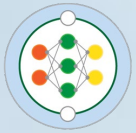

M2lines

Deterministic and Stochastic Tendency Adjustments Derived from Data Assimilation and Nudging

Will Chapman, Judith Berner

U.S. NSF National Center for Atmospheric Research

Mar, 2024

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Co-Authors

Judith Berner

Special thanks: Kevin Raeder, Jeff Anderson , Patrick Callaghan

Funders

M2lines

SCHMIDT FUTURES

M²LInES - Multiscale Machine Learning In Coupled Earth System Modeling

M²LInES (pronounced M-square-lines) is an international collaborative project with the goal of improving climate projections, using scientific and interpretable Machine Learning to capture unaccounted physical processes at the air-sea-ice interface.

Recent Publication:

Quarterly Journal of the Royal Meteorological Society

RMetS Royal Meteorological Society

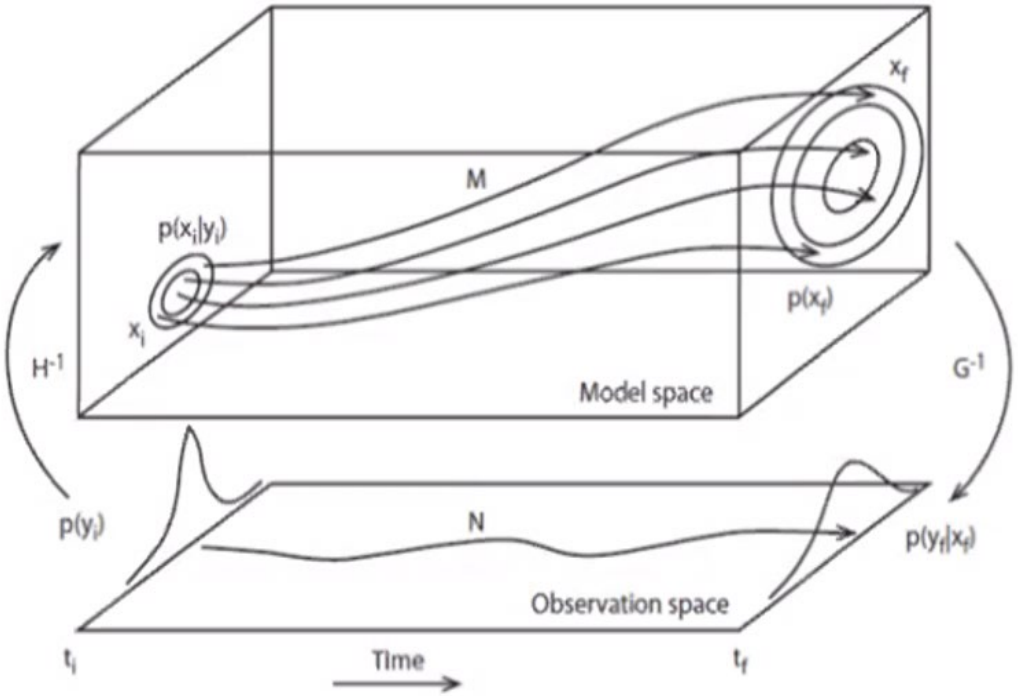
RESEARCH ARTICLE

Deterministic and Stochastic Tendency Adjustments Derived from Data Assimilation and Nudging

William E. Chapman PhD, Judith Berner PhD

First published: 27 December 2023 | https://doi.org/10.1002/qj.4652

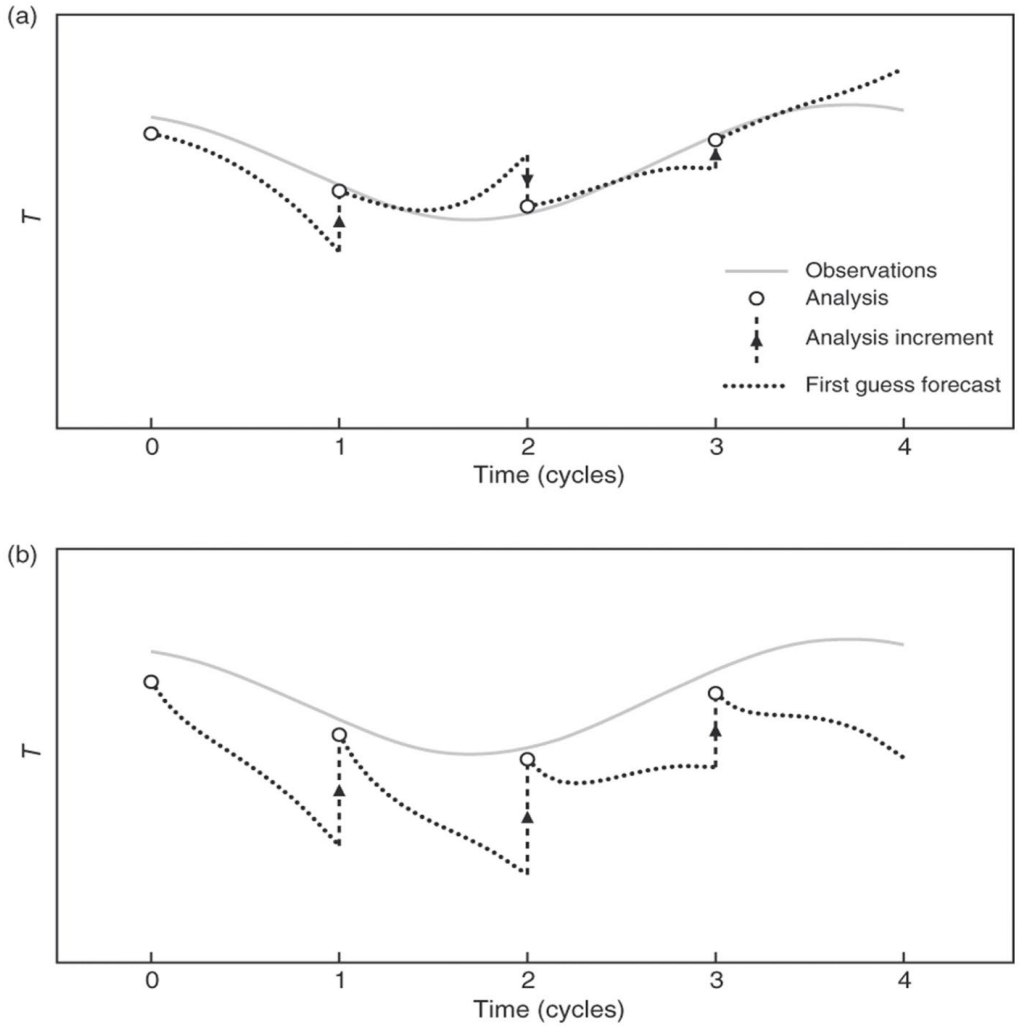
Background - Data Assimilation



Balmaseda, Magdalena A. "Data assimilation for initialization of seasonal forecasts." *Journal of Marine Research* 75.3 (2017): 331-359.

- DA combines a model first guess (a short model forecast) with observations in an optimal way for the purpose of state-estimation and initialization
- Observations will “pull” the model trajectory closer to the observed trajectory

DA used to Identify Systematic Model Error



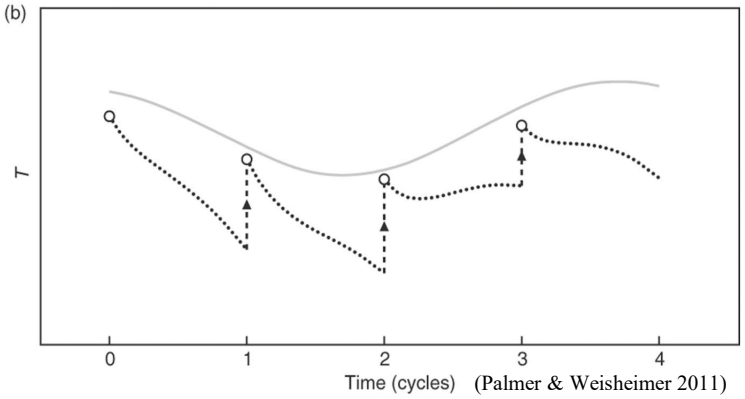
- **Schematic**: *The analysis increment is correcting the model trajectory systematically (averaged over many initializations) to a warmer state.*
- *This is evidence of a systematic model error (assuming unbiased obs)*

Palmer, T. N., and Antje Weisheimer. "Diagnosing the causes of bias in climate models–why is it so hard?." *Geophysical & Astrophysical Fluid Dynamics* 105.2-3 (2011): 351-365.

Increments used to identify structural model error

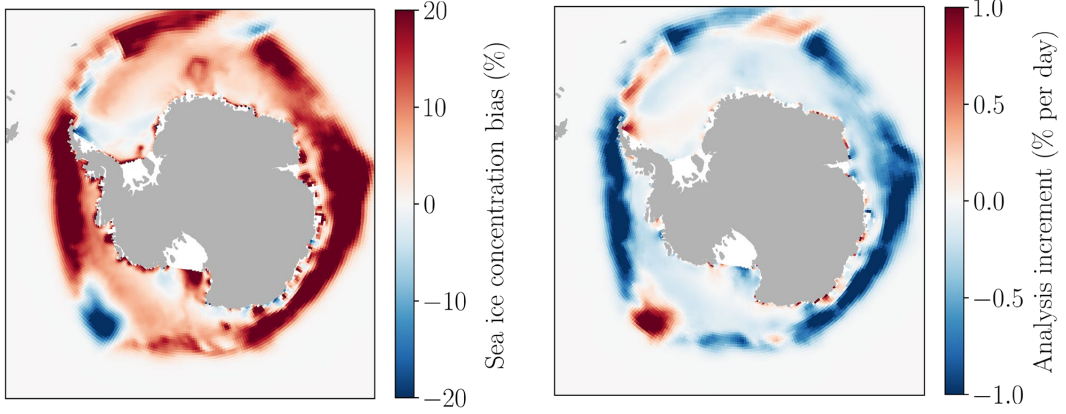
Although the amplification of the effect of [INSERT FORCING] on [INSERT BIASED PROCESS] will occur on ***timescales of decades***, the intrinsic timescale associated with [INSERT BIASED PROCESS] itself is typically on the order of hours. Hence it should in principle be possible to assess whether the anomalously small values of [INSERT PROCESS] are realistic or not, by studying the performance of such models in short-range weather prediction mode.

biased model



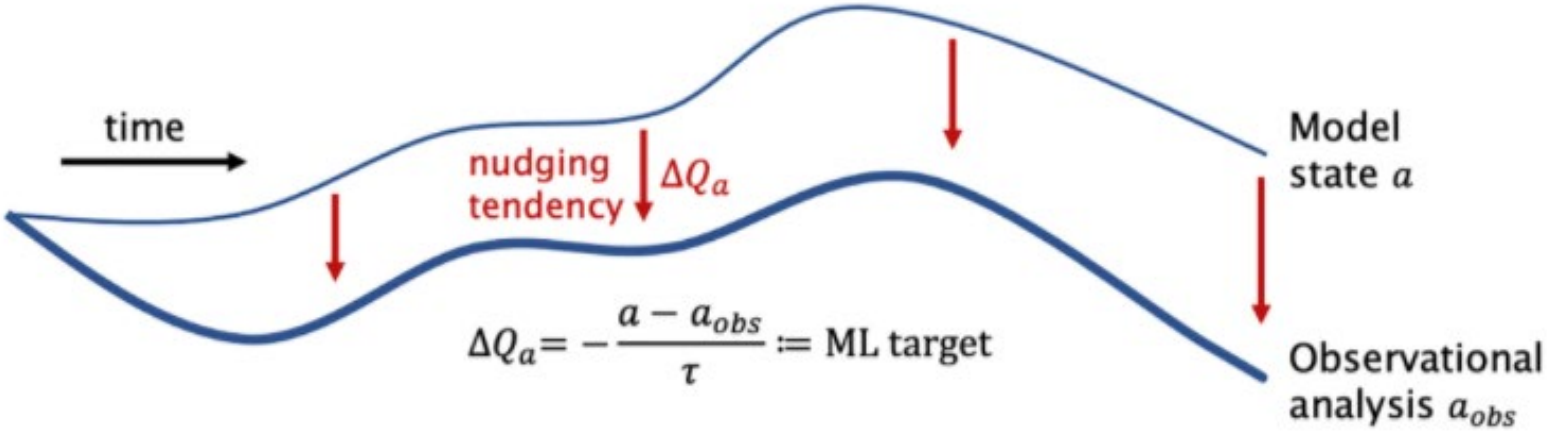
BIAS

Avg. Increment



Gregory, William, et al. "Deep learning of systematic sea ice model errors from data assimilation increments." *Journal of Advances in Modeling Earth Systems* 15.10 (2023): e2023MS003757.

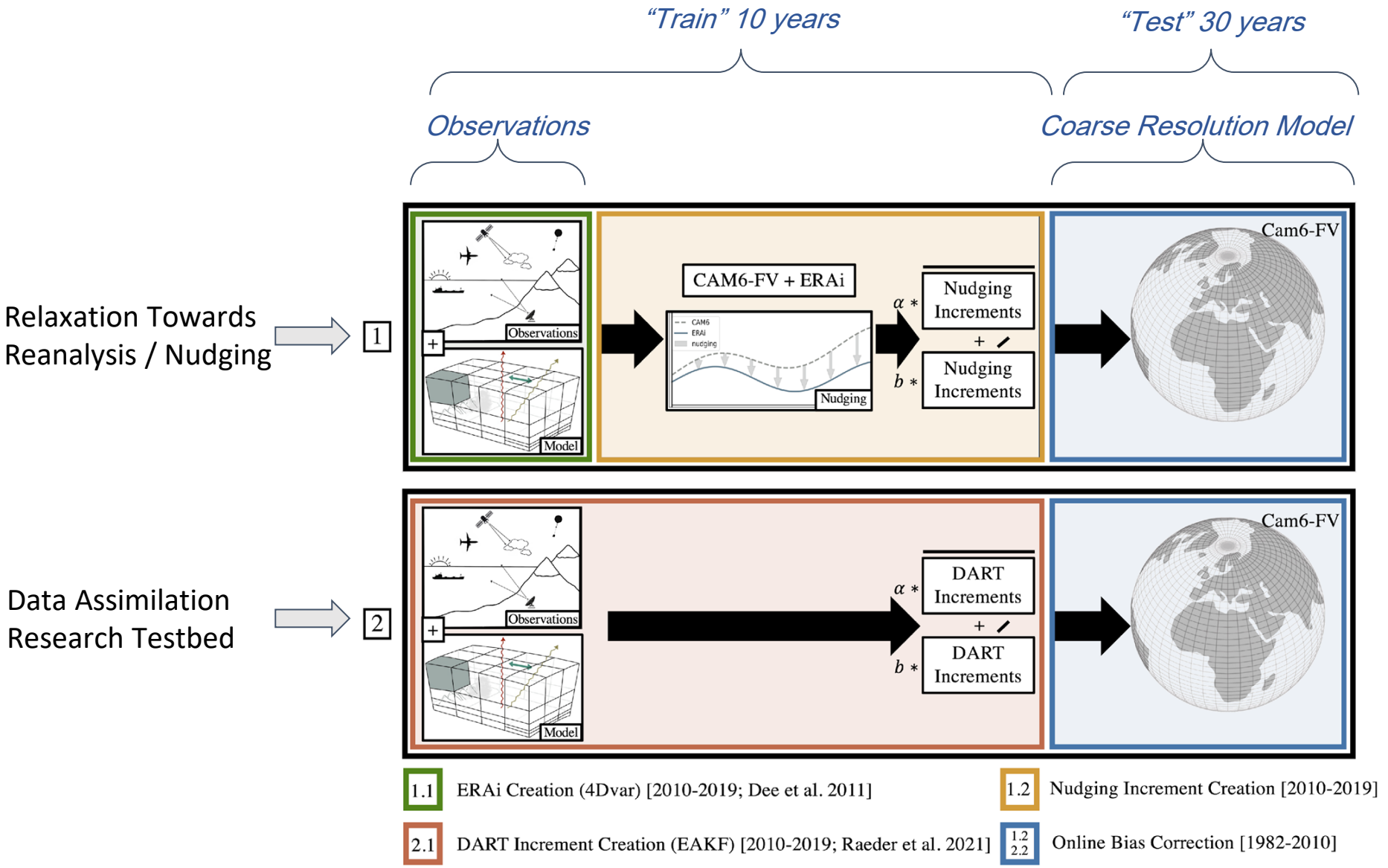
Nudging



Watt-Meyer, Oliver, et al. "Correcting weather and climate models by machine learning nudged historical simulations." *Geophysical Research Letters* 48.15 (2021): e2021GL092555.

A linear relaxation term is added to the prognostic equations of certain variables. Where a is a prognostic variable, $-v \cdot \nabla a$ is advection by the model.

Two Error Learning "Pathways"



Climatology of DA/Nudging Increments

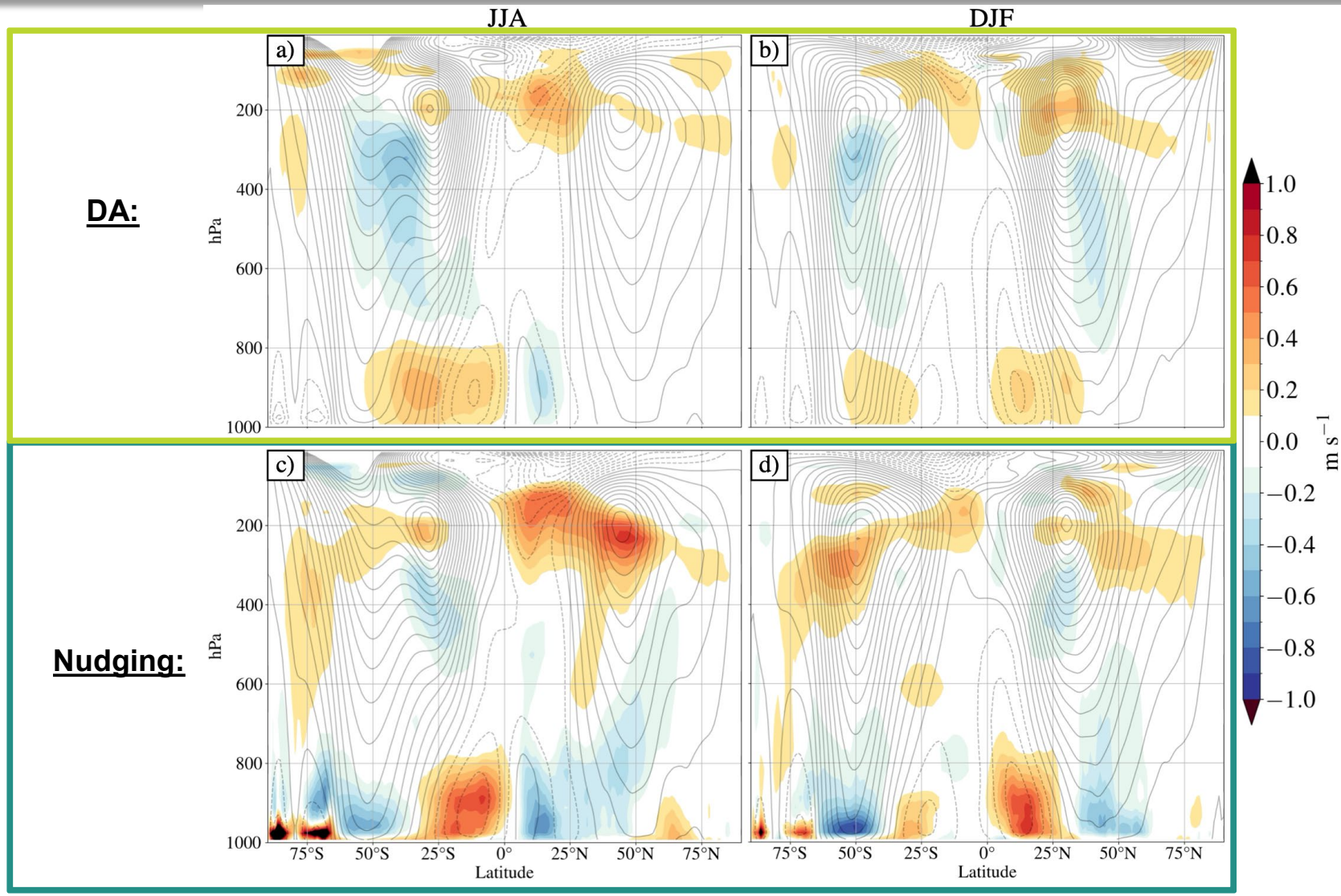


FIGURE 3 The zonal-mean u DA increments ($m\,s^{-1}\,d^{-1}$) in JJA (a, c) and DJF (b, d) for the DART (Row I) and nudging system (Row II). Contours show the u wind climatology [2 $m\,s^{-1}$ intervals, negative is dashed]. All fields are averaged over the period 1982-2010.

Model Improvements

*To what extent does re-inserting DA increments and nudging increments during model runtime **reduce climatological model bias** of the free-running model?*

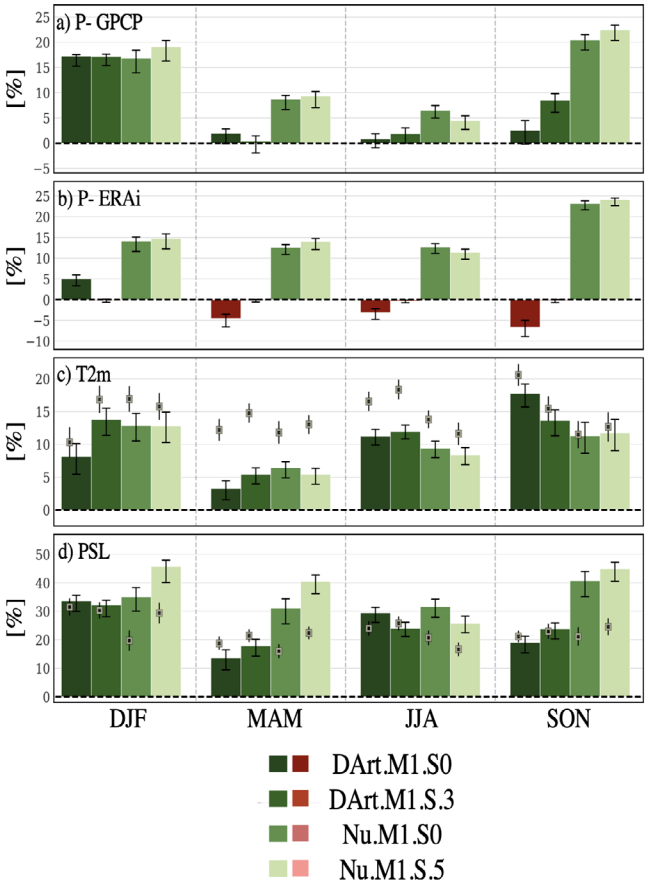
CAM has STRONG biases in Precipitation and this is common across many models

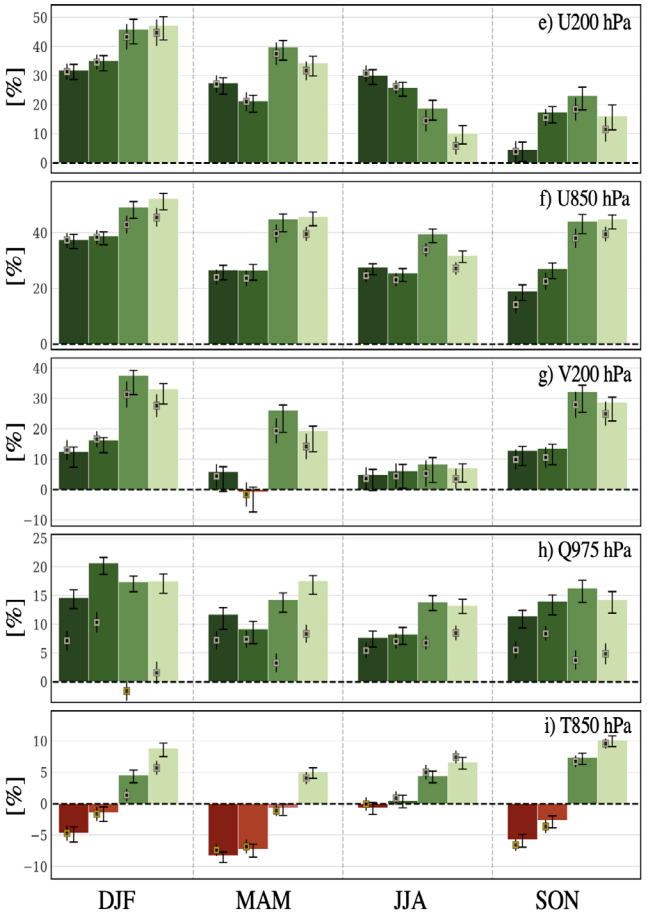
Precipitation GPCP

Precipitation ERAi:

Surface Temp:

Sea Level Pressure:





Zonal Wind 200hPa

Zonal Wind 850hPa

Meridional Wind 850hPa

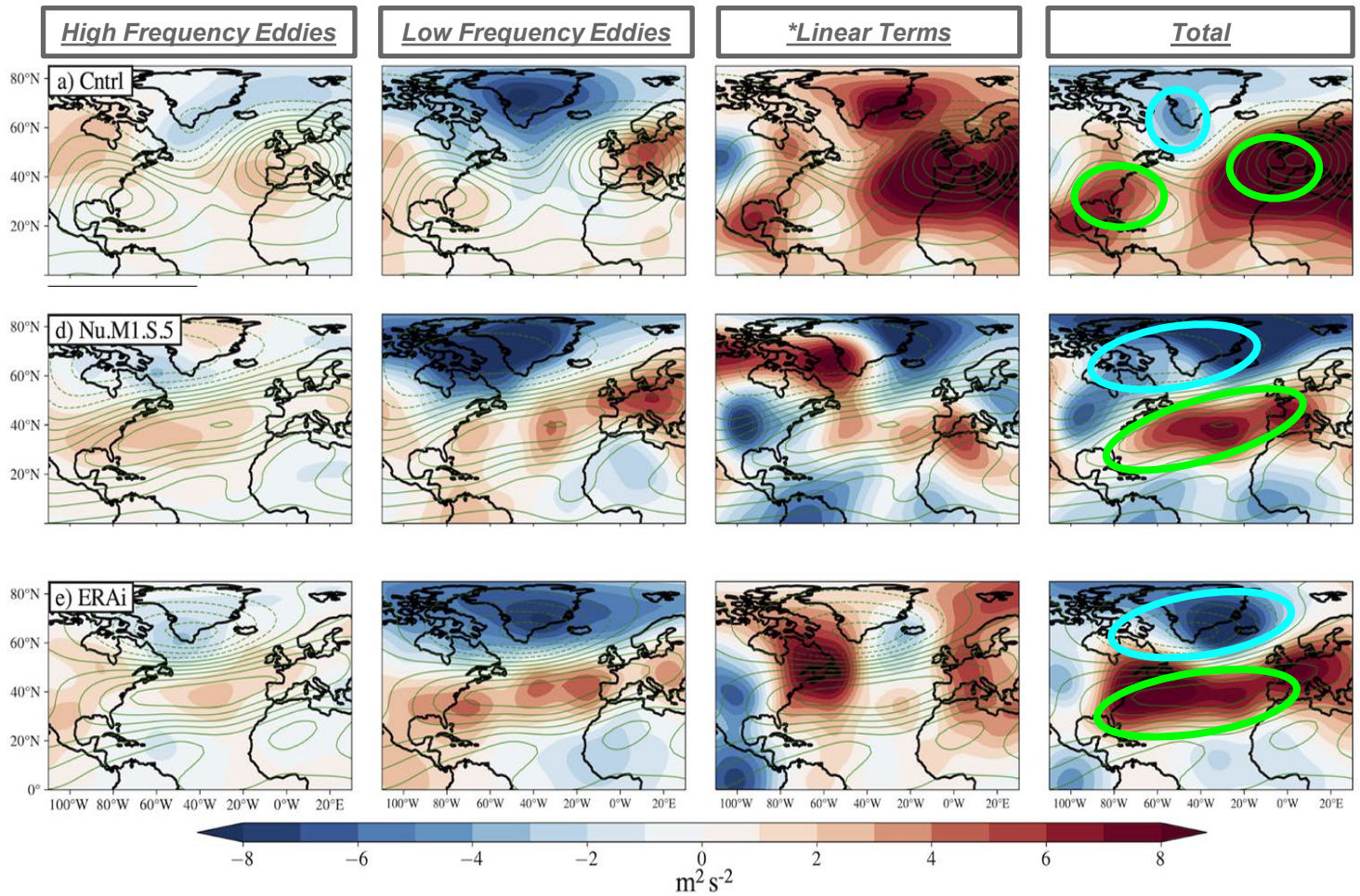
Sp. Humidity 975hPa

Temperature 850hPa

Improvement to Major Atm. Modes

*Will representing subgrid-scale uncertainty in online increment corrections via **stochasticity help to improve low-frequency modes of variability** without degrading mean state climatological bias?*

NAO Stream Function Tendency Decomposition (10-1 day before peak event):



***Linear Terms:** Planetary vorticity advection by the anomaly + interaction of anomaly with zonal mean climo. flow + divergence term.*

DA vs. Nudging Advantages / Disadvantages

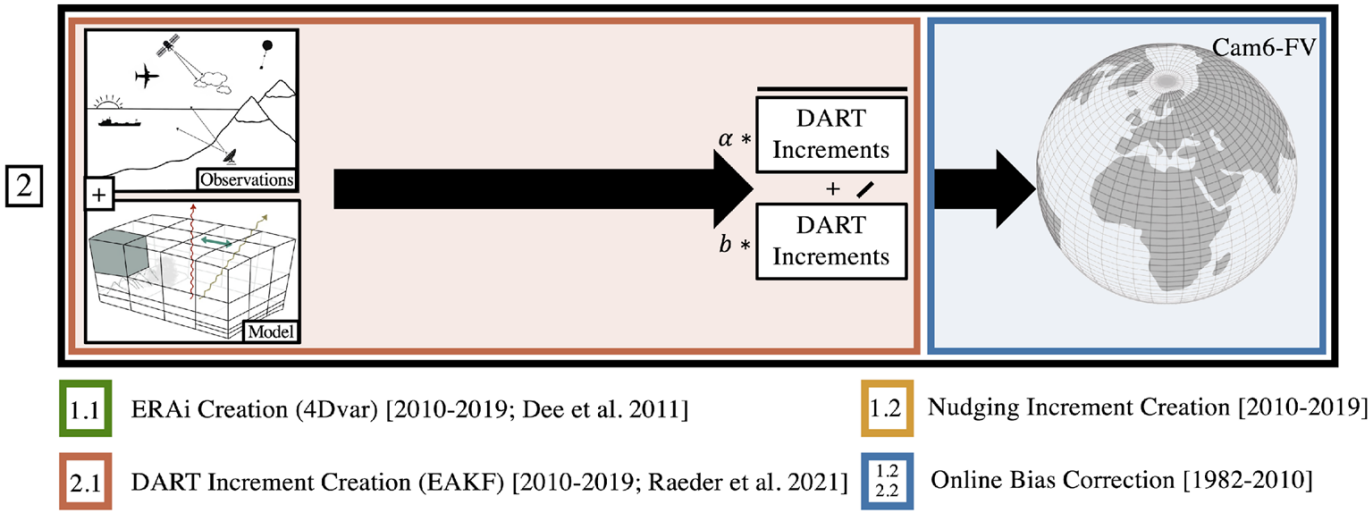
- We find that the nudging increment adjustment outperforms the correction provided by the DART increments (***but only just***).

- A disadvantage of **the DA increments** is that they **depend on observations which are spatially inhomogeneous and can be sparse**. Especially in data-limited regions, the analysis increment will unlikely represent model-error.

- On the other hand, nudging increments will benefit from the balance and conservation properties inherent in reanalysis as well as the spatial homogeneity of a gridded product. A noted **disadvantage of the nudging tendencies is that the model will adopt the same biases present in the reanalysis**.

- While the exact computational cost is system-specific, all data assimilation systems are resource-intensive. Indeed, they are often not readily available, **which makes an online -bias correction based on nudging tendencies a viable and flexible approach to study the impact of model bias in climate models**.

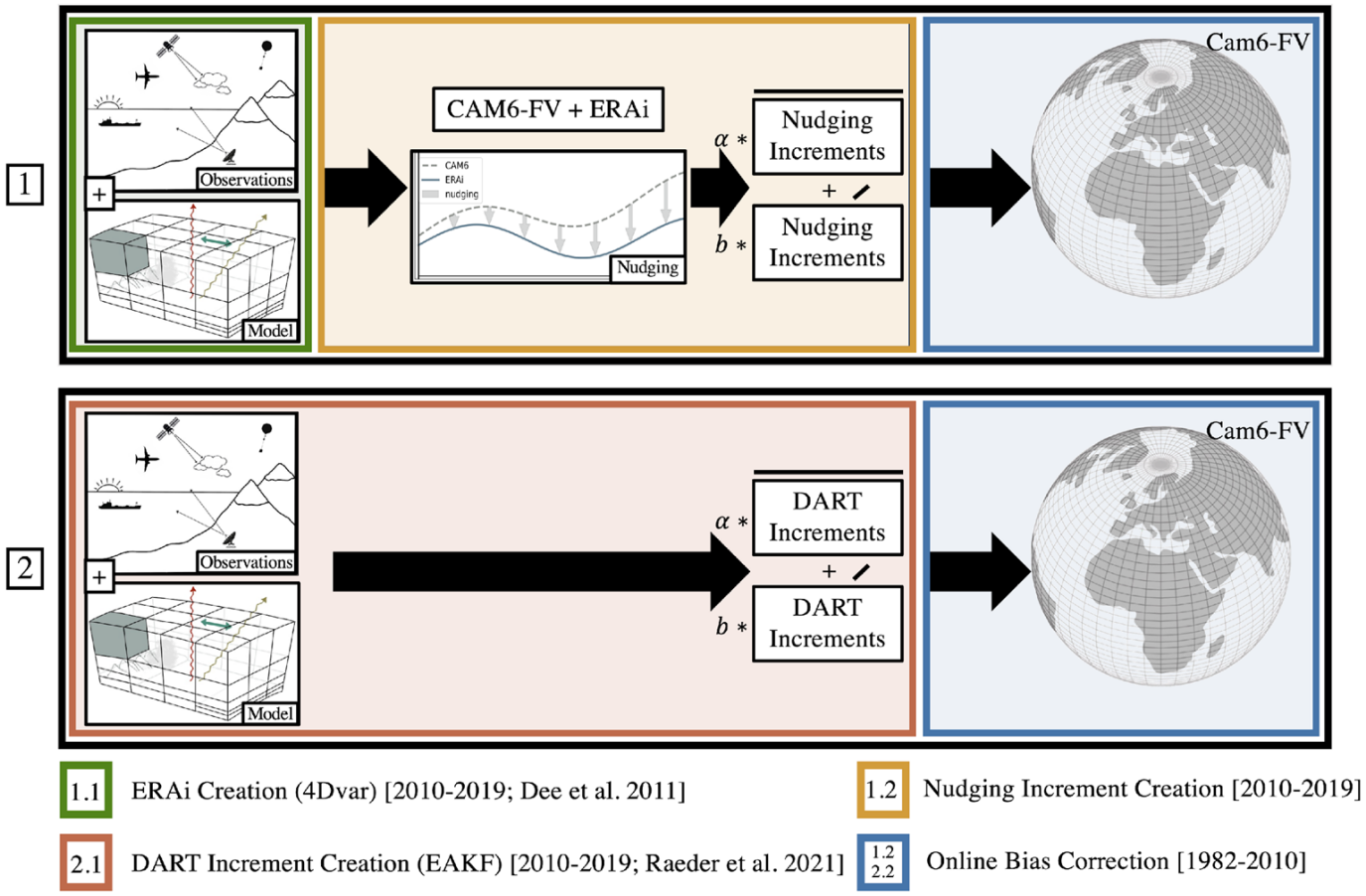
Conclusions



- Nudging increments and DA increments pick up the same general features of systematic model bias, particularly in the tropics at lower model levels
- Overall, we find a positive impact of an online model -error representation based on re-inserting DA increments and nudging on the climatological bias.
- The addition of a stochastic tendency reduced this bias and created an more accurate representation of major modes of variability when compared to observations.

Machine Learning Emulation

Can this process be replaced with a Machine Learning pipeline to create a "state-dependent" correction?



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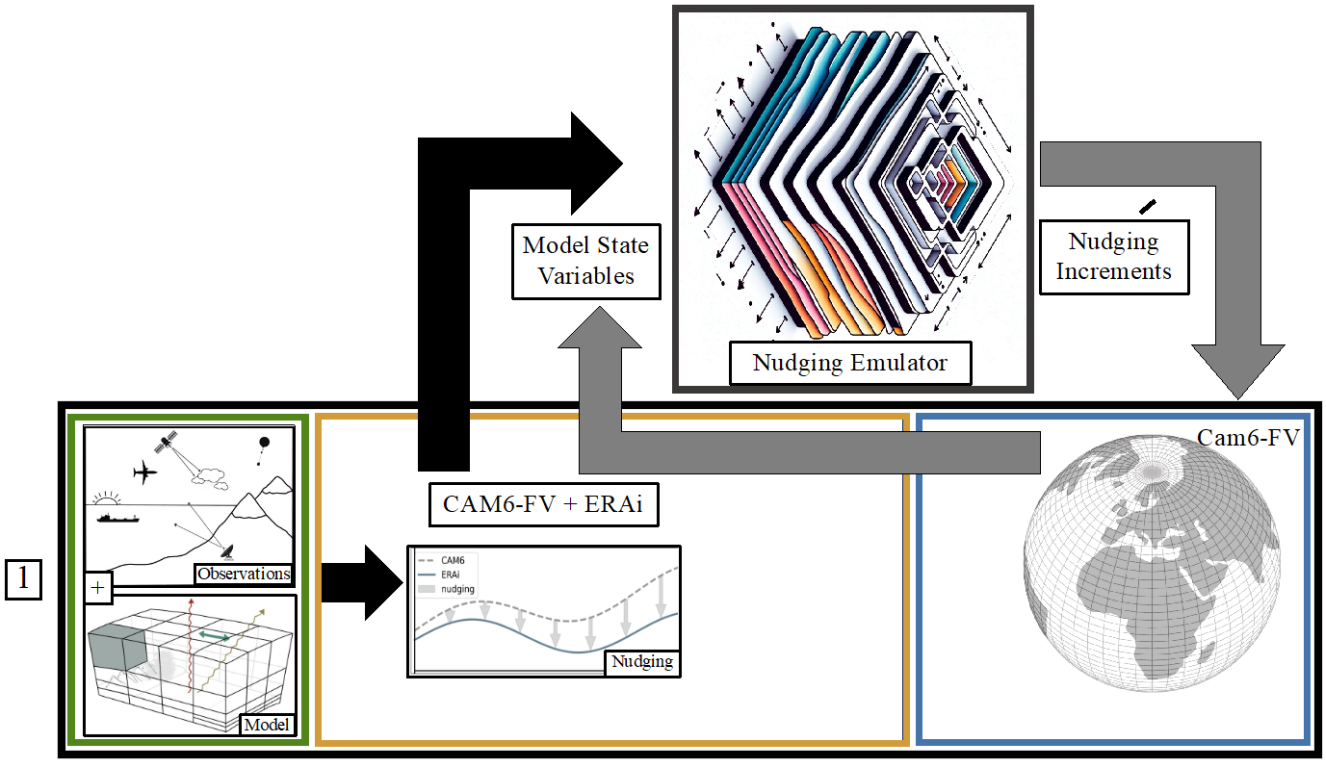


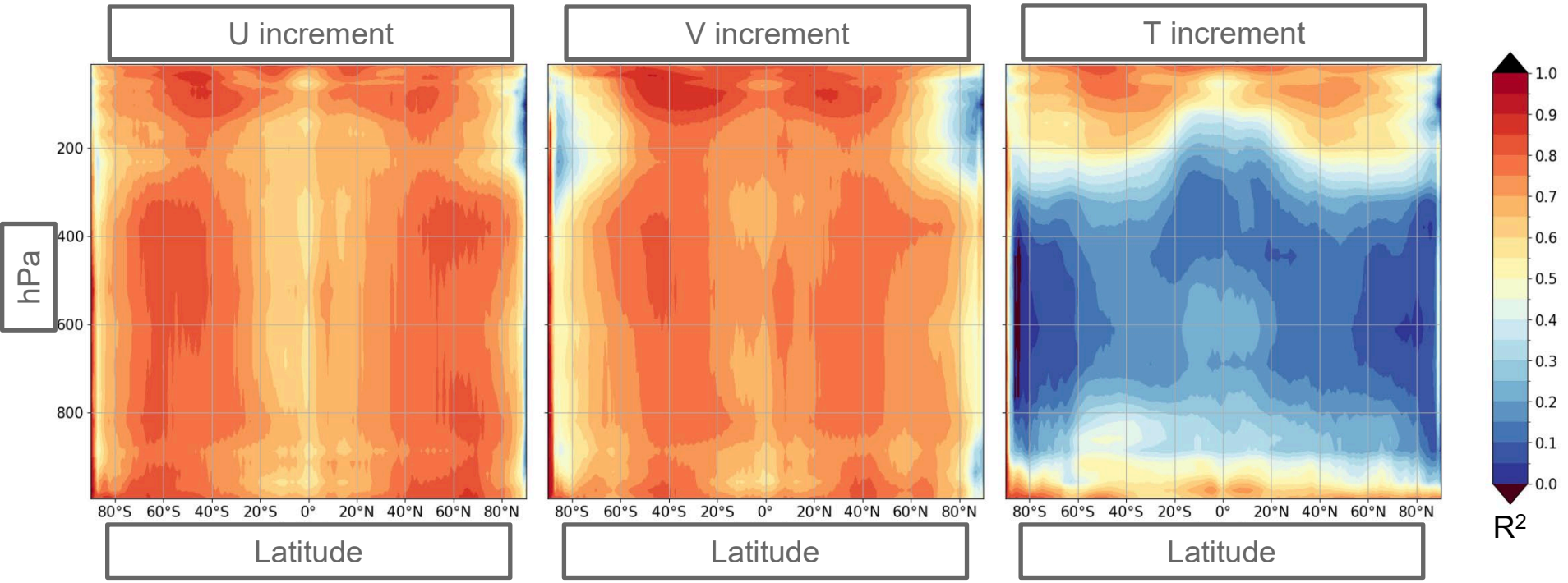
1.1 ERAi Creation (4Dvar) [2010-2019; Dee et al. 2011]

1.2 Nudging Increment Creation [2010-2019]

1.3 Machine Learning Emulator

1.4 Online Bias Correction [1982-2010]

ML is Skillful (OFFLINE Skill)



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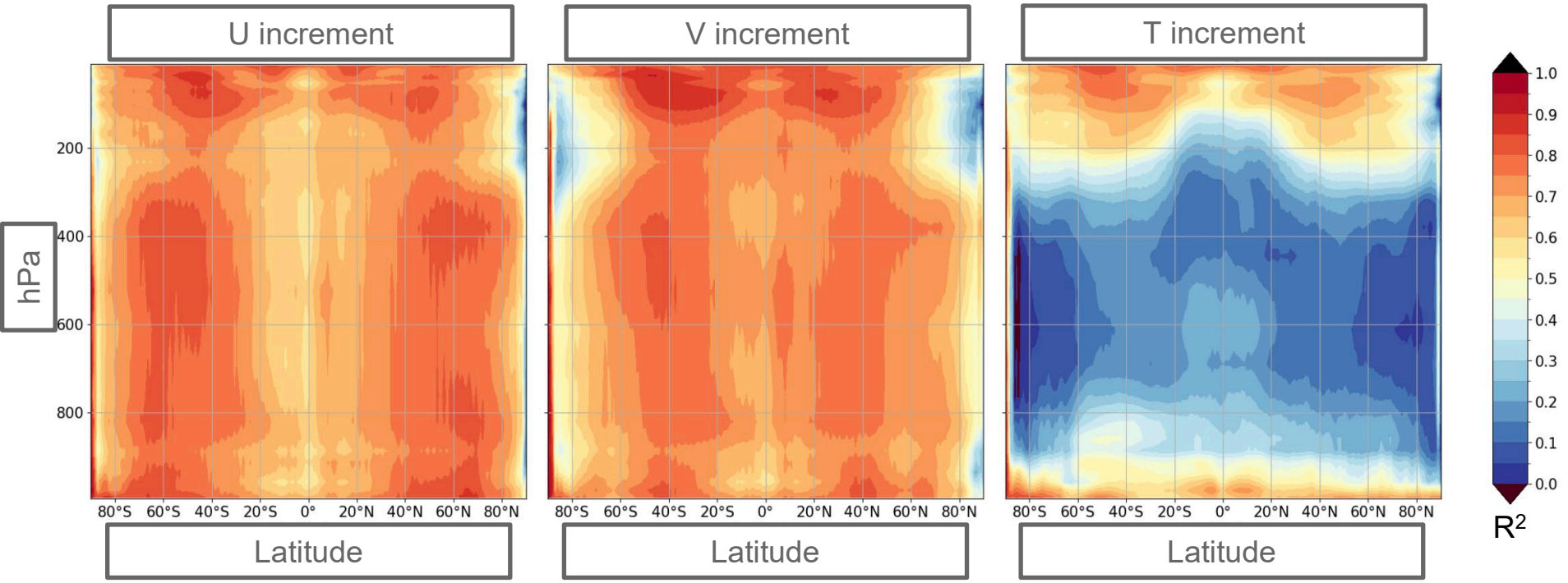
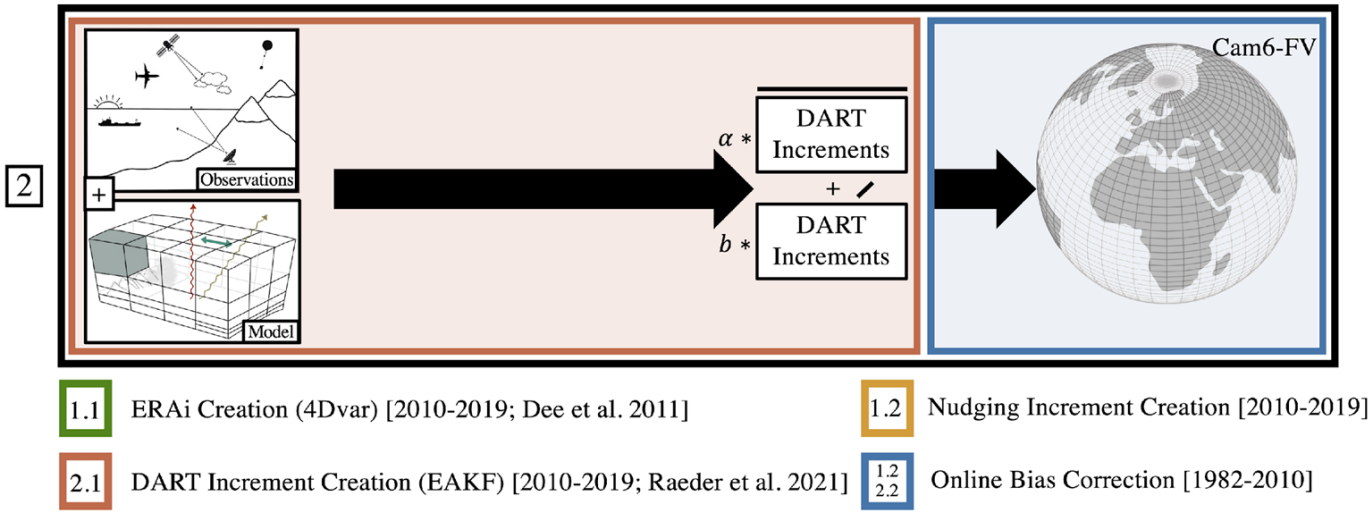


Results are pending in online simulation!

Conclusions



- We find that overall, nudging increments and DA increments pick up the same general features of systematic model bias, particularly at lower model levels
- We find a positive impact of an online model -error representation based on re-inserting DA increments and nudging on the climatological bias.
- The addition of a stochastic tendency reduced this bias and created an more accurate representation of major modes of variability when compared to observations.