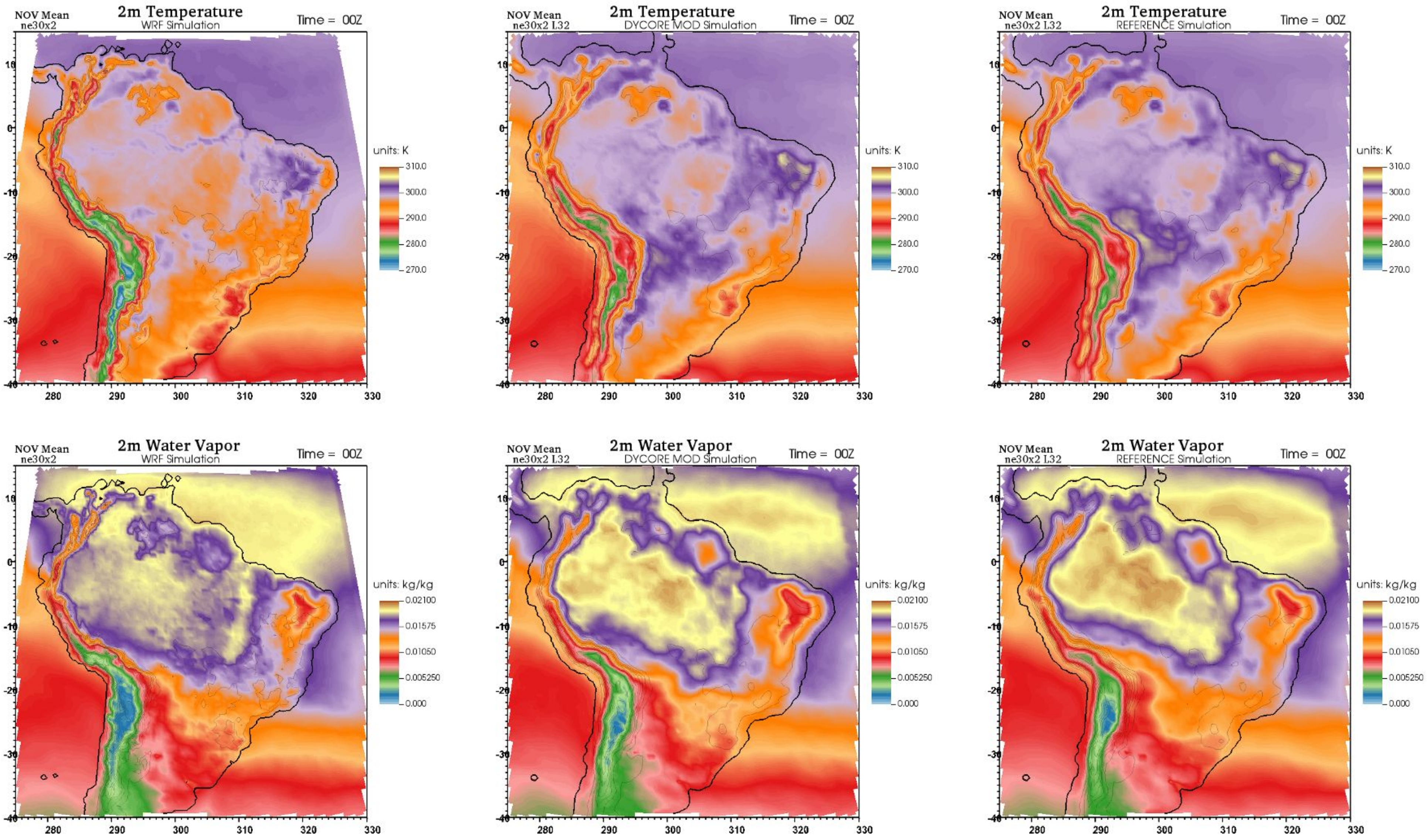
Note:

The reduction of temperature bias in the Amazon basin and along the Andes.

The reduced amplitude of the water vapor surges.

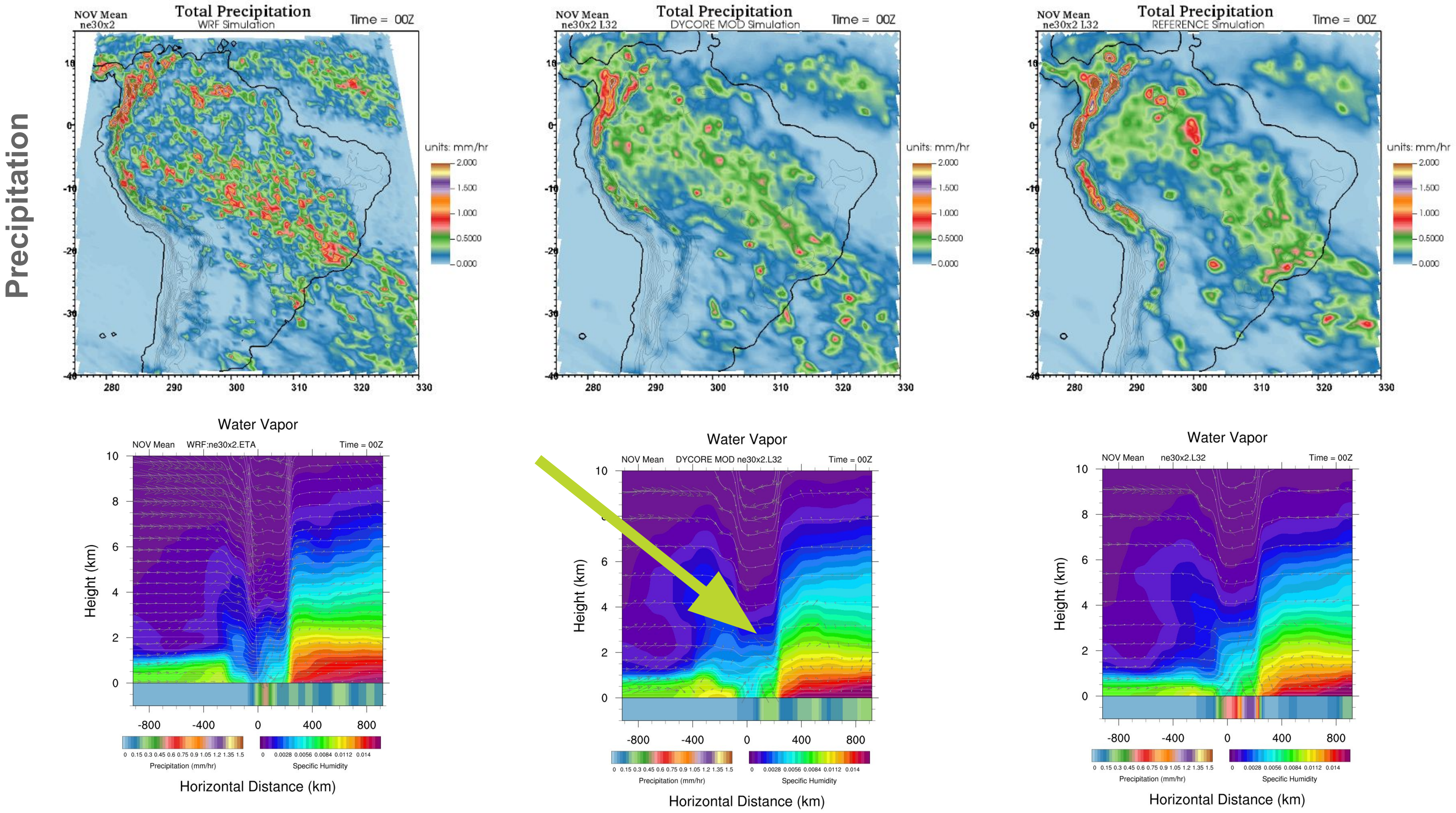
2m Temperature

2m Water Vapor



Revised DYCORE Results

WRF **DYCORE MOD** **REFERENCE**



Note:

The dry 'halo' is mostly eliminated.

Precipitation is more localized in stronger migrating cells.

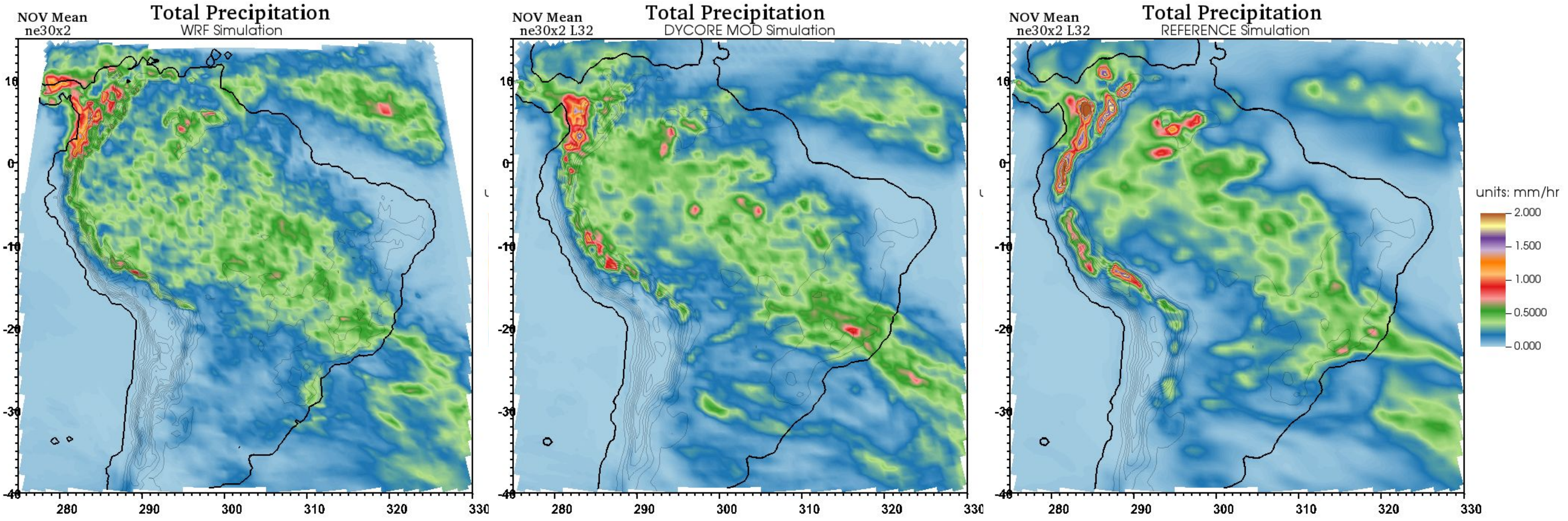
Improvement in Andes precipitation.

The revised model is better able to maintain the sharp gradient of water vapor along model levels.

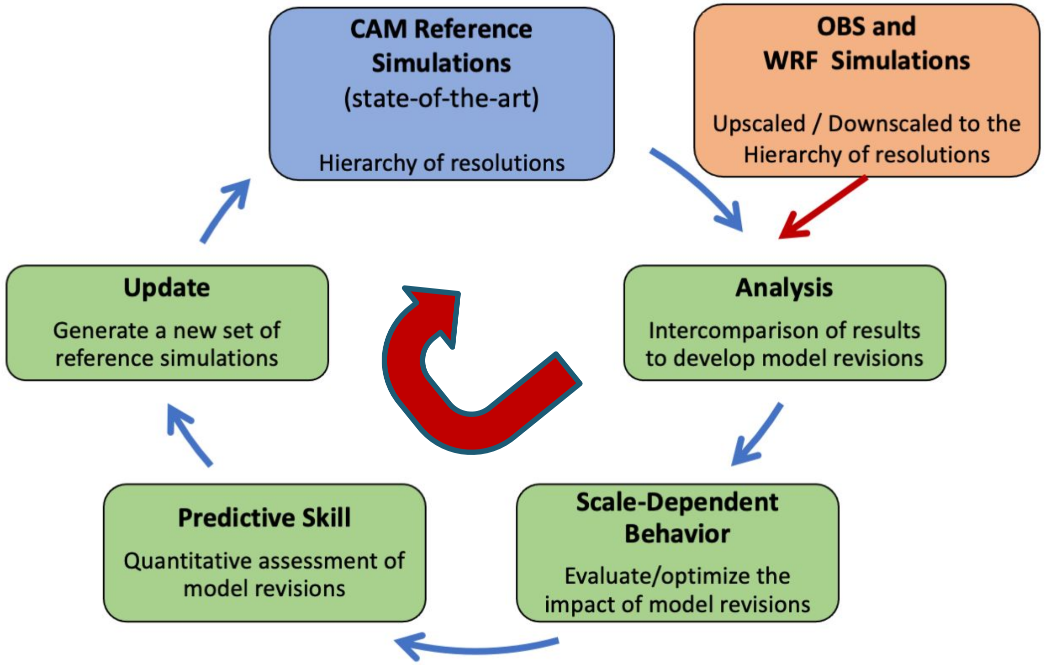
Results with Alternate Spectral Tracer Damping

Monthly Mean Precipitation for November 2010

The dry halo and heavy precipitation over the ridge has been eliminated.
The precipitation better resembles the upscaled WRF results.



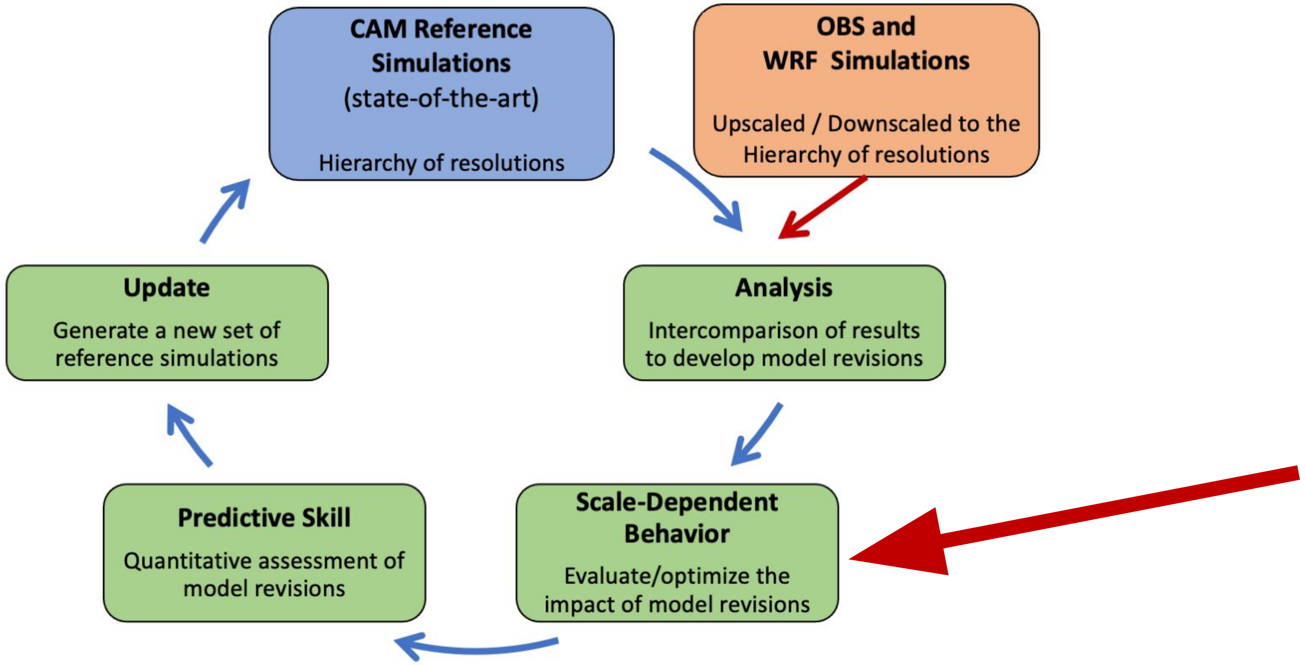
Still to be done...



To complete the development workflow for the DYCORE mods:

- Complete Testing for Tracer Damping
- Remove and Replace Damping of Momentum
- Evaluate Scale dependent behavior of these DYCORE corrections.
- Evaluate/Document Predictive skill after modifications.
- Iterate with focus on the anomalous 2m water vapor.

Question for AMWG



Should we establish a standard set of regional hierarchical grid resolutions to evaluate model revisions?

- Develop standard analysis tools and fixed metrics to quantify biases as a function of resolution.
- To provide a common framework to evaluate scale-dependent bias between models OBS data.
- With contemporaneous simulations for model intercomparisons (MPAS, WRF, CESM) and compared against OBS.
- To provide quantitative measures that can be used to maintain benchmark scores for scale-aware skill that quantify the current state-of-the-art results for each model.