Evidence for multiple drivers of North Atlantic multi-decadal climate variability

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[1] Observed North Atlantic Ocean surface temperatures have changed in a non-monotonic and non-uniform fashion over the last century. Here we assess the relative roles of greenhouses gases, anthropogenic aerosols, natural forcings and internal variability to the North Atlantic surface temperature decadal fluctuations using multi-model climate simulations driven by estimates of observed external forcings. While the latter are the main source of decadal variability in the tropics and subtropics, there is a large contribution from the unforced component to subpolar Atlantic variations. Reconstruction of forced response patterns suggests that anthropogenic forcings are the main causes of the accelerated warming of the last three decades while internal variability has a dominant contribution to the early 20th-century temperature multi-decadal swings and recent abrupt changes in the subpolar Atlantic. Significant inter-model spread with regard to the spatial response patterns to anthropogenic forcing leads to substantial uncertainty as to robust attribution statements for the mid-to-late 20th century North Atlantic warm and cold periods. **Citation:** Terray, L. (2012), Evidence for multiple drivers of North Atlantic multi-decadal climate variability, *Geophys. Res. Lett.*, *39*, L19712, doi:10.1029/2012GL053046.

1. Introduction

[2] The recent and future climate evolution of the North Atlantic sea surface temperature (NASST) is emerging as a topic of the highest priority in current climate research due to its influence on wide-ranging climate events such as Arctic seaice loss, African and Amazonian droughts and tropical cyclones [*Trenberth et al.*, 2007]. While future North Atlantic decadal-to-multi-decadal climate change will be driven by a combination of internal variability and anthropogenic as well as natural forcings, the relative importance of these effects is still unclear for the 20th century. The classical view suggests that internal variability can explain to a large extent the early (1900–1975) NASST multi-decadal fluctuations and significantly contribute to its recent (1975–2010) rise in addition to the anthropogenic component [*Ting et al.*, 2009; *Knight*, 2009; *DelSole et al.*, 2011]. However, other studies have proposed a larger role for the externally forced component, whether from volcanic and solar [*Ottera et al.*, 2010] or anthropogenic [*Booth et al.*, 2012] forcing. The latter study, based on one climate model (hadgem2-es), has suggested that improved representation of aerosol-cloud microphysical effects leads to a larger contribution from anthropogenic tropospheric aerosols to 20th century NASST decadal-to-multi-decadal variability. Resolving these discrepancies, (the NASST attribution problem thereafter) remains an important task.

[3] The issue of partitioning forced, either natural or anthropogenic, and internal components is difficult to achieve with observations alone. Ensembles of climate simulations with both individual and combined forcings are needed to isolate and quantify the relative contributions of forced and internal variability. Previous studies using simulated datasets have focused largely on the Coupled Model Intercomparison Project version 3 (CMIP3) results. The purpose of this study is to provide an update of the NASST attribution problem by considering the recent datasets from the Coupled Model Intercomparison Project version 5 (CMIP5) multi-model exercise. In addition to historical simulations ensemble with estimated changes in all external forcings, we also use several attribution experiments where one prescribes the changes in one given forcing while all the others are fixed to their pre-industrial value. Such experiments were scarce in CMIP3 preventing robust attribution studies.

[4] The following questions guide our investigation. What is the geographical distribution of the fraction of total decadal variability explained by the forced and internal components? Do different regional NASSTs have the same evolution over the 20th century (from both observations and models)? Do models agree on the temporal and spatial characteristics of the main forced and internal variability modes? Can we derive an observational constraint to reduce the spread in estimates of both forced and internal variability spatial patterns and time evolution? The remainder of the paper is outlined as follows. The observed and simulated datasets and methods are given in Section 2. Results are presented in Section 3, structured according to the sequence of questions listed above. A discussion and summary are provided in Section 4.

2. Data and Methods

[5] For the observed 1850–2010 global sea surface temperatures (SST), we use the most recent version of the HadSST3 dataset as merged in the HadCRUT4 dataset on a 5° × 5° latitude/longitude grid [*Morice et al.*, 2012]. We consider as ocean grid-points all grid-points having a land fraction less than 25%. Our results are not sensitive to this threshold within the [0–30%] range.

[6] We use multi-model ensembles of simulations performed within the framework of CMIP5 (see Table S1 in

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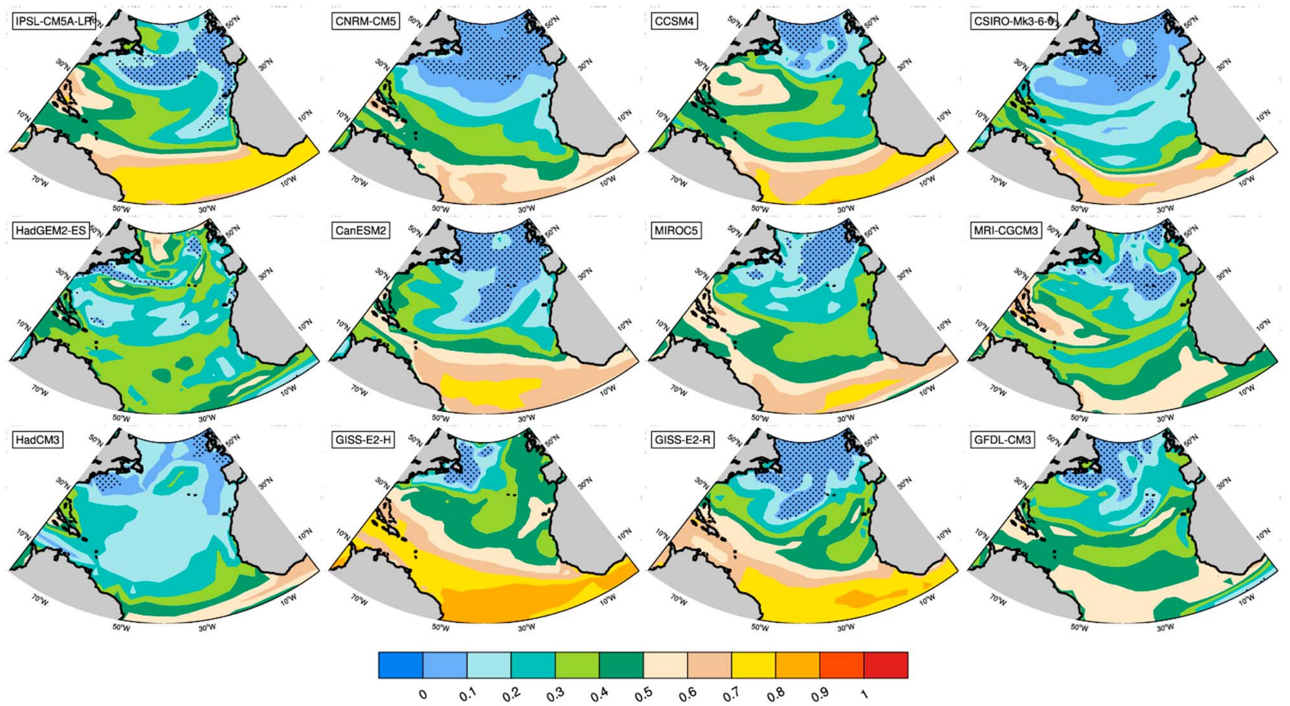

Figure 1. ALL ensemble multi-model ratio (ρ_{LF}) of the externally forced -natural and anthropogenic- variance, σ_{EF} to the total variance, $\sigma_{T,}$ of fluctuations with a period greater than 10 years, estimated over the 1850–1960 period. Stippling indicates regions where the null hypothesis *H0:* $\rho_{LF} = 0$ cannot be rejected at the 5% level using an F-test.

Text S1 of the auxiliary material).[1] Both control (piCTRL) and historical (1850–2005) experiments are used. The latter include the ALL (all external forcings), GHG (greenhouse gases only), AER (aerosols only) and NAT (natural forcings only) ensembles (Table S2 in Text S1 of the auxiliary material). We use the surface temperature variable on the atmospheric model grid and select ocean points using individual model land fraction files and the same threshold as in the observations. All observed and simulated annual mean surface temperature are low-pass filtered to emphasize decadal time scale (see auxiliary material). We define an Atlantic multi-decadal variability (AMV) index (AMV-NA) as the SST anomalies averaged over 0–60°N, 75–7.5°W. We also use two additional SST indexes, using 0–45°N and 45–60° as latitudinal boundaries.

[7] In order to discriminate between forced and internal decadal variability, we use an extension of the classical analysis of variance (ANOVA) methodology to the frequency domain with a cut-off of 10 years as described by *Rowell and Zwiers* [1999] (see auxiliary material). We also use a signal to noise maximizing empirical orthogonal function (SNEOF) analysis to derive our estimate of forced decadal variability [*Allen and Smith*, 1997; *Venzke et al.*, 1999]. It requires a sensitivity test to the truncation level used to confine the analysis to well sampled directions of internal variability (see Text S1 and Figure S3 of the auxiliary material). We then use the optimized first mode as our best estimate of the spatio-temporal pattern of the combined and individual forced response (Figure S2 of the auxiliary material).

3. Results

[8] The ratio of forced to total SST decadal variance (ρ_{LF}) decreases in all models from the tropics towards polar latitudes (Figure 1). This general behavior can be explained from simple arguments relying on the relative efficacy of ocean mixing between low and high latitudes. Model ρ_{LF} estimates exhibit a large spread, in particular in the tropics and subtropics where they can vary by a factor of two. Regions with the lowest ratio are located in the Subpolar Atlantic where the forced variance fraction is usually less than 30% and can be as low as 0–10%. Note that most models have subpolar regions where the null hypothesis *H0:* $\rho_{LF} = 0$ cannot be rejected at the 5% level. The ρ_{LF} geographical distribution suggests that various regional NASSTs decadal changes can exhibit large differences due to the nonuniform influence of external forcings. This provides a cautionary note as to the systematic use of only basin-averaged changes and corroborates the use of regional AMV indexes as was suggested by *Lozier et al.* [2008].

[9] We now investigate the temporal characteristics of observed and simulated AMV indexes (Figure S1 of the auxiliary material). The observed AMV-NA index shows large multi-decadal variability with a cold North Atlantic until 1930 followed by a warm phase ending in the late sixties. An abrupt cooling then precedes the large rise of the last decades. The forced AMV-NA index (here the multi-model mean) suggests that the response to combined external forcings dominates the North Atlantic averaged evolution for

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053046.

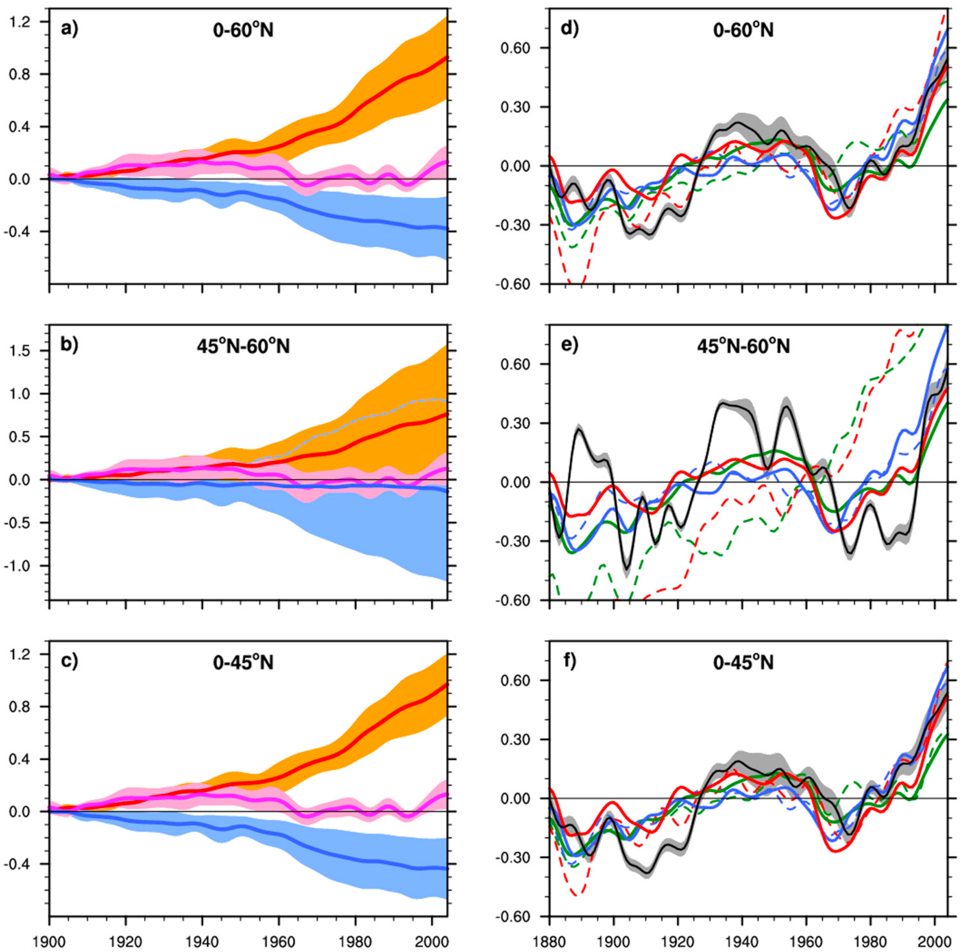

Figure 2. Reconstruction of the forced response contribution to the AMV indexes: (a) 0–60°N, (b) 45°N–60°N, and (c) 0–45°N, from the GHG (red line), NAT (pink line) and AER (blue line) ensembles. Shading represents ±1 standard deviation (s.d) of the appropriate inter-model spread. The dashed blue line shows the AER upper-range. The reconstructed estimates have been scaled to average to 0 over the 1881–1920 period. Note that the Y-Axis range differs between Figure 2b and Figures 2a and 2c. Time evolution of the AMV indexes: anomalous annual mean Atlantic SST averaged over (d) 0–60°N, (e) 45°N–60°N, and (f) 0–45°N, from observations (black line) and combined forcings response (solid color lines) from three models (csiro-mk3-6-0 in green, canesm2 in blue, gfdl-cm3 in red). Dashed lines (same color coding) represent the sum of the individual forcing model response. Anomalies are estimated using the mean of the 1901–2000 period and low-pass filtered. Grey shading represents the observational error as estimated by ±3 s.d of the provided SST 100-sample distribution [see *Morice et al.*, 2012].

the last 30 years. It also contributes to the earlier multi-decadal variability but to a lesser extent in particular at subpolar latitudes, leaving internal variability as the dominant contributor to the NASST increase from 1900 to the 1950s and subsequent decrease. Even the two models (hadgem2-es and gfdl-cm3) having a strong aerosol forced response fail to fully reproduce this steep transition [*Booth et al.*, 2012]. The simulated cooling in response to volcanic eruptions is the precursor of the transition period of the 1960's in the climate models while the latter is delayed by several years in the observations. The forced response inter-model spread accounts for a large part of the total uncertainty, particularly for the last forty years.

[10] We now focus on the other historical ensembles in order to separate as much as possible the contributions of the various natural and anthropogenic forcings to the combined forced response. Applying SNEOF analysis to the GHG, AER and NAT ensembles, we then reconstruct the individual forced responses for the various AMV indexes (Figures 2a–2c). GHG and AER forcings are the dominant and opposite factors of the forced NASST evolution from 1950 onwards. The North Atlantic has warmed by 0.6 ± 0.2 K in the 20th century due to GHG forcing and cooled by 0.3 ± 0.2 K due to AER forcing (with values given by the 1970–1999 averaged anomaly ± 1s.d). The GHG forcing response has similar amplitude in the subpolar North Atlantic compared to the tropical and subtropical regions. The AER response exhibits a large spread [−0.1 ± 0.8 K] in the subpolar region, with four models showing a warming, including a large one by the csiro-mk6-3-0 model. This suggests that some of the model responses in the subpolar north Atlantic are not restricted to direct radiative changes and/or a low

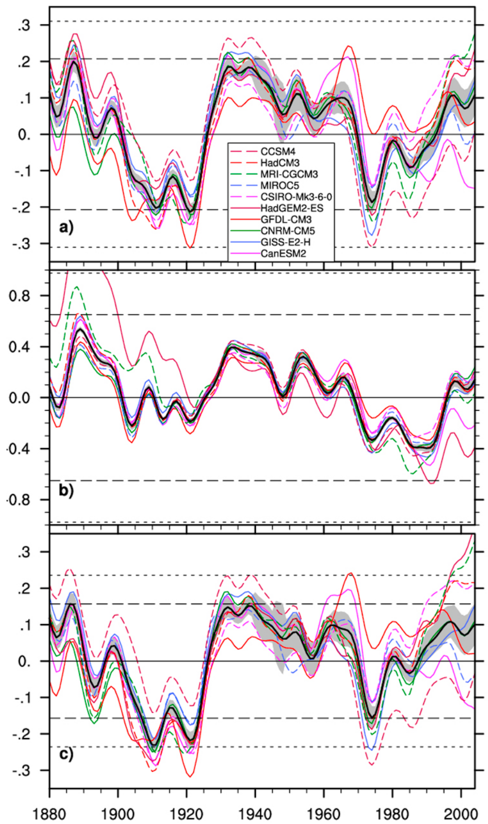

Figure 3. Best-estimate (thick black line) of internal variability contribution to the observed AMV indexes: (a) 0–60°N, (b) 45°N–60°N, and (c) 0–45°N, obtained as the residual of the observed AMV indexes after subtracting the multi-model mean forced component. Thin color lines give individual model estimates. Grey shading indicate ±2 s.d of the observational error. Dashed and dotted lines indicate ±2 s.d and ±3 s.d of low-pass filtered AMV indexes variations purely due to internal variability (from the multi-model piCTRL integrations). Note that in Figure 3b Y-axis range differs from that of Figures 3a and 3c.

signal-to-noise ratio (Figure 1) leading to a biased estimate of the aerosol forced response. The NAT forcing is playing a lesser role on long time scales but does modulate NASSTs by 0.1–0.2 K for almost a decade after major volcanic eruptions.

[11] The linear additivity assumption doesn't seem to hold in the subpolar Atlantic as far as the gfdl-cm3 and csiro-mk6-3-0 are concerned (there is substantial disagreement between the red and green dashed and solid lines in Figure 2e). The nonlinearity of gfdl-cm3 has been linked to cloud-induced dynamical effects in a former model version by *Ming and Ramaswamy* [2009]. Another interesting feature is the change of sign of the nonlinear residual before and after 1960 in both the extended tropics and subpolar latitudes. This appears to be partly related to a much stronger cooling decadal episode (0.5 K) following the Agung eruption in the ALL ensemble compared to NAT.

[12] Comparison of observed NASST and reconstructed all-forcing response (Figure 2d) suggests that anthropogenic forcing is the main factor behind the North Atlantic accelerated warming from 1980 onwards. Note that uncertainty remains as to the forced contribution to the extended (1930–1970) NASST mid-century warm phase amplitude with the source of the spread originating mainly from the GHG and AER forced responses (Figures 2b and 2e). Figures 2d–2f also provides evidence for a substantial role of internal variability in explaining the amplitude and timing of the multi-decadal swings until the 1970's. Interestingly, tropical NASST internal variability seems to be a key player in the cold phase (1900–1930) while subpolar internal variability has the largest contribution to the warm phase (1930–1970) (Figures 2e and 2f). The latter also seems to be the main factor behind the duration of the most recent cold phase (1970s to mid-1990s) in the subpolar Atlantic whose timing is inconsistent with that of a forced response.

[13] The range of internal variability contribution to observed multi-decadal variability can be estimated by subtracting the multi-model mean response pattern to all combined forcings (Figure S2 of the auxiliary material) from the observations. Assuming that the observed multi-decadal variability is not outside the simulated total variability by the ALL ensemble (which seems a reasonable assumption, see Figure S1 of the auxiliary material), the above residual estimate can be compared to the raw internal variability provided by piCTRL simulations. Assuming no interaction between the forced response and internal variability [see *Ting et al.*, 2011], any large discrepancy between these two estimates would suggest an unrealistic forced response. Using individual model forced response provides a consistency metric to reject models having a forced response which is inconsistent with observations and raw internal variability. We thus apply this metric and reject two models (giss-e2-r and ipsl-cm5a-lr) that show large inconsistencies over extended periods of the 20th century. We then use the mean of the remaining ten models as our response pattern best-estimate and individual model responses to represent model uncertainty.

[14] The best estimate of the internal variability contribution to the AMV-NA index shows large multi-decadal variability in agreement with previous studies (Figures 3a–3c). It is always within the two-sigma range of raw internal variability. Individual model excursion beyond that range suggests a strong response to the Krakatoa volcanic eruption and a high transient climate response regional fingerprint. The internal variability contribution does not exceed 0.2 K and is smaller than 0.1 K for the last decades corroborating results by *Trenberth and Shea* [2006] and *Ting et al.* [2009]. Not surprisingly, similar multi-decadal variability is observed for the tropics and subtropics with slightly reduced amplitude. The early-to-mid 20th century sequence of cold and warm phases (from 1900 up to 1970) appears as an extreme of the raw internal variability distribution, particularly in the tropics and subtropics (Figures 3a and 3b). The subpolar Atlantic exhibits large decadal and multi-decadal internal variability with no sign of a long term trend. The internal variability best-estimate is found to be consistent with the raw internal variability. However, a few individual models exceed the two- and even three-sigma threshold after the Krakatoa eruption indicating a likely overestimation of the induced cooling. Internal variability is also an important driver of the cooling observed over the last decades (roughly since the late 1960s up to the mid-1990s) as well as the mid-1990s abrupt warming. Note that the observational error is not negligible, particularly in the tropics and subtropics over the 1940s and

1950s where it represents a substantial fraction of the model uncertainty [*Thompson et al.*, 2008].

4. Summary and Discussion

[15] We have evaluated the contribution of different variability sources to the 20th century NASST evolution using the CMIP5 multi-model results as well as observed data sets. Given that the relative influence of forced versus internal decadal variability greatly varies with latitude, we first suggest that it can be misleading to only analyze North Atlantic averaged SSTs. Using a signal-to-noise maximizing EOF analysis, we suggest that anthropogenic forcing is the main driver behind the recent accelerated temperature rise in the tropics and subtropics. We also identify internal variability as the main driver of subpolar NASST changes. It has a strong contribution to the early century warming during the 1920s and 1930s, the pronounced cold phase from the 1970s up to the mid-1990s and two remarkable abrupt events (Figures 2e and 3b). While the observed NASST rises smoothly in the tropics and subtropics during the last three decades, the subpolar NASST recent evolution is marked by two very abrupt changes: the 1968–1972 cooling event which contributed to the concurrent shift in inter-hemispheric SST difference [*Thompson et al.*, 2010] and the sudden 1995–1996 warming event [*Marsh et al.*, 2008; *Reverdin*, 2010].

[16] The mid 1990s rapid warming has been attributed by *Robson et al.* [2012] to a surge in northward ocean heat transport in the mid-1990s. They argue that this surge was primarily caused by a strengthening of the Atlantic meridional overturning circulation, following the persistent positive of the North Atlantic Oscillation (NAO) index in the late 1980s and early 1990s. They further suggest that at 50°N the components of the ocean heat transport associated with temperature anomalies are dominant. Our results confirm the attribution of this rapid NASST warming to internal variability. They also suggest that, in addition to ocean circulation changes due to NAO forcing, the GHG forcing of the northern subtropical Atlantic SSTs could have contributed to the amplitude of the upper branch of the anomalous ocean heat transport.

[17] The 1968–72 abrupt change was attributed by *Thompson et al.* [2010] to a discrete cooling event in the Northern Hemisphere oceans with the largest amplitude in the subpolar Atlantic. They argue that the short time scale of the NASST drop is inconsistent with aerosol forcing and/or oscillatory multi-decadal NASST variability. While our results agree with theirs as to the prime cause of the drop (internal variability), they also suggest that it was preceded by an earlier one (beginning in 1954–5) of similar duration and reduced amplitude. While this earlier drop could be partially caused by external forcing (likely aerosol and volcanic forcing), a robust attribution statement is difficult because of the forced response spread (Figure 2e). The attribution of the second drop is more robust as the rate of change of the forced contribution is inconsistent with that of the observations. It would be interesting to check whether initialized global coupled models show any predictability of these abrupt events at lead times of one to a few years. First analyses of the CMIP5 decadal prediction experiments already suggest that ocean initialization improves the overall skill over Atlantic mid-to-high latitude areas [*Kim et al.*, 2012; *van Oldenborgh et al.*, 2012].

[18] Characterizing the past evolution of multi-decadal NASST forced and unforced variability remains a challenge due to uncertainties associated with a robust estimation of the forced response and observational uncertainties associated with limited data sampling and evolving measurements and analysis techniques. Thus, in addition to the improvement of observational NASST data sets, there is also a continuing need for better constraining the forced response spatial patterns and reducing epistemic uncertainty. Using physical process-based metrics to discriminate between models would be a difficult but promising first step in that direction.

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