Regional Replay: A Unique Reanalysis-Based Tool for Addressing Model Error

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Introduction

We outline a framework for identifying and quantifying **regional** errors and their **global impacts** in climate models by forcing the model with analysis increments (either instantaneous or a long term mean) over limited regions. An example is given based on MERRA-2 (Gelaro et al. 2017) and the NASA/GMAO GEOS AGCM (Molod et al. 2015), with a focus on JJA.

Methodology and Experiments

Replay (RPL): takes advantage of the incremental analysis update procedure employed in the GEOS data assimilation system to force a model to track a pre-existing analysis (Figure 1). The equations governing replay have the form:

$$\frac{\partial x}{\partial t} = f(x) + \Delta x \qquad (1),$$

Where Δx =(analysis-forecast)/6hours is the instantaneous analysis increment, and f(x) consists of all the dynamics and physics terms of the model.

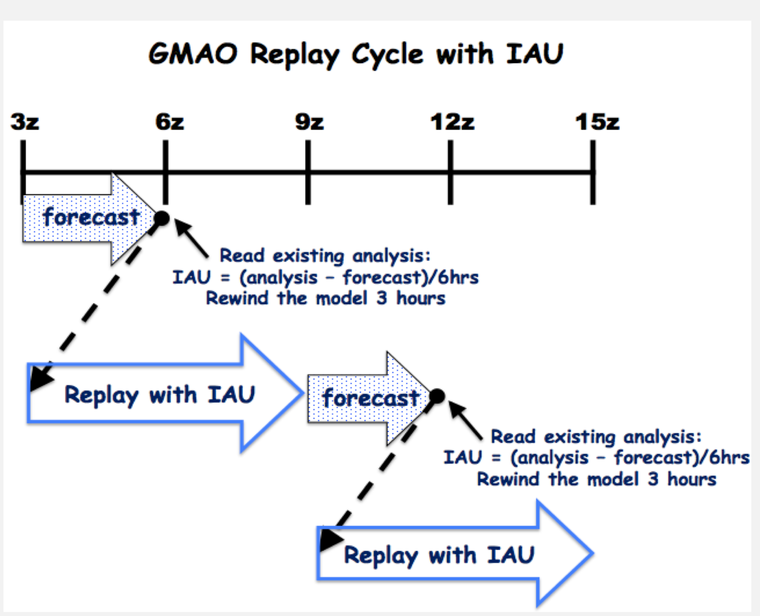

Figure 1: Overview of "replay". The blue arrows indicate that the replay is essentially a continuous model simulation that is driven by a sequence of IAU (Incremental Analysis Update) forcing terms (updated every 6 hours). See equation 1.

Tendency Bias Correction (TBC): Following Chang et al. (2018), the governing equations for the TBC approach have the same form as (1), except that the forcing term is a long term mean of the increments. In particular,

$$\frac{\partial x}{\partial t} = f(x) + \overline{\Delta x} \qquad (2),$$

where the $\overline{\Delta x}$ are the instantaneous Δx averaged over the years 1980-2017 (denoted by the overbar).

The RPL & TBC experiments consist of two sets of GEOS AGCM simulations in which the correction terms (either **TBC:** $\overline{\Delta x}$ or **RPLY**: Δx) are applied in various regions (Figure 2) that together span the globe.

The Regions Over Which Corrections were Applied

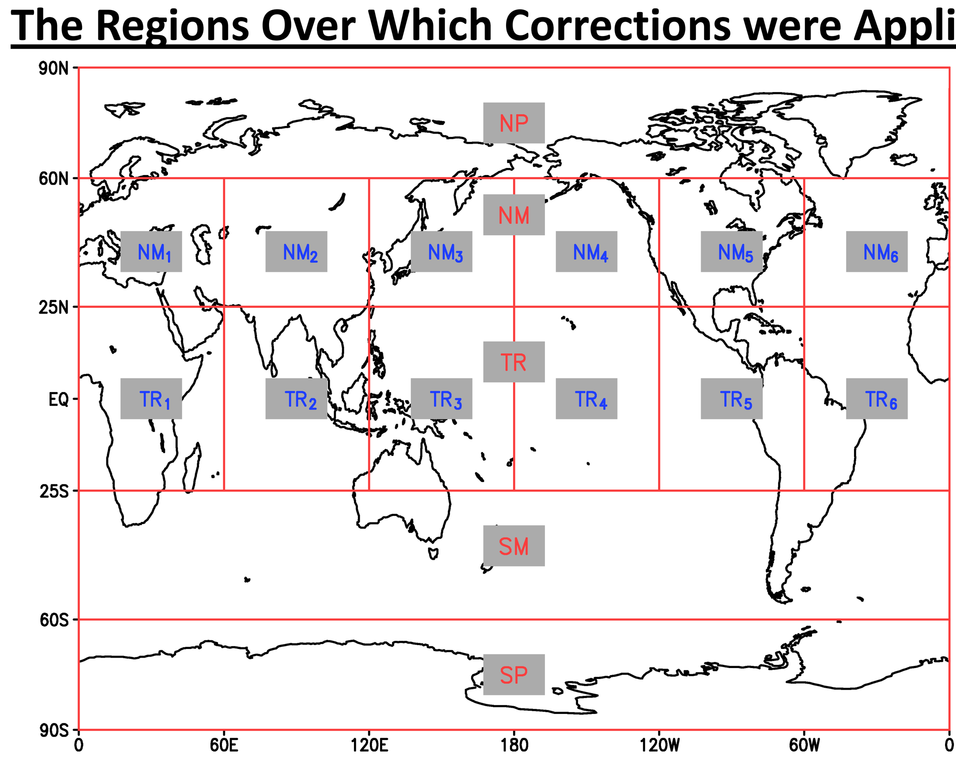

Figure 2: The regions over which the corrections were applied in the experiments with the global GEOS AGCM forced with observed SST. In each experiment, the correction term (either **TBC:** $\overline{\Delta x}$ or **RPLY**: Δx) was limited to one of the 17 regions specified above, and run for the period 1980-2017. A TBC run was also made in which the increments $\overline{\Delta x}$ were applied globally. In addition, a **CNTRL** run was made without any correction terms.

JJA 250mb U-wind: TBC

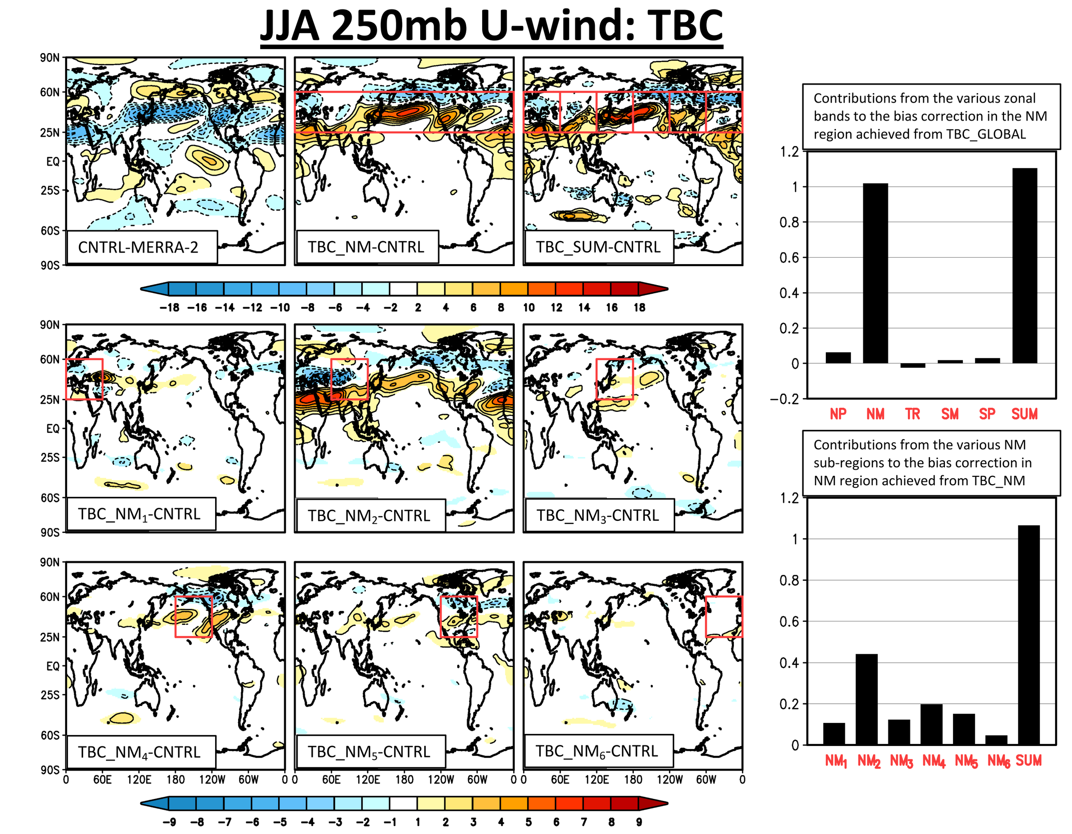

Figure 3: Results for the TBC experiments for the JJA 250mb u-wind. Upper left panel is the model bias (CNTRL-MERRA-2). The other panels are the experiments (TBC-CNTRL) for the regions indicated by the red boxes. The upper right map is the sum of the results of the 6 NM regions. The bar graphs are the 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) .**

JJA T2m: TBC

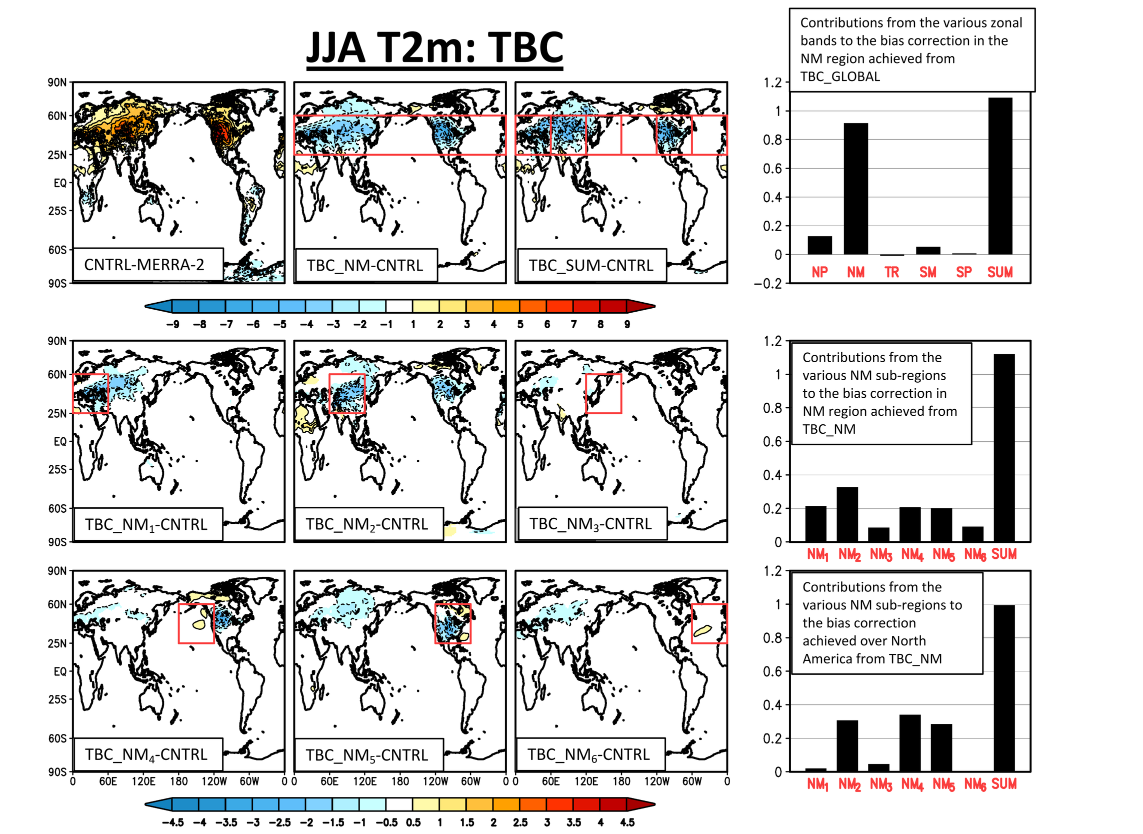

Figure 4: Same as Figure 3, except for T2m. The additional bar graph in lower right shows the contribution to North America from the NM sub-regions. **Key results: much (69%) of the AGCM long term warm bias in NM over land can be corrected by the TBC in that region. About 2/3 of the correction over North America is due to remote forcing (corrections in NM_2 and NM_4): only about 1/3 is locally forced (NM_5). Results are for the most part linear (cf. upper middle and upper right panels).**

JJA Precipitation: TBC

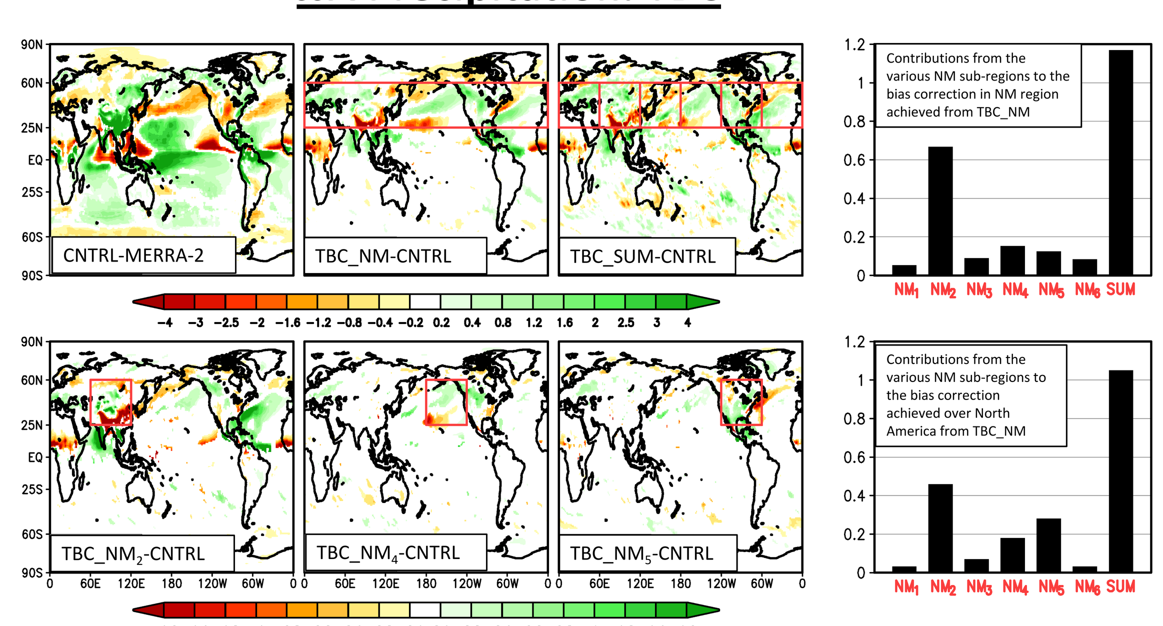

Figure 5: Same as Figure 3, except for precipitation, and lower right bar graph shows the contribution to North America from the NM sub-regions. For clarity, only the results for those regions having the largest impact are shown for the spatial maps. **Key results: a considerable amount (43%) of the bias in the NM region can be corrected by the TBC that region, with the NM_2 region accounting for more than 60% of that. The NM_2 region accounts for more than 40% of the correction over North America. Results are for the most part linear (cf. upper middle and upper right panels).**

JJA 250mb eddy height: TBC

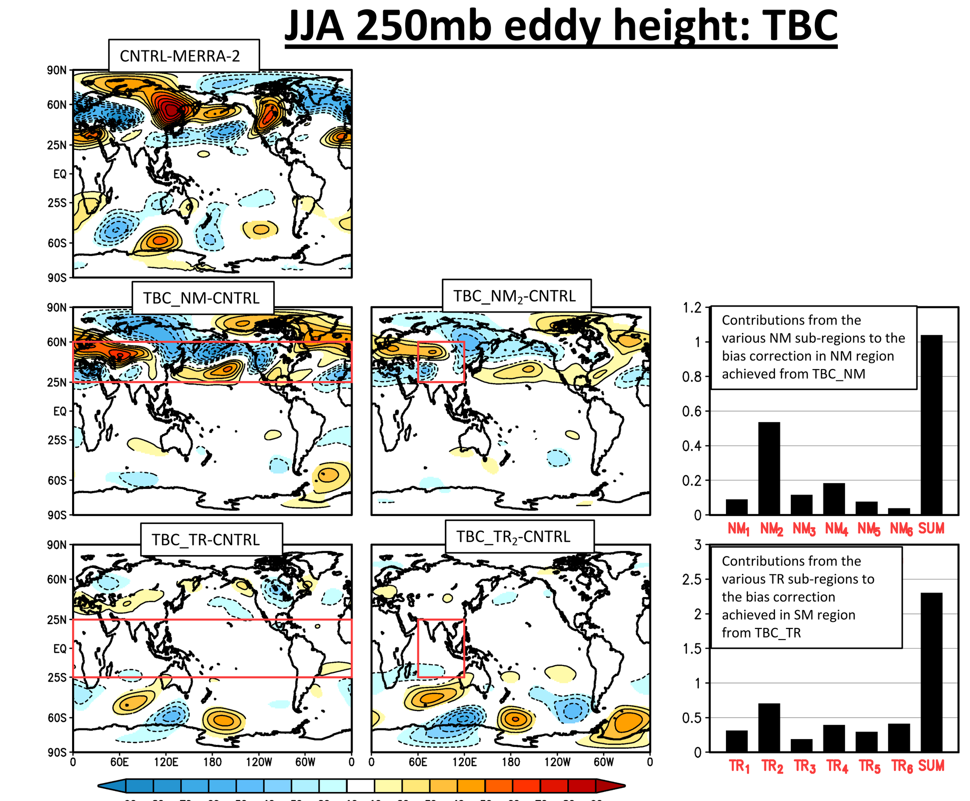

Figure 6: Same as Figure 3, but for 250mb eddy height and for selected regions contrasting the impacts of the corrections in the NH middle latitudes (NM) and tropics (TR). **Key results: much of the bias in the NH can be corrected by TBC within the NM region. In contrast, correcting the tropics has little impact in the NM, but does act to correct stationary wave biases in the SH middle and high latitudes: much of that comes from the TBC over the Indian Ocean region (TR_2). Results are not linear in the SM region (sum is >1 in lower right bar graph).**

JJA 250mb U-wind: RPLY

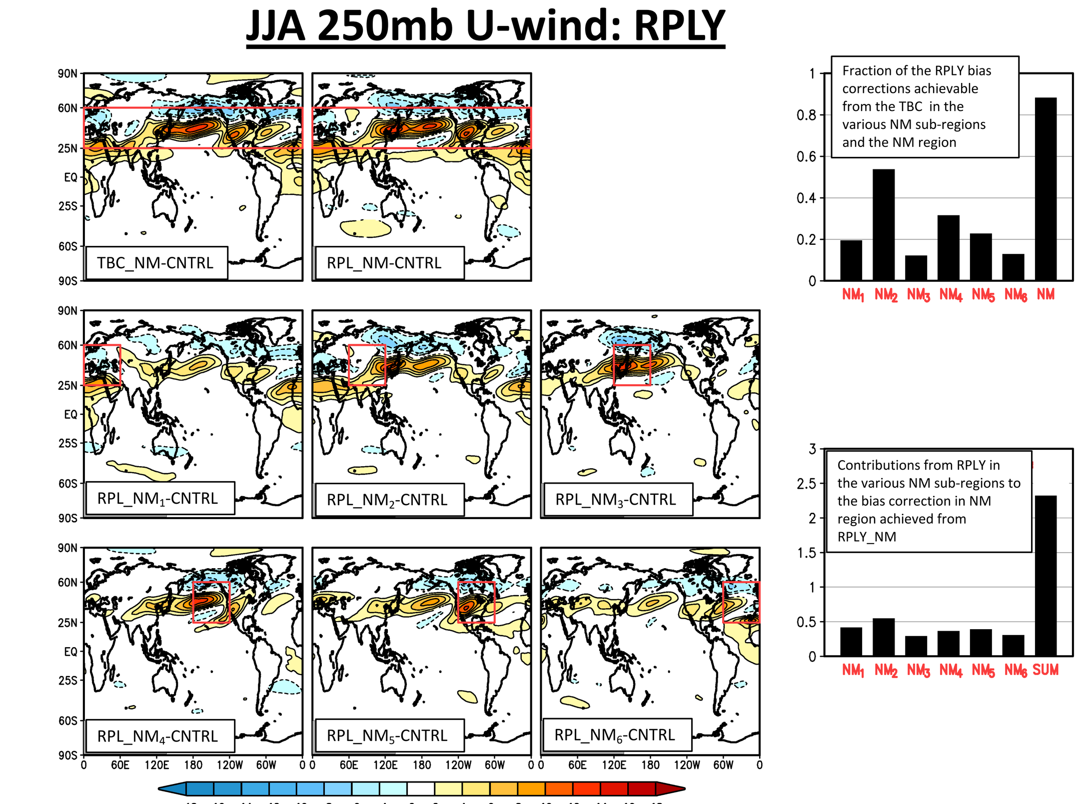

Figure 7: Results for the NM RPLY experiment (second from left upper panel) for the JJA 250mb u-wind. For comparison, the upper left panel shows the TBC results for the same (NM) region. The RPLY experiments for each sub-region (lower left six panels) show what is achievable when the model is forced to track the analysis exactly at every time step in those regions (cf. Figure 3). **Key results: the TBC in NM accounts for > 80% of bias correction possible from RPLY in NM. The TBC in the Tibet region (NM_2) accounts for more than 50% of what is achievable from the RPLY in that region.**

Conclusions

- **regional TBC, as an extension of the global TBC examined in Chang et al. (2018), provides a powerful tool for identifying the sources of model bias, and quantifying their global impacts in global weather and climate models**
- **regional RPLY quantifies what is possible if one could track the analysis exactly in that region. As such, it provides an upper bound to how much of the long-term bias that can be corrected by TBC. More generally, we consider regional RPLY to be a tool for quantifying a model's climate sensitivity**
- **our results indicate that the TBC impacts tend to be linear in the summer hemisphere (the sum of the results of the sub-regions add up to the results for the corresponding larger region). That does not appear to be true for the winter hemisphere (suggesting, in that case, some limitations in the interpretation of the regional results)**

Chang, Y., S. Schubert, R. Koster, A. Molod and H. Wang, 2018: Tendency Bias Correction in Coupled and Uncoupled Global Climate Models with a focus on impacts over North America. Accepted in J. Climate.

Gelaro, R., and coauthors, 2017: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *J. Climate,* 30, 5419–5454, https://doi.org/10.1175/JCLI-D-16-0758.1

Molod, A. M., L. Takacs, M. Suarez, and J. Bacmeister, 2015: Development of the GEOS-5 atmospheric general circulation model: evolution from MERRA to MERRA2. *Geosci. Model Dev.*, 8, 1339-1356, doi:10.5194/gmd-8-1339-2015.

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