Using variable-resolution CAM and ML to investigate orographic flow around the Andes

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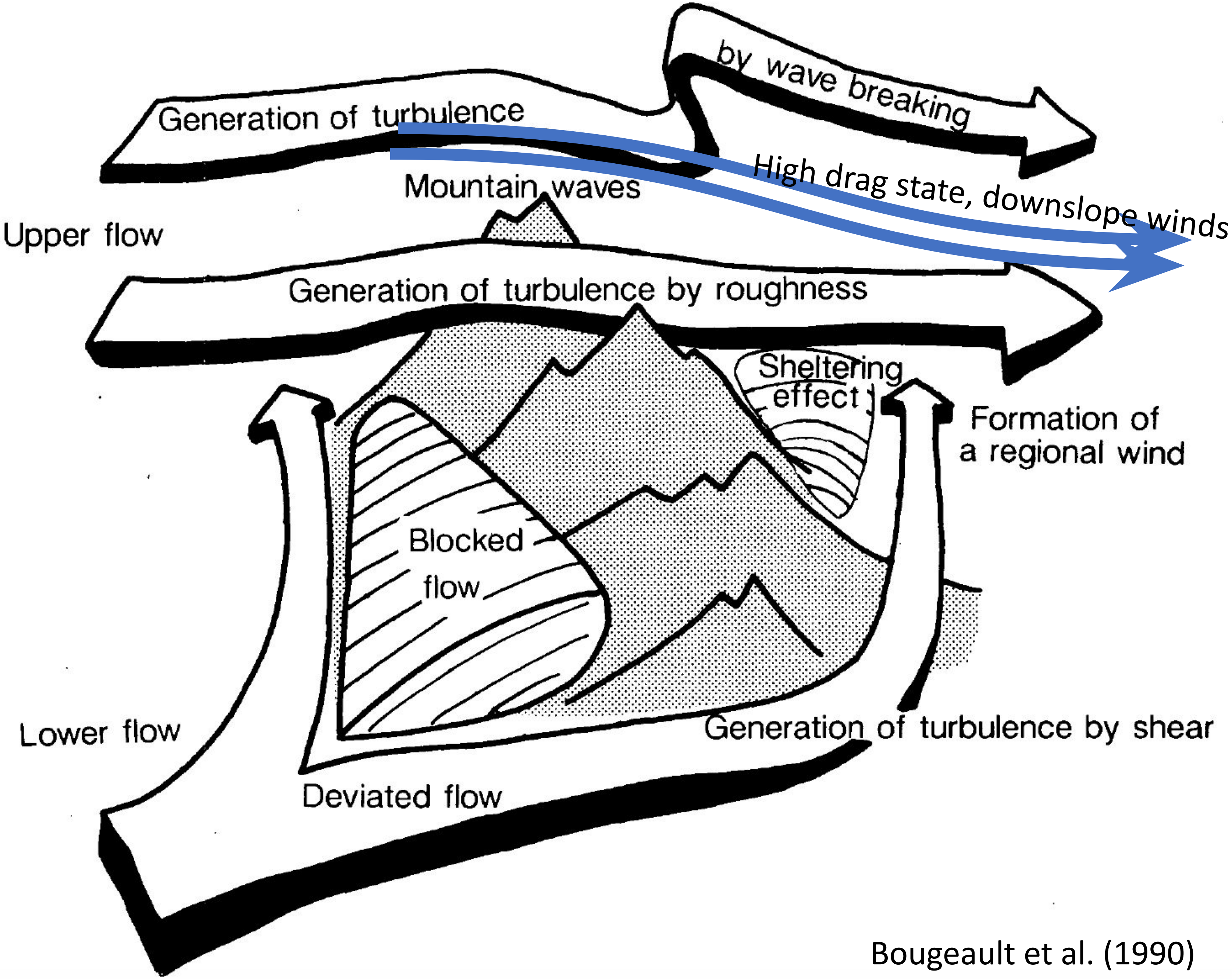
Outline

- **Background**
  - **Orographic drag**
  - **Variable resolution set-up**
  - **Nudge-to-fine**
- **Results**
  - **Nudging tendencies**
  - **Machine Learning**
- **Questions and Future directions**



Bougeault et al. (1990)

FIG. 2. A schematic of the flow around and over the Pyrénées (see subhead a in section 3).

Variable-Resolution Community Atmosphere Model (VR-CAM)

- South America VR-CAM configuration:
- Spectral Element (SE) dynamical core
- Outer (unrefined) domain “ne30”,* i.e., ~100km or ~1o resolution
- Refined domain over South America 7km, no deep conv. param[2]
- U,V,T,q nudged to reanalyses in outer domain. *No nudging in refined domain*
- 1-hourly instantaneous fields saved for 3 1-year length runs. Here we use 6-hourly data for June 2010-Dec 2010

- [2]Other refinement-levels (28km,14km) used w/ and w/out deep scheme.

“Nudge-to-fine” as an approach to identify model error

- **Nudging - essentially linear relaxation of model prognostic variables to a desired solution – has been used extensively to estimate model physics errors**
- **In a “nudge-to-fine” configuration, a coarse resolution (e.g. dx~100km) model is nudged to a higher resolution version of itself.**
- **Recently, nudge-to-fine combined with machine learning has been proposed as a technique to improve model performance (e.g. Watt-Meyer et al. 2021)[1]**
- **Nudge-to-fine requires coarse graining high-resolution model output which can be problematic around complex topography**

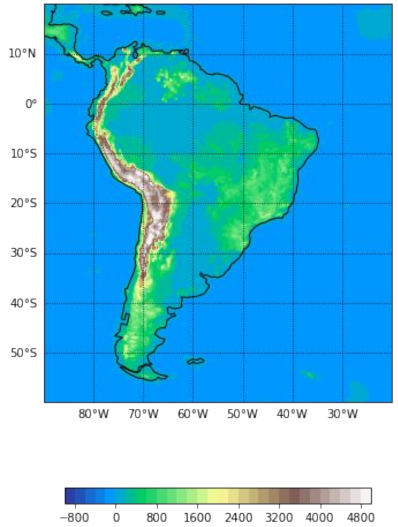
[1]Watt-Meyer, O., Brenowitz, N. D., Clark, S. K., Henn, B., Kwa, A., McGibbon, J., ... & Bretherton, C. S. (2021). Correcting weather and climate models by machine learning nudged historical simulations. *Geophysical Research Letters*, *48*(15), e2021GL092555.

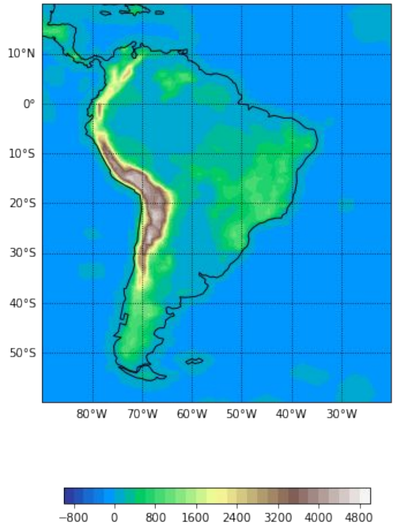
7km topography

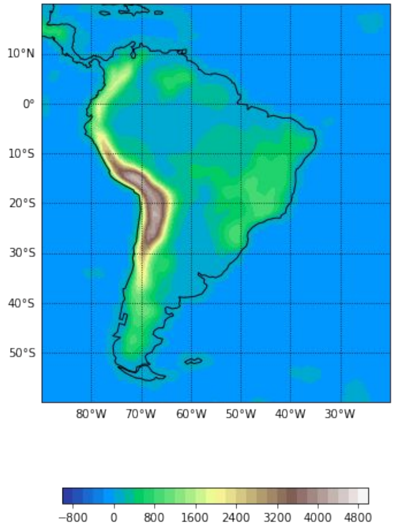
7km topography conservatively remapped to ne30

Default topography for CAM-SE ne30 additional smoothing applied

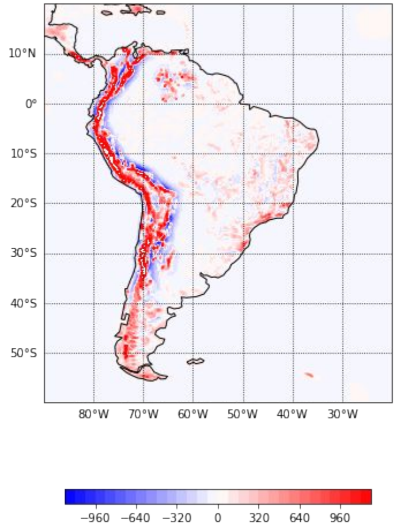
Topography

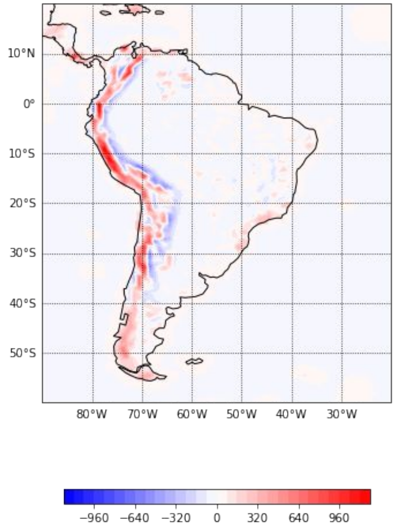


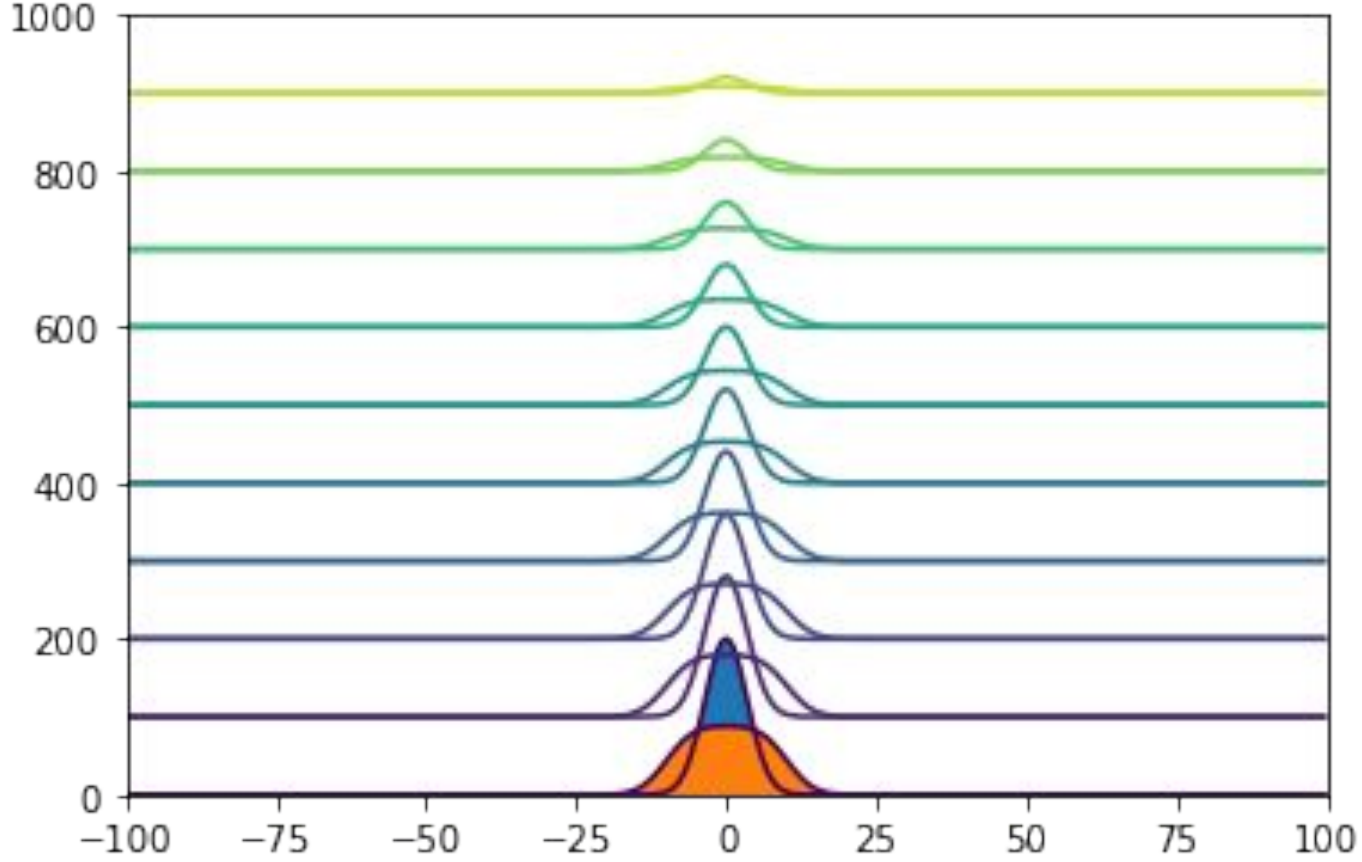




Difference from default ne30 Topography







Schematic showing eta-surfaces in coarse-grained VR-CAM and global CAM. Orange shows terrain in global CAM. Blue shows terrain in coarse-grained VR-CAM. "Block" option zeroes out global CAM horizontal winds in visible blue region.

The problem: Surface topography is rougher in coarse-grained VR_CAM output than in default CAM 100km – due to additional topography smoothing applied to CAM topography during BC file generation. (This problem arises when using reanalysis data as well.) ***How do we deal with horizontal winds?***

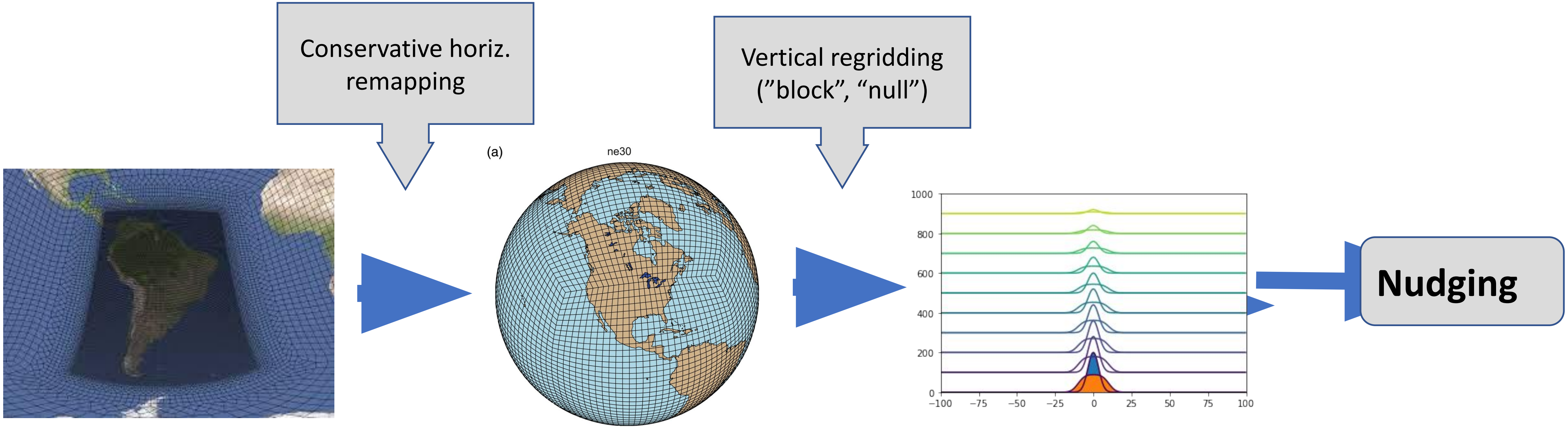
What to do?? Two options:

1) **Nothing (Null option):** Simply use eta-coordinate wind profiles without modification. ***This may be default strategy in most nudging applications*.***

2) **Block option:** Subterranean wind set to 0 where smoother grid is below surface in rougher grid

*Surface temperature and temperature profile ***are*** typically adjusted

From VR-CAM 7km□nudging



Flow chart for generating nudging data from VR-CAM 7km output.

Nudged runs:

- June 1,2010-Dec 1,2010
- Spectral element dycore ne30
- L32

NoGW-Block

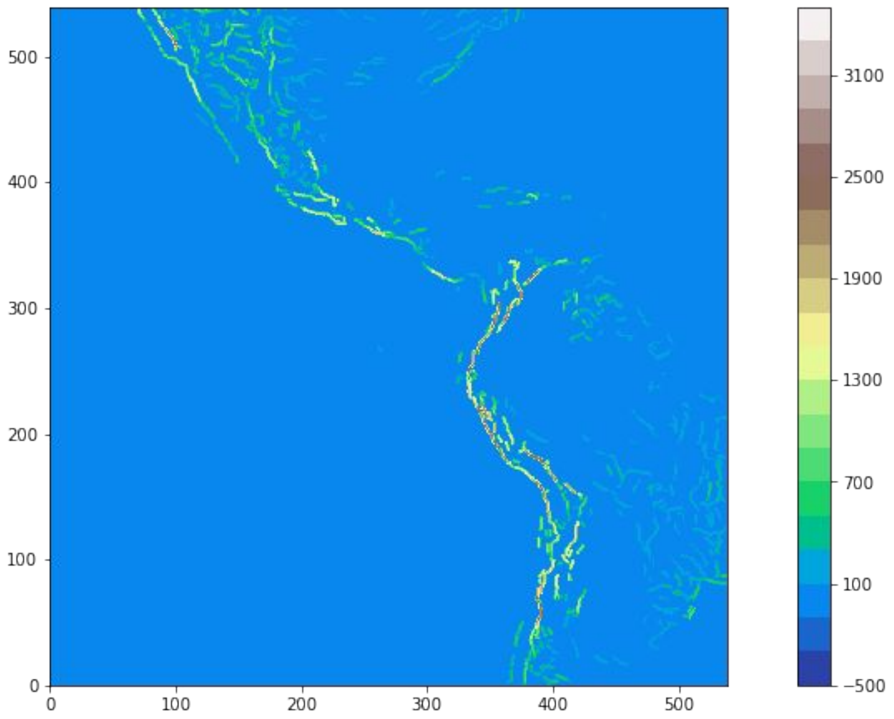
  - No orographic GW drag
  - “Block” option for coarse graining

NoGW-Null

  - As above but “null” option

AOGW-Block

  - Uses anisotropic “ridge” OGW



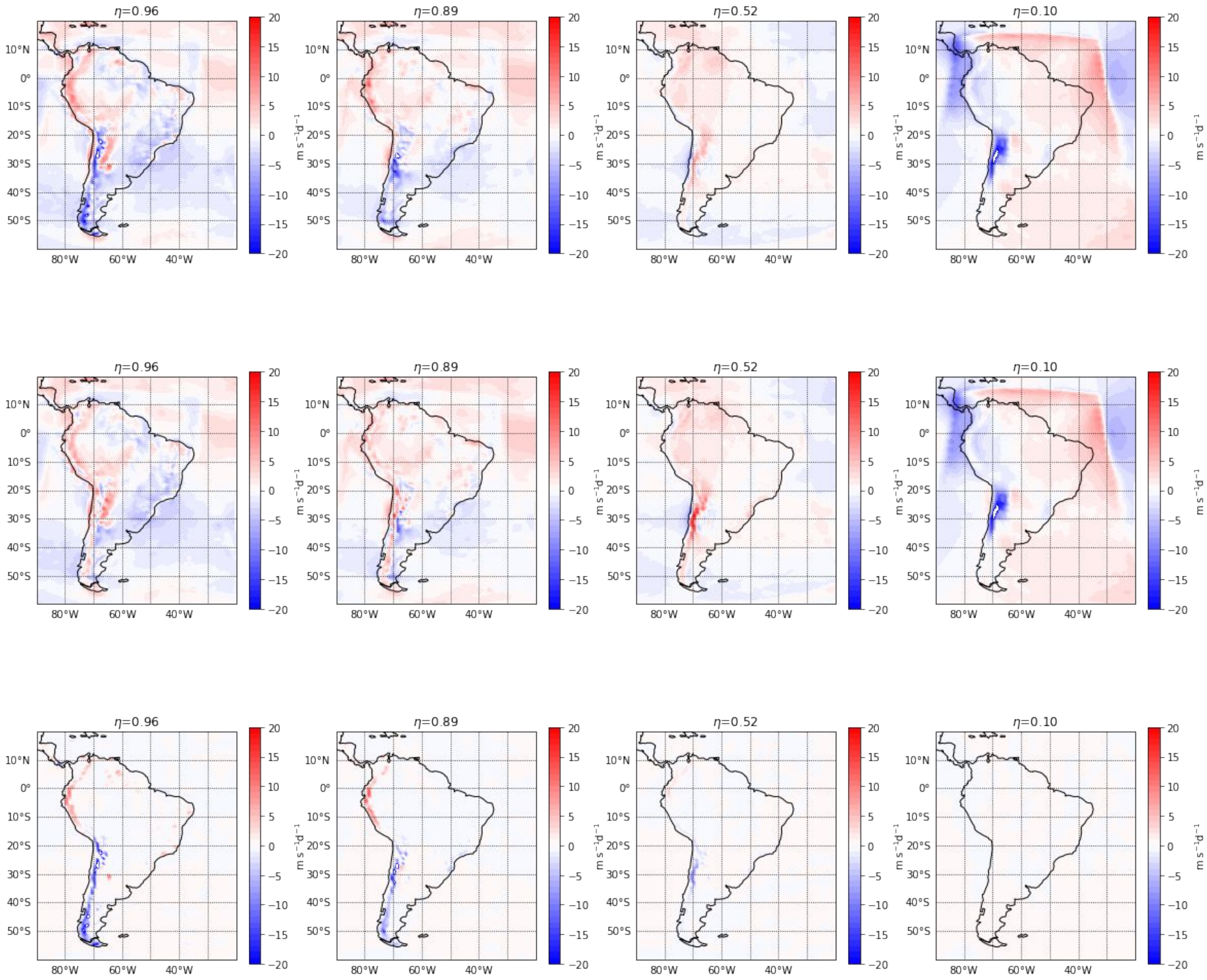
AOGW: Uses “ridge-finding” scheme that analyzes orientation, obstacle height, obstacle length

Mean nudging tendencies on *U* (δU_{ndg})

NoGW-Block

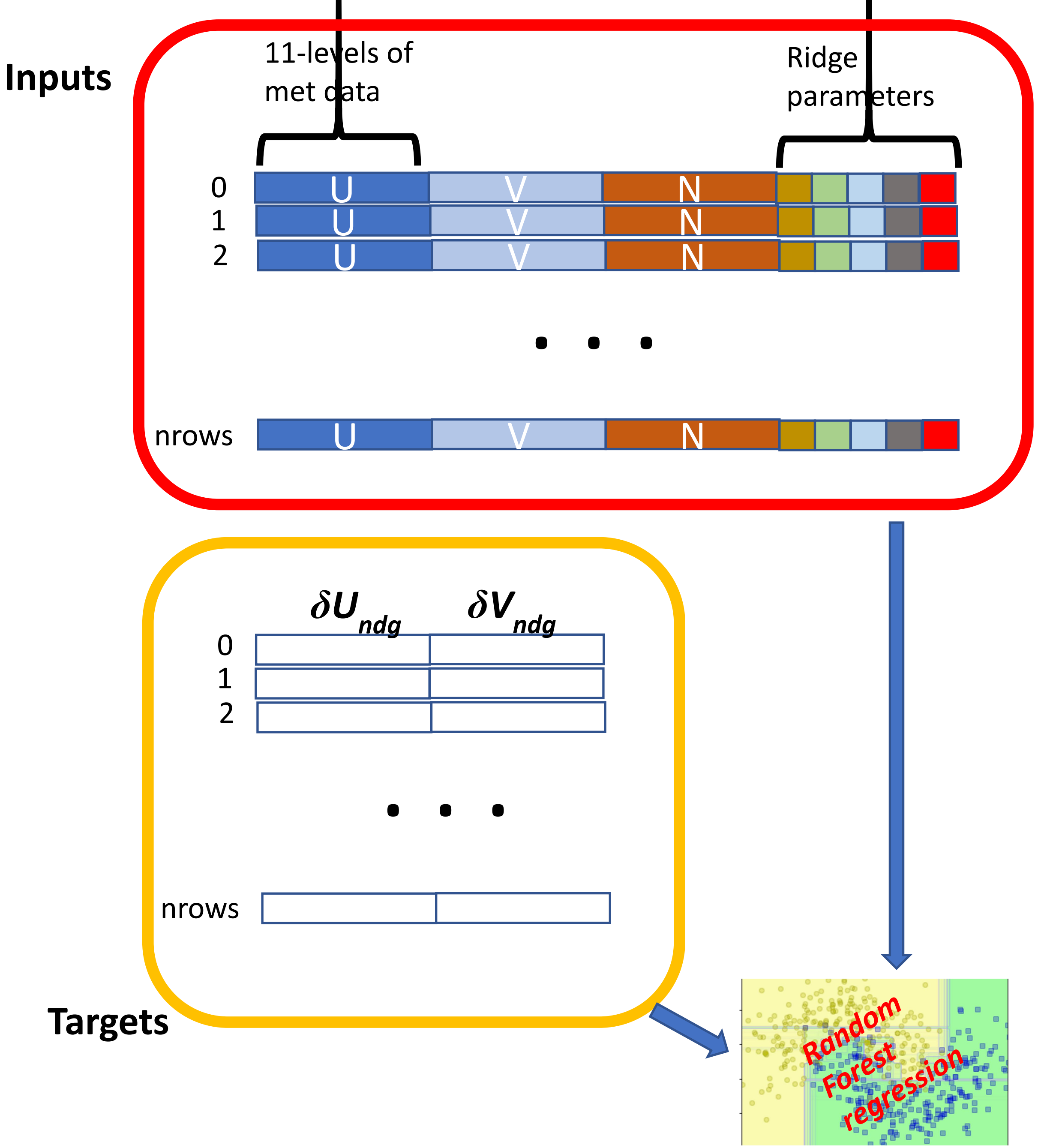
NoGW-Null

Difference



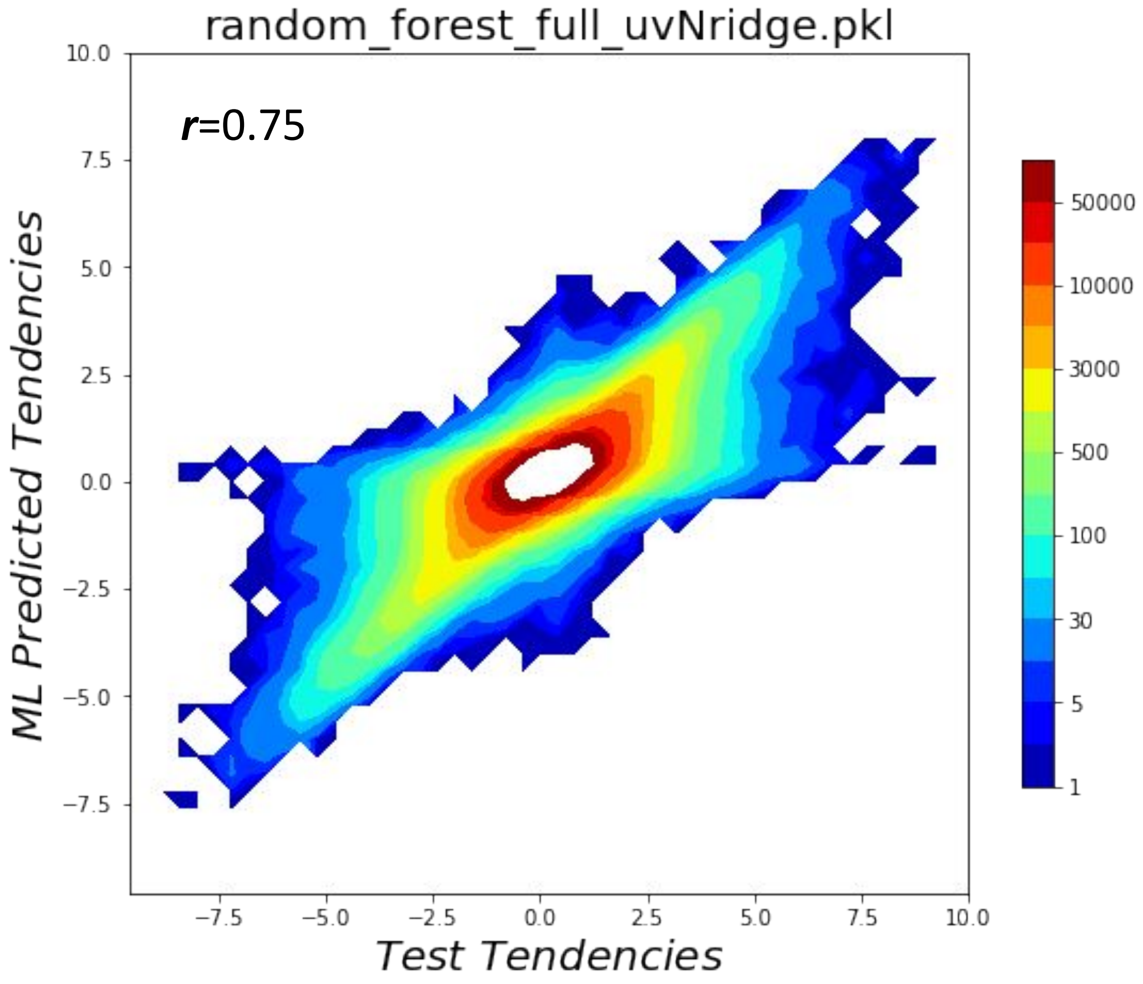
Learn to predict profiles of δU_{ndg}, δV_{ndg} from profiles of *U, V, N (stratification),* and topographic parameters

- Bottom 11 levels (from ~600 hPa to bottom)
- Only where where topography exits (~1000 gridpoints)
- 6-months 4x daily data
- ~980,000 instances □80% Training, 20% Test
- Random Forest regressor

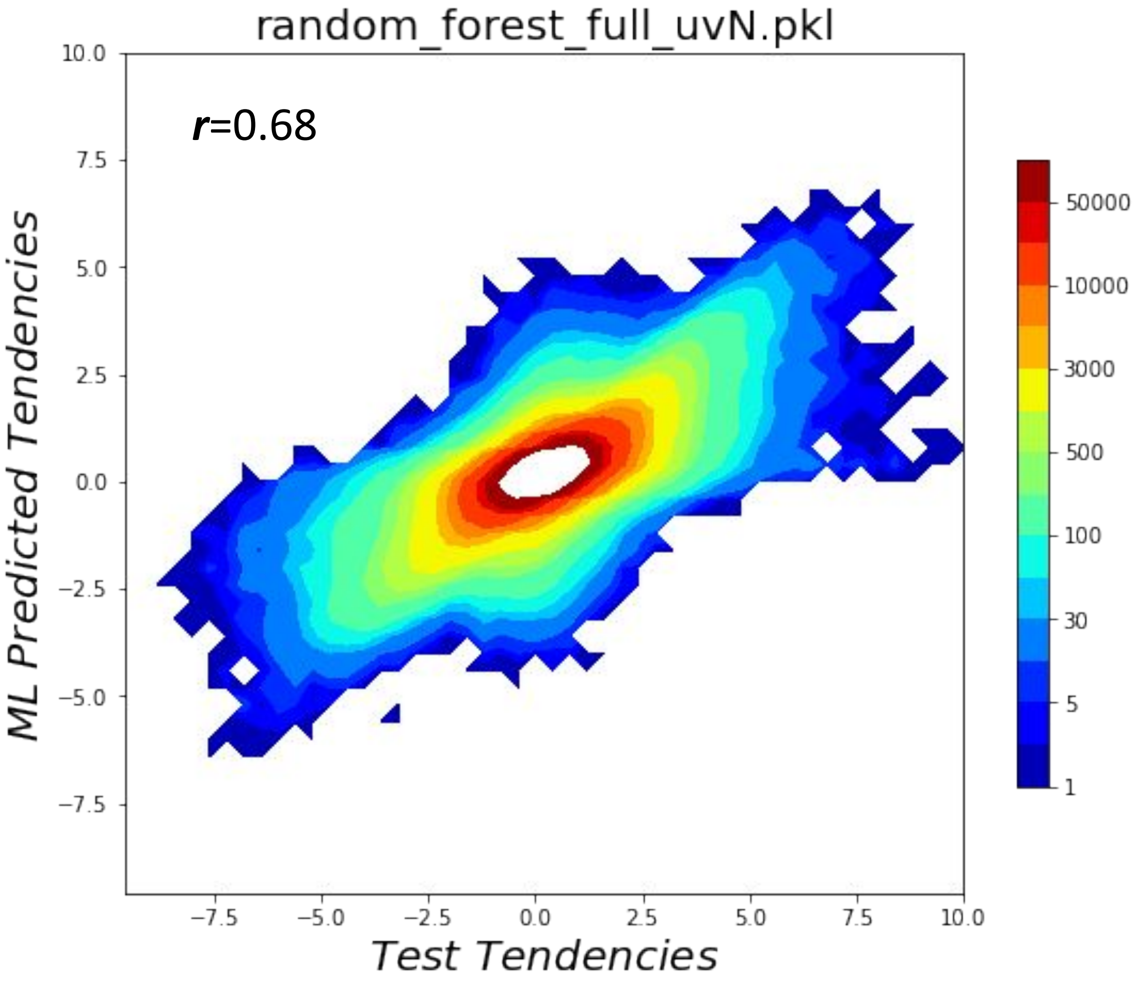


ML Predicted tendencies vs Test data (scaled)

Trained with:
Meteorological profiles+Ridge info

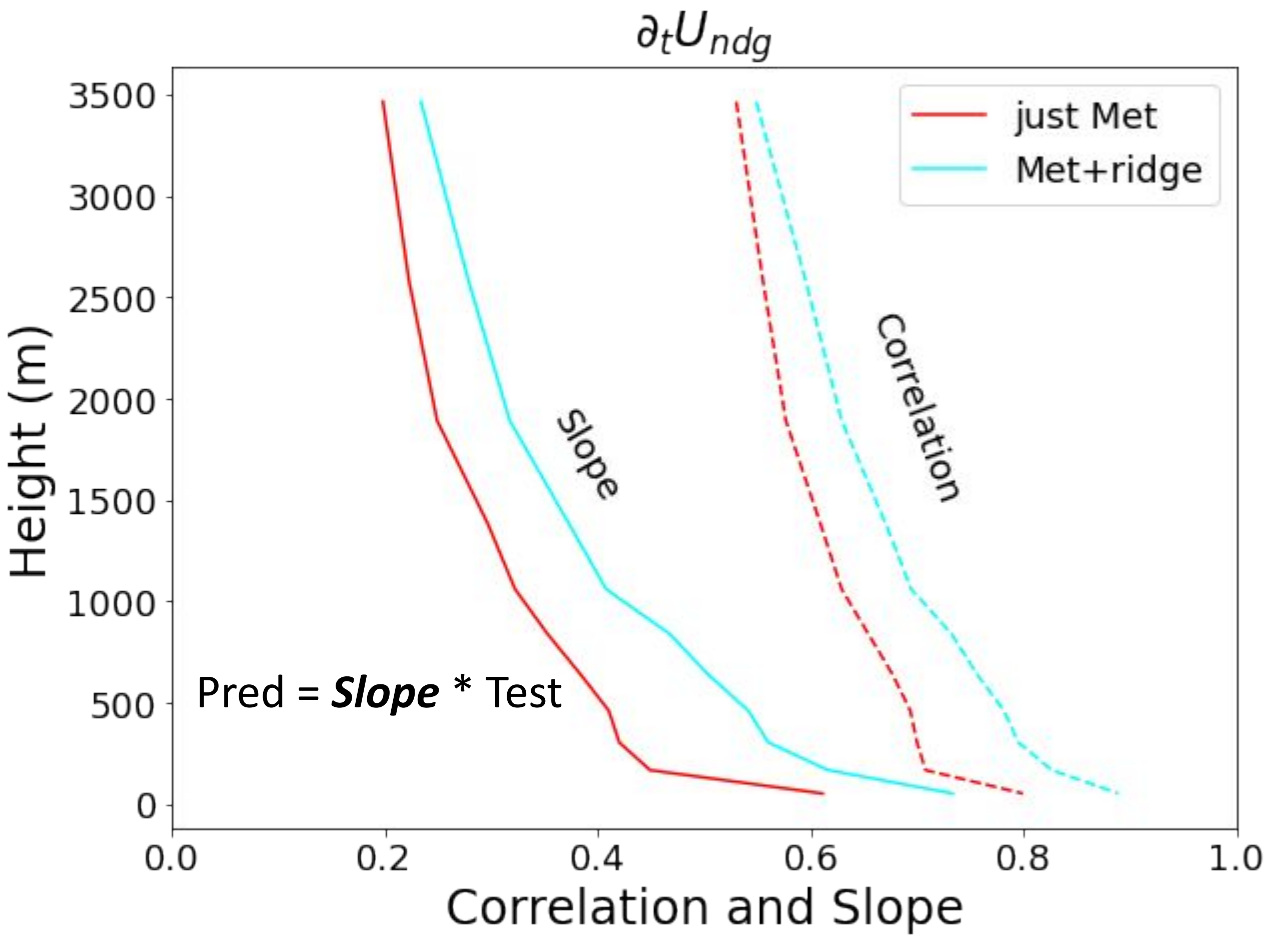


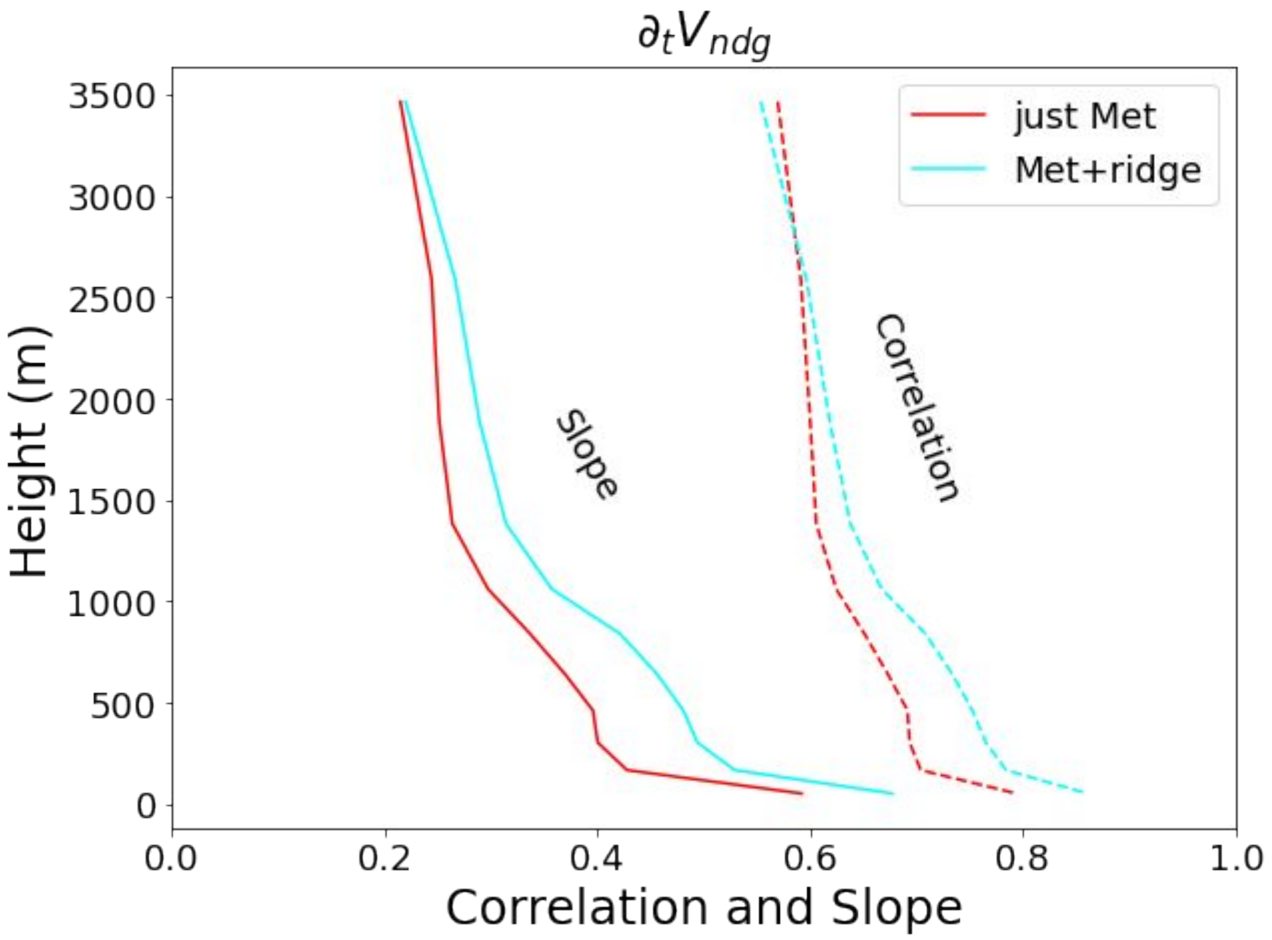
Trained with:
Just Meteorological profiles



ML Predicted tendencies vs Test data

Correlations between prediction and test as well as linear fit slopes at different altitudes





Are nudging tendencies really model error?

Climate resolution model with nudging to fine

$$\partial_t \Phi + \mathcal{D}(\Phi) = \mathcal{P}^*(\Phi) + \epsilon(\Phi) - \frac{\Phi - \widetilde{\phi}}{\tau_n}$$

Φ is climate resolution model variable

$\widetilde{\phi}$ is coarse grained high-resolution model variable

$\mathcal{P}^*(\Phi)$ is "correct" physics

$\mathcal{D}(\Phi)$ is dynamics

$\epsilon(\Phi)$ is model error

If we assume

$$\partial_t \widetilde{\phi} + \mathcal{D}(\widetilde{\phi}) = \mathcal{P}^*(\widetilde{\phi})$$

and

$$|\mathcal{D}(\widetilde{\phi}) - \mathcal{D}(\Phi)| \ll \epsilon(\Phi)$$

$$|\mathcal{P}^*(\widetilde{\phi}) - \mathcal{P}^*(\Phi)| \ll \epsilon(\Phi)$$

$\Rightarrow$

$$\epsilon(\Phi) \approx \frac{\Phi - \widetilde{\phi}}{\tau_n}$$

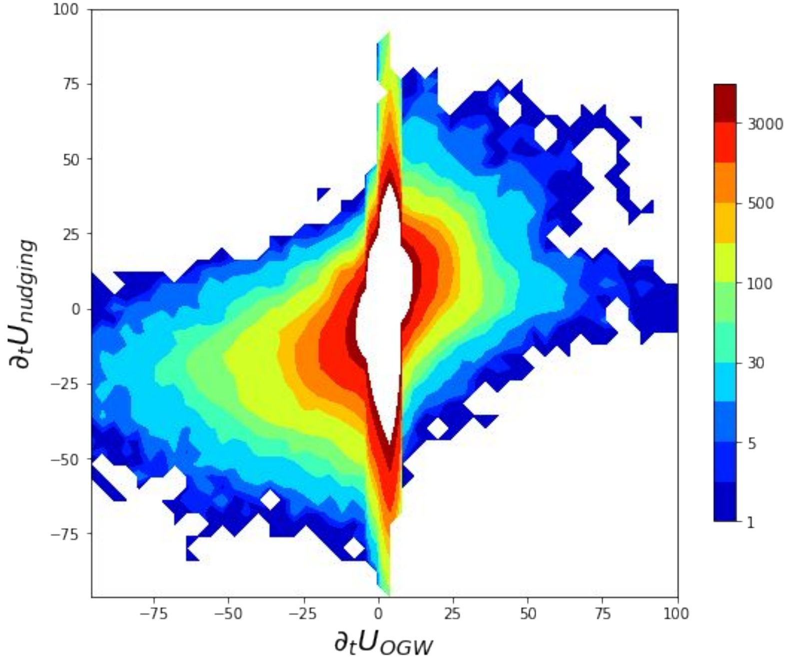
Are nudging tendencies really model error?

$$|\mathcal{D}(\widetilde{\phi}) - \mathcal{D}(\Phi)| \ll \epsilon(\Phi) \quad ??$$

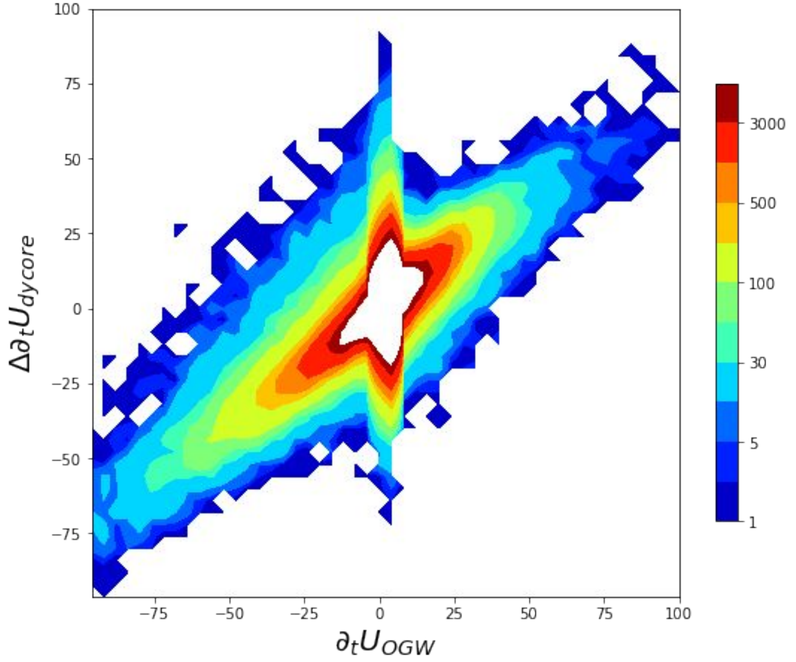
- Did not save dynamics tendencies in VR runs
- Proxy We estimate $|\mathcal{D}(\widetilde{\phi}) - \mathcal{D}(\Phi)|$ by examining dynamics tendency in runs with and without OGW

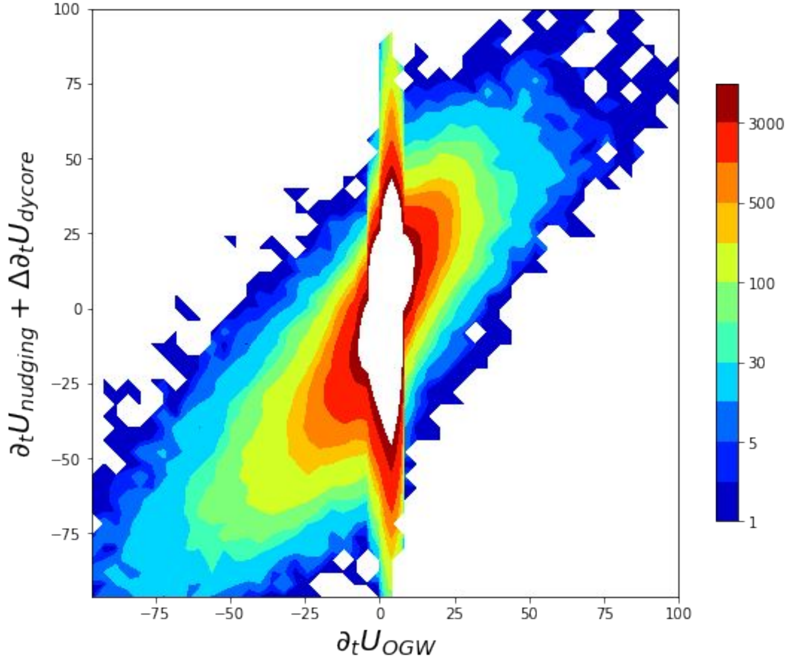
6-hourly tendencies on U in NoGW-Block (vertical) plotted against OGW tendency on U in AOGW-Block (horizontal)

Nudging Tendency in NoGW
vs OGW tendency in AOGW



Difference in dynamics tendency
between NoGW and AOGW
vs OGW tendency in AOGW





Maybe change in dynamics tendency $\mathcal{D}(\widetilde{\phi}) - \mathcal{D}(\Phi)$ should be included as part of model error?

Summary

- Details in coarse graining of fine model may matter (LBCs)
- Definition of model error may need attention
- Information on unresolved topography provides useful information to ML model

More Future Work

- Dycore issues
- Investigate structure of ML model, e.g., drop in skill with vertical …
- Other ML models … convolution to capture horizontal propagation?
- Collaborate with data assimilation people to understand model error

Thanks