# Use of assimilation increments for bias correction (and predictability studies)

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# Outline

- IAU, “Replay” and Tendency Bias Correction (TBC)

- TBC Applications:
  - Climate Mean Bias and forecast skill
  - Evaluation of sources of Model Error
  - Use in Assimilation

- Future plans/thoughts

## GMAO Seasonal Prediction group uses coupled Earth-System models and analyses, in conjunction with satellite and *in situ* observations, to study and predict phenomena that evolve on seasonal to decadal timescales. A central motivation for GMAO is the innovative use of NASA satellite data to improve forecast skill

- Atmosphere/Ocean Coupled Model Development
- Ocean Analysis Development
- Development of Initialization/Perturbation Strategy for ensembles of Sub/Seasonal Forecasts
- Coupled Assimilation Strategy Development

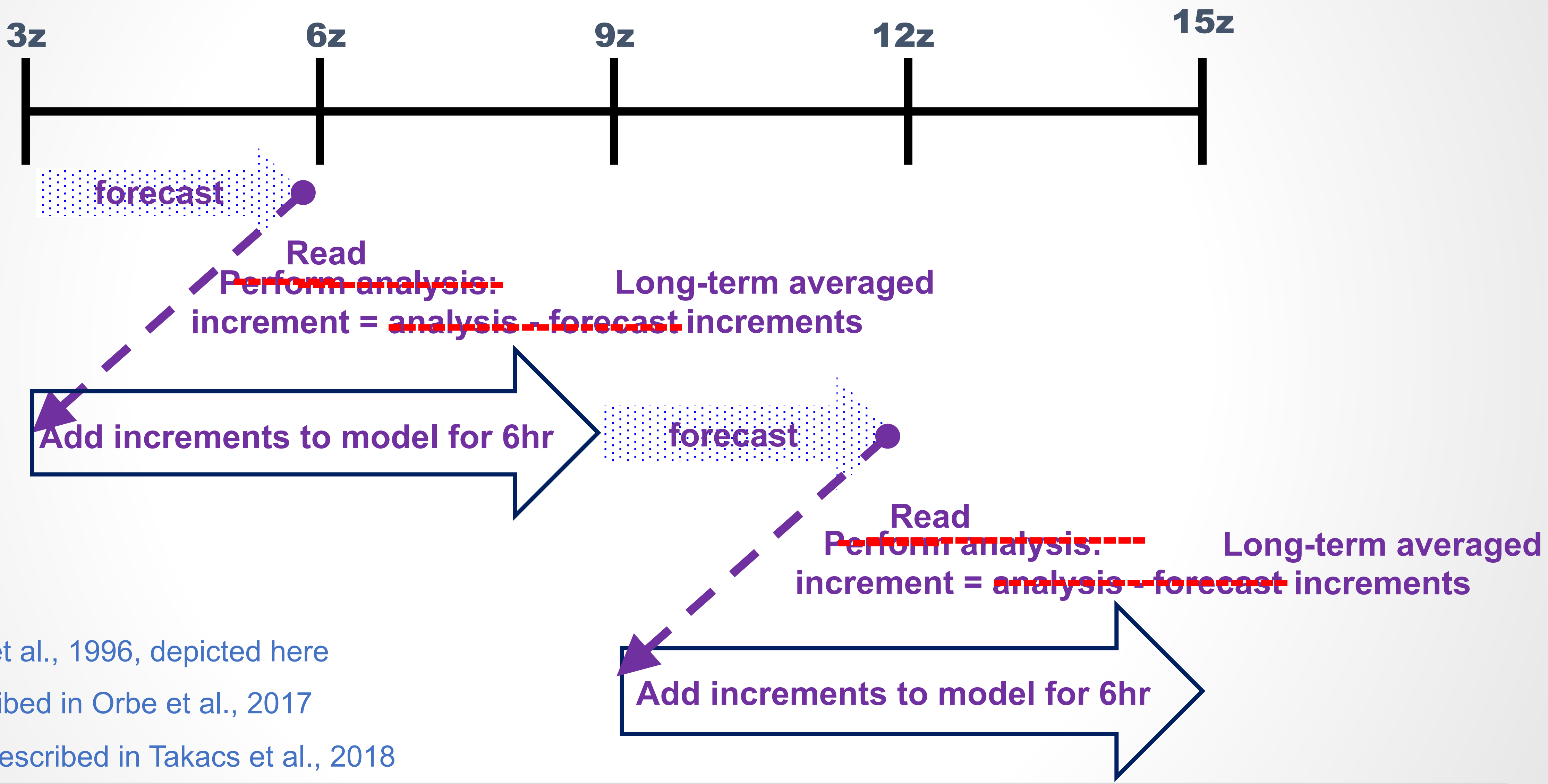
- Production of Coupled Data Assimilation (Re)Analysis
- Production/Dissemination of Sub/Seasonal Forecasts

- Validation/Assessment of Forecast Fidelity
- Validation/Assessment of Assimilated Ocean State

- Predictability Studies

**GEOS-S2S-2 was released in November 2017 (Molod et al., 2020)**
**GEOS-S2S-3 System "frozen" December 2021, weakly coupled reanalysis ("MERRA-2 Ocean") and forecasts under way and due for public release late 2023**

# IAU, "Replay" and TBC at GMAO: Flow Diagram



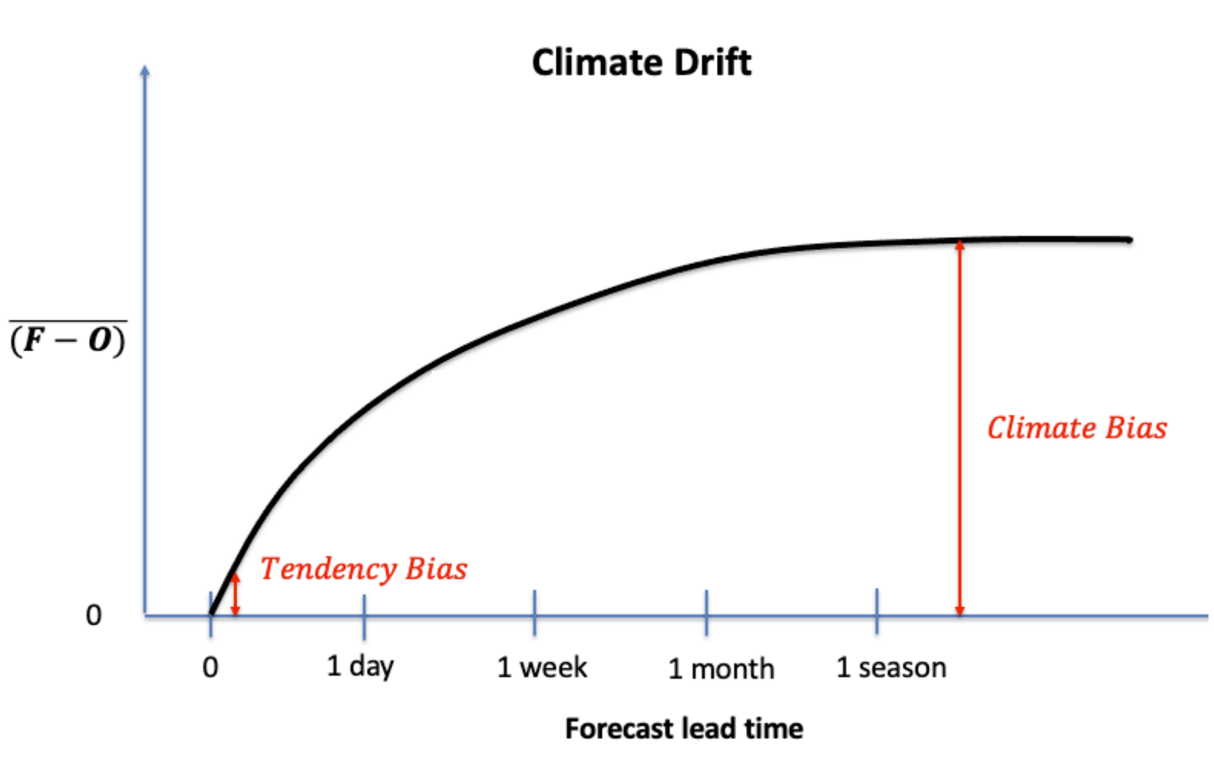

IAU of Bloom et al., 1996, depicted here

"Replay" described in Orbe et al., 2017

Updated IAU described in Takacs et al., 2018

# Underlying Motivation/Questions






- Can we reduce the model's climate bias by correcting the initial drift or tendency bias?
- Does reduced climate bias manifest itself in increased forecast skill at subseasonal to seasonal lead times?

Some terms/concepts:

"Drift" refers to time mean differences between the model forecasts and observations (or reanalysis) that are functions of lead time.

The "tendency bias" and the model's climatological bias represent the two end points of the bias evolution or drift, with the former measuring how the model initially starts to drift away from the observed climate and the latter measuring where it ends up.

# Climate Mean Bias/Forecast Skill: Atmospheric Correction in Atmospheric Model

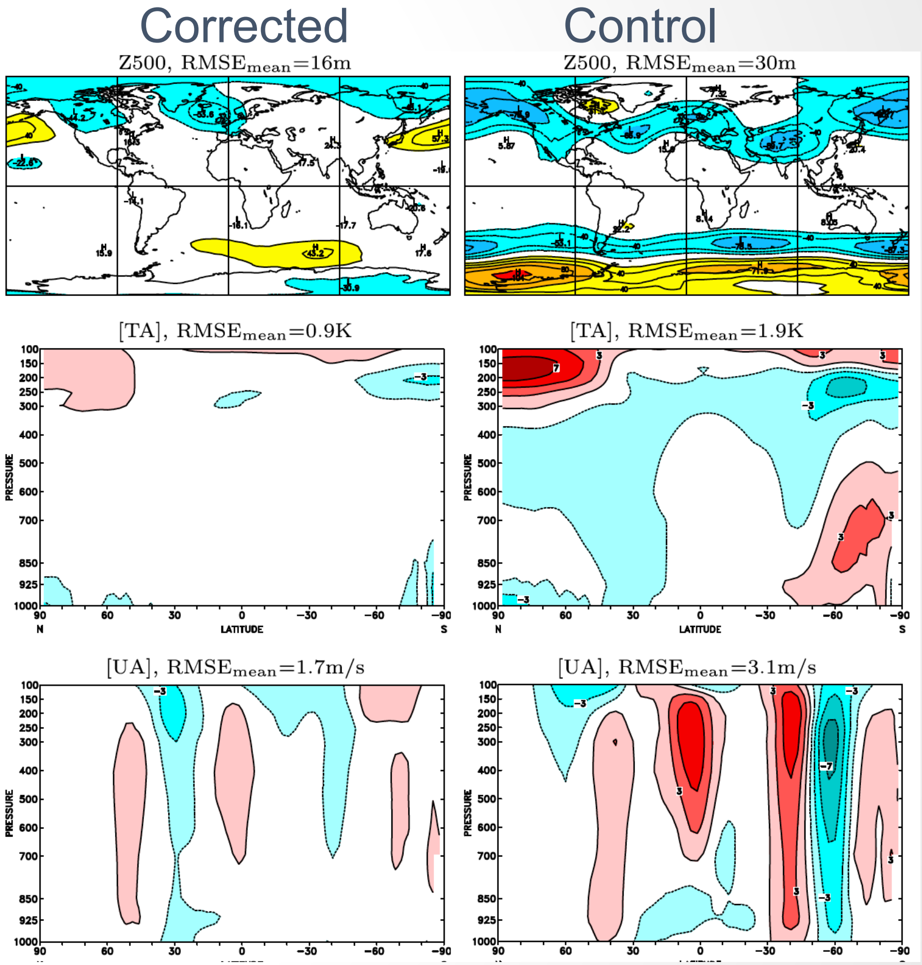
## Experiment

Long “AMIP” simulation (~30 years using an atmospheric model forced with observed sea surface temperatures) with nudging to EC Interim → compute daily mean “nudging increments” from 6-hour increments, and filter to keep the lowest 3 annual harmonics.

## Results:

Time mean climate root mean squared error is reduced. Also improved interannual variability and seasonality.

Used AMIP as proxy for seasonal forecast (randomized initial conditions), see modest ENSO skill improvement




Kharin and Scinocca, 2012

# Climate Mean Bias/Forecast Skill: Atmospheric Correction in Coupled Model

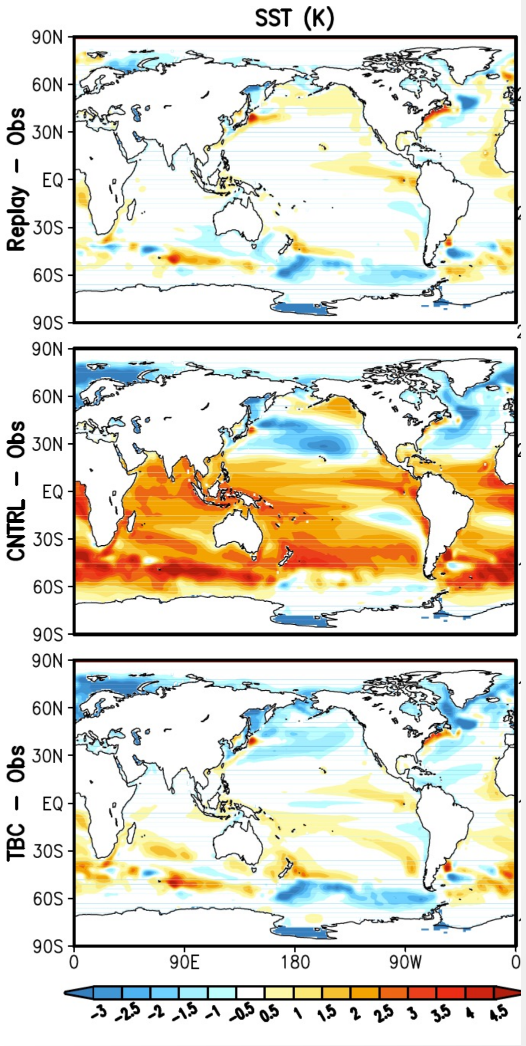
## Experiment

Long coupled simulation in which atmosphere is “replay”ed to MERRA-2. TBC terms are interannual averages of replay increments at each 6-hour interval. Since the experiment is only correcting atmospheric quantities, the ocean in only indirectly constrained by the TBC.

## Results

Various improvements to the climate bias of the mean state, stationary waves and related transients, and more realistic ENSO variability and associated teleconnections

TBC-related skill improvements were rather modest at best at both subseasonal and seasonal time scales. The modest improvements were at subseasonal scales, for eddy heights over the Pacific–North American region and T2m over North America.

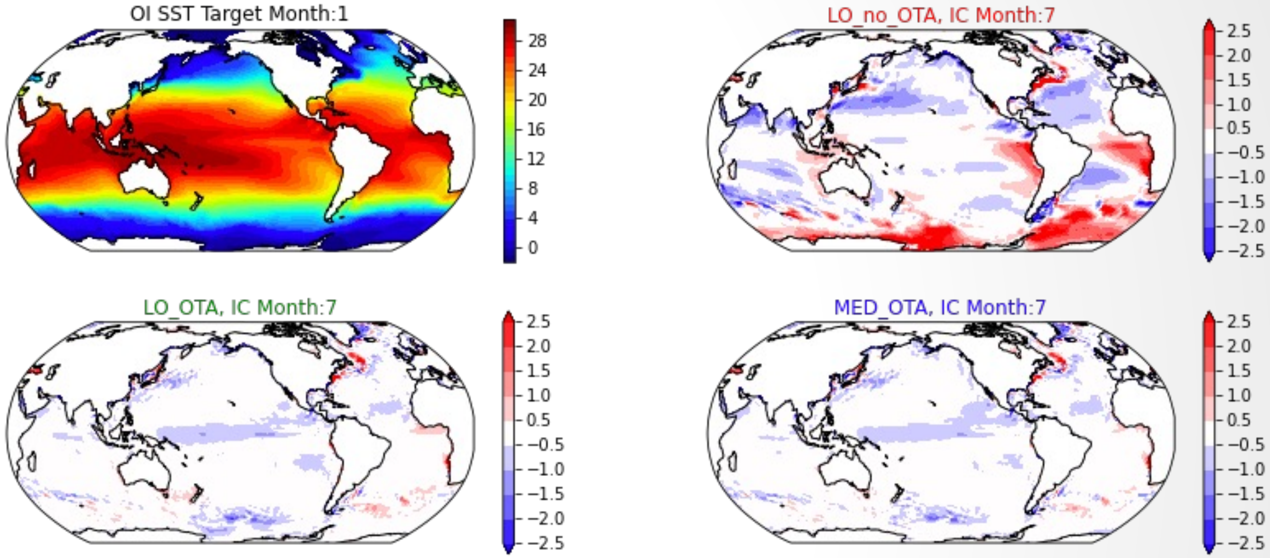



Chang et al., 2019

# Climate Mean Bias/Forecast Skill: Ocean Correction in Coupled Model

## Experiment

Long coupled simulation in which atmosphere is run free and ocean assimilation conducted using SPEAR-ODA with ARGO data only. Ocean Tendency Adjustment (OTA) terms are the climatological annual cycle of the analysis increments. Seasonal prediction and climate projection simulations were conducted




## Results

Mean SST drift and mean bias at 6 months lead time in seasonal forecasts was reduced. In addition, the Nino3.4 drift was reduced.

For climate projection the climate bias was reduced. Added machine learning to OTA to make increments depend on the ocean state and surface fluxes – so far found that the Neural Network does good job of simulating the true ocean temperature

# Climate Mean Bias/Forecast Skill: Atmosphere/Ocean Correction in Coupled Model

<u>Experiment</u>

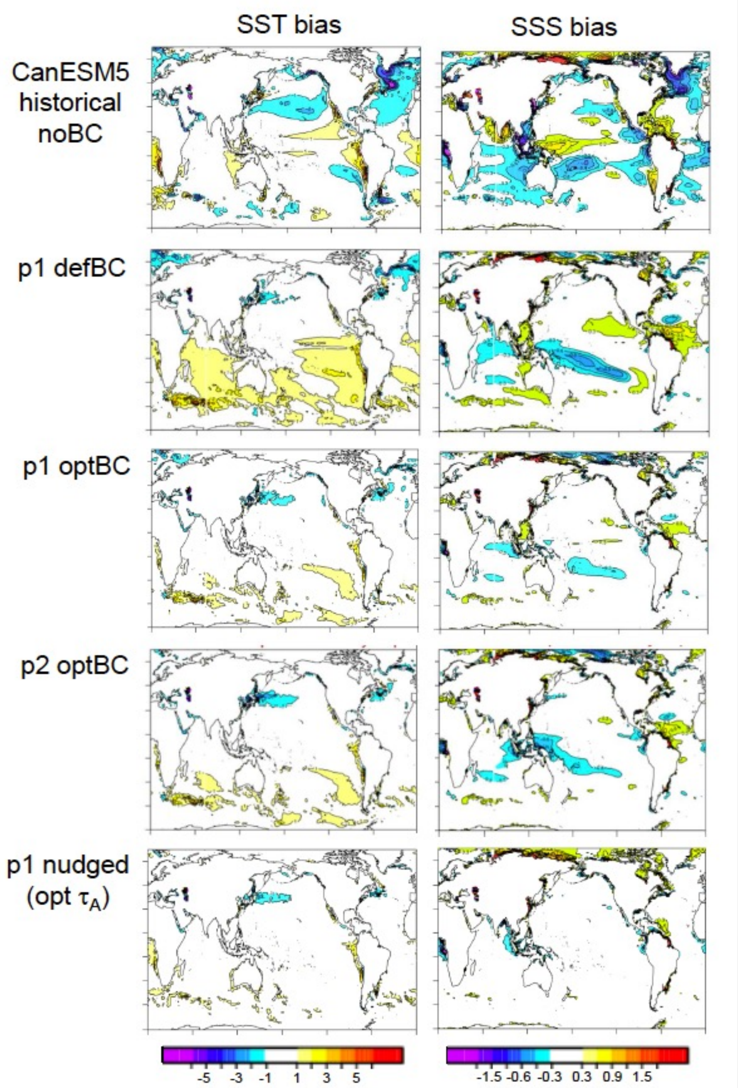
Long (30 year) coupled simulation in which atmosphere and ocean were nudged to assimilations. Tendency adjustment (TA) increments in both fluids are the mean seasonal cycle of increments from nudging experiment

Performed 30 year free running simulation and seasonal hindcasts with and without TA

<u>Results</u>

Free running SST and SSS biases were reduced, and SST seasonality (and ENSO seasonality) were improved

Seasonal prediction of ENSO: skill not improved – also SMALL (significant?) improvement in z500mb height, temp and precip when averaged at all lead times (1-9 months) and initial condition months



# Climate Mean Bias/Forecast Skill – Summary

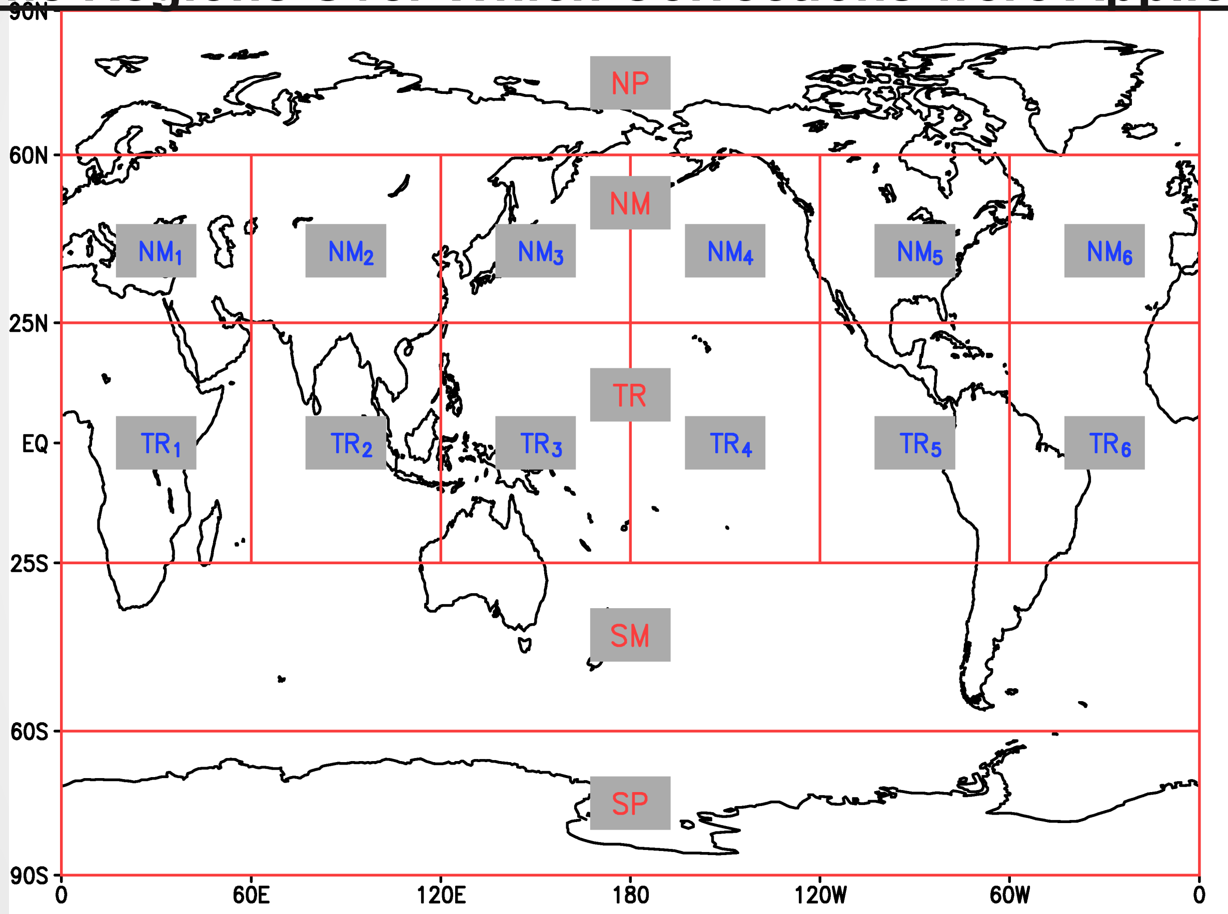
Saw examples from coupled and uncoupled models, using increments from assimilation, nudging and “replay”

ALL examples demonstrated general improvement in climate bias

ALL examples showed little to no improvement in forecast skill at subseasonal to seasonal leads

# Evaluation of sources of Model Error

**The Regions Over Which Corrections were Applied**




## Regional TBC and Replay: A Tool for Addressing Model Error

**TBC** corrections were applied together and separately in the regions shown here.

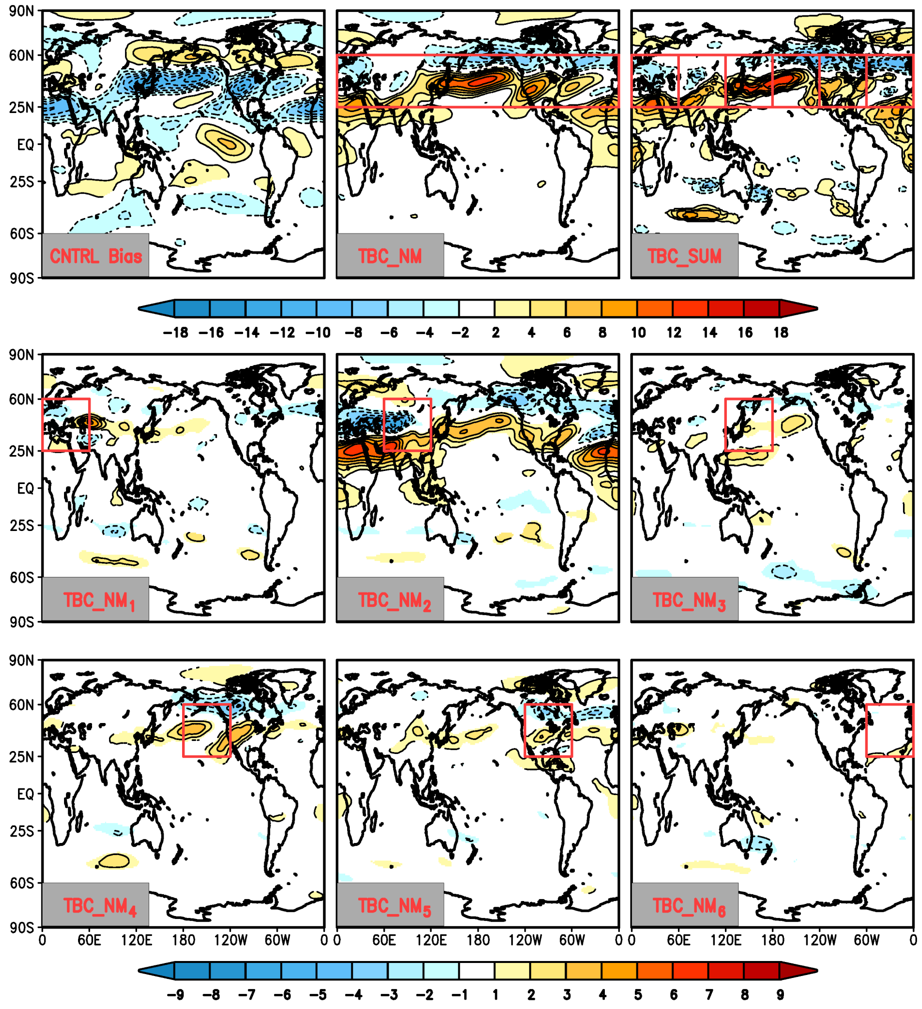
Experiments were performed with the GEOS AGCM forced with observed SST and run for the period 1980-2017. A TBC experiment was also conducted in which the increments were applied globally. In addition, a **CNTRL** run was made without any correction terms.

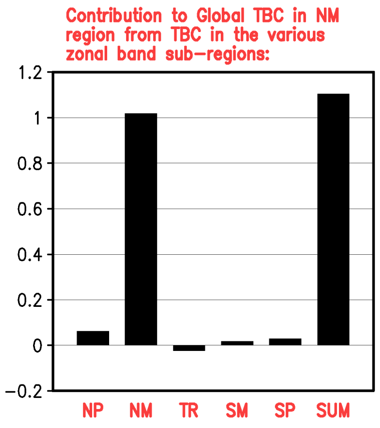
Schubert et al., 2019

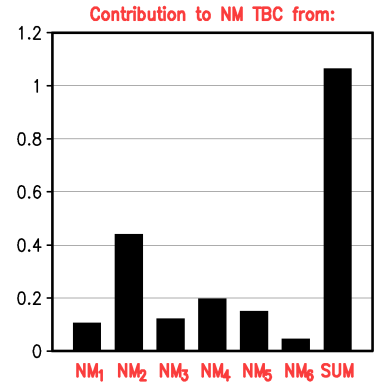
# Evaluation of sources of Model Error (cont'd)



## JJA 250mb U-wind: TBC




Upper left panel is (CNTRL-MERRA-2). The other panels are the experiments (TBC-CNTRL) for the regions shown by the red boxes. The upper right map is the sum of the results of the 6 NM regions. The bar graphs are the normalized spatial inner products from the various experiments.

**Key results: much (87%) of the AGCM long term bias in the NM region can be corrected by the TBC in that region, and much of that (>40%) is achieved by the correction over the Tibet region ($NM_2$). Results are for the most part linear (cf. upper middle and upper right panels) .**

Schubert et al., 2019

# Use of Analysis Increments in Assimilation – Atmosphere



## Motivation:

Provide the atmospheric analysis with a background that is unbiased, and "ask" the analysis to correct the random error only. This is more consistent with the underlying assumptions of the "BLUE" methods.

$$GCM_{fg}(t_a) = GCM_{das}(t_a - 3hr) + \left[\left(\frac{\partial g}{\partial t}\right) + IAU_{fg}\right] 3hr$$

$$AMF(t_a) = ANA(t_a) - GCM_{fg}(t_a)$$

$$IAU = AMF(t_a)/\tau_{iau} + IAU_{fg}$$

$$GCM(t_a - 3hr + \Delta t) = GCM_{das}(t_a - 3hr) + \left[\left(\frac{\partial g}{\partial t}\right) + IAU\right] \Delta t$$

## Technique:

"IAU with memory" computes a time averaged analysis increment over a time scale determined *a priori*. We see that the ensemble time-mean AMF will be zero (indicating statistically unbiased analysis adjustments) only if the model's climatology is equal to that of the after-analysis. In general, for GCMs containing model bias, this will not be the case.

In the Analysis-minus-forecast (AMF) obtained from the "IAU with memory" technique used in GEOS, the contribution from the model bias has been eliminated. This substantially reduces the Mean Analysis Error

Takacs, NASA Tech Memo, 1996

# Use of Analysis Increments in Assimilation – Ocean in Coupled

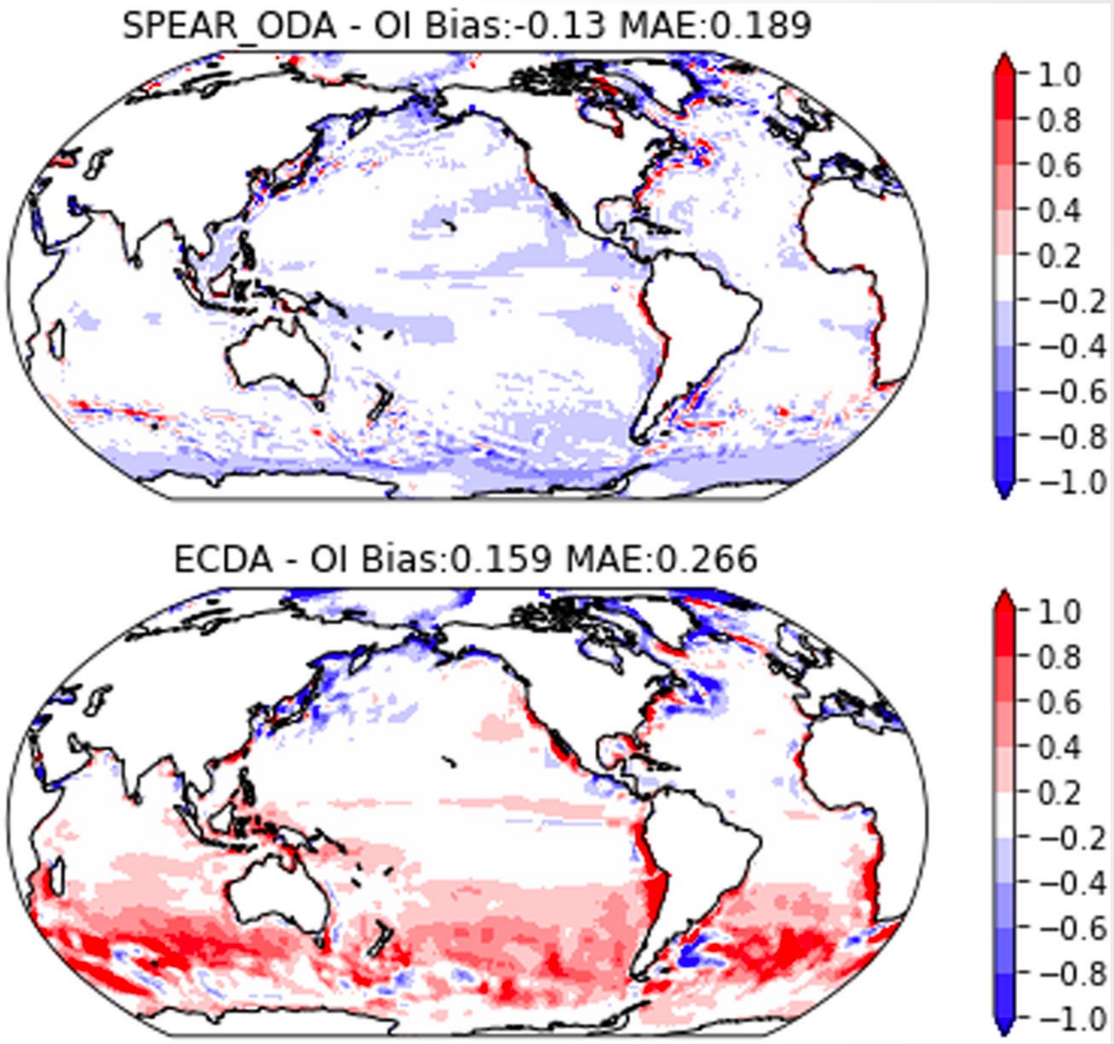
National Aeronautics and Space Administration

Ocean Tendency Adjustment (OTA) terms are the climatological annual cycle of the analysis increments.

In SPEAR-ODA Ocean Assimilation with coupled model, the mean analysis error (ie., bias) in SST was reduced, and assimilated sea ice was in better agreement with NSIDC estimates.

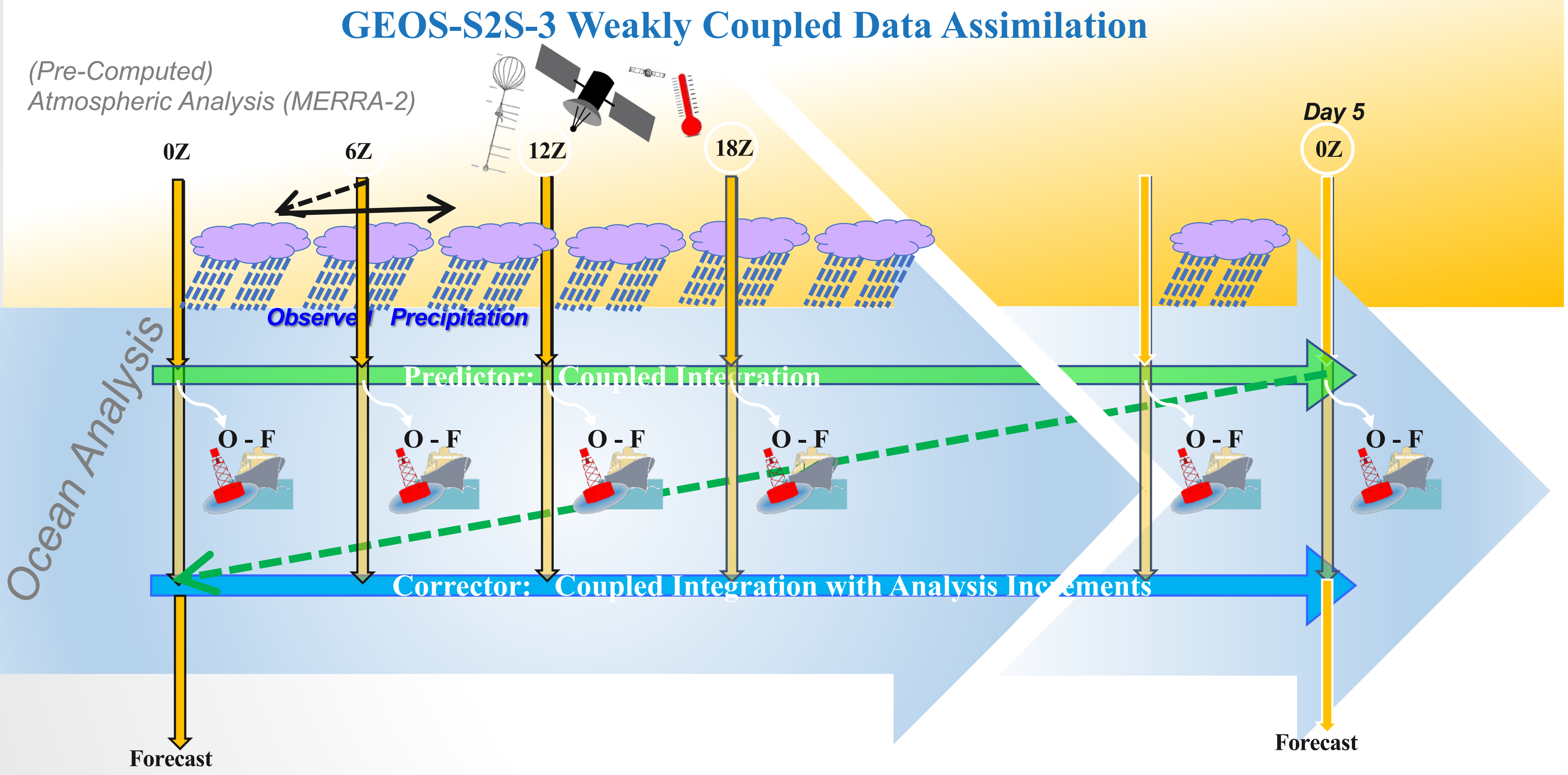
The mean analysis error in ocean temperatures showed less improvement, however.

This use of OTA in the assimilation was viewed as an approximation to the methods proposed in, eg., Dee, 2005 for the atmosphere and Balmaseda, 2007 for the ocean, both of which use assimilation to estimate the bias rather than the averaged increments.




Lu et al., 2020

# Use of Analysis Increments in Assimilation – Ocean with Replayed Atmosphere




**"MERRA-2 Ocean" reanalysis is running from 1982-present**
**"GEOS_IT Ocean" is spinning up and will run in Near-Real Time**

Preliminary experiments were conducted in the GEOS weakly coupled data assimilation system.

Ocean TBC terms were computed as month-long running mean of ocean IAU increments in each 5-day window.

# Summary

- TBC (or similar technique) has been used in atmosphere, ocean and coupled models and assimilation systems
- Shown to be a useful tool for assessing local vs remote error in models
- Climate mean bias or mean analysis error was generally reduced
- Forecast skill gains were marginal at best

# Future Directions - Thoughts about Forecast Skill

**Why is there little or no impact on forecast skill after demonstrating that TBC can significantly reduce climate bias?**

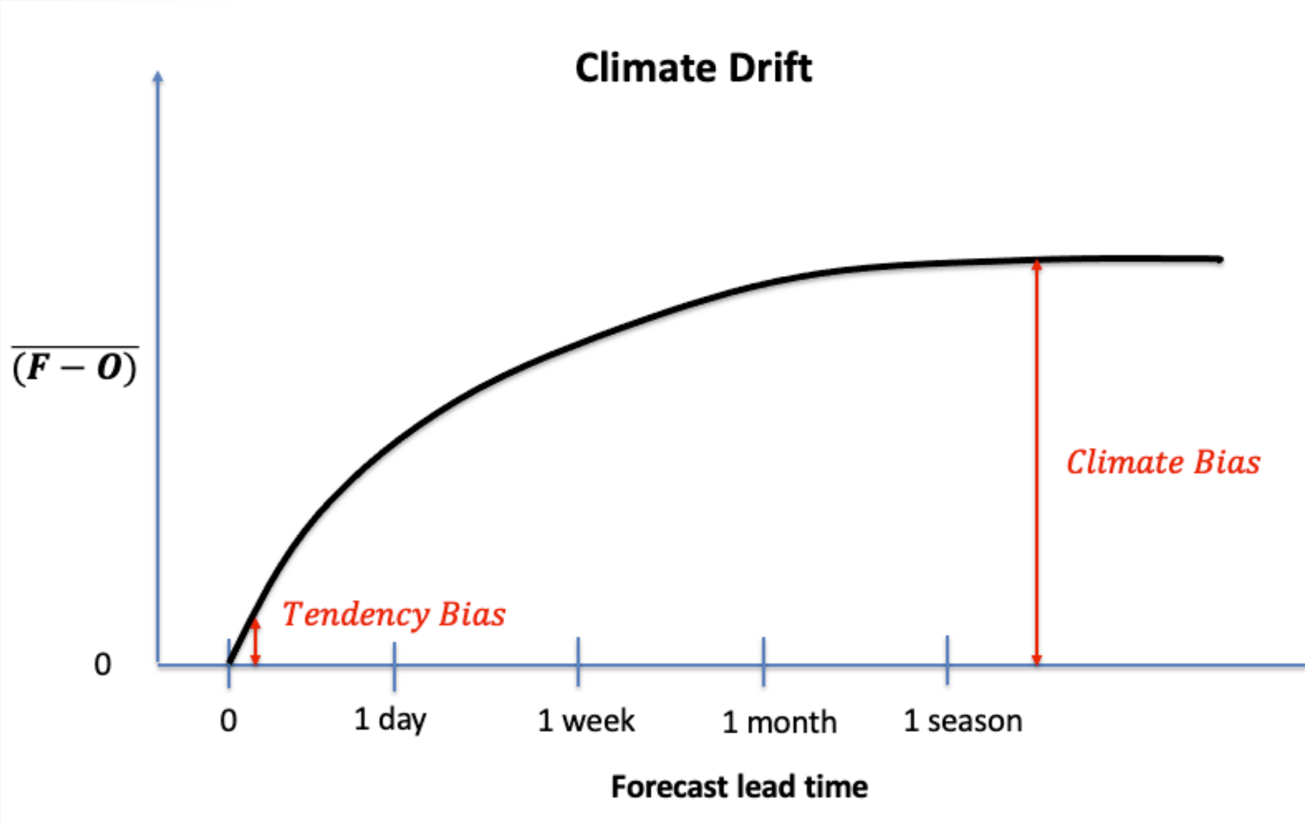
The connection between forecast skill and the quality of a model's climate (including variability) is not straightforward, though it seems plausible that a model with a better long-term climate should have better forecast skill. However…. Some possible obstacles are:

? The "true" errors cannot be represented by a simple constant forcing term and are, in fact, state dependent (e.g., Leith 1978; Danforth et al. 2007)

? Correcting climate drift (which is a function of forecast lead time) can presumably only lead to improved forecast skill if a substantial amount of the bias (and its correction) occurs before all predictability is lost. The two time scales (associated with drift development and predictability) serve to define a window of forecast leads during which TBC can be expected to have an impact on skill.

# Future Directions – GMAO

1. Use atmospheric replay increments and ocean IAU increments, both modified by ML to model state dependance, to estimate TBC terms.
2. Use in weakly coupled assimilation with goal of improving Mean Analysis Error
3. Use in forecasts initialized from coupled assimilation to evaluate impact on skill




<u>Question for thought/exploration:</u>

Can TBC increments, together with climate bias, be used to estimate the lead-time evolution of model drift (currently estimated from extensive retrospective forecasts)?

# Thank you for your attention!