Observed and Simulated Fingerprints of Multidecadal Climate Variability and Their Contributions to Periods of Global SST Stagnation

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(Manuscript received 9 June 2016, in final form 21 September 2016)

ABSTRACT

This study investigates spatiotemporal features of multidecadal climate variability using observations and climate model simulation. Aside from a long-term warming trend, observational SST and atmospheric circulation records are dominated by an almost 65-yr variability component. Although its center of action is over the North Atlantic, it manifests also over the Pacific and Indian Oceans, suggesting a tropical interbasin teleconnection maintained through an atmospheric bridge. An analysis shows that simulated internal climate variability in a coupled climate model (CSIRO Mk3.6.0) reproduces the main spatiotemporal features of the observed component. Model-based multidecadal variability includes a coupled ocean–atmosphere teleconnection, established through a zonally oriented atmospheric overturning circulation between the tropical North Atlantic and eastern tropical Pacific. During the warm SST phase in the North Atlantic, increasing SSTs over the tropical North Atlantic strengthen locally ascending air motion and intensify subsidence and low-level divergence in the eastern tropical Pacific. This corresponds with a strengthening of trade winds and cooling in the tropical central Pacific. The model's derived component substantially shapes its global climate variability and is tightly linked to multidecadal variability of the Atlantic meridional overturning circulation (AMOC). This suggests potential predictive utility and underscores the importance of correctly representing North Atlantic variability in simulations of global and regional climate. If the observations-based component of variability originates from internal climate processes, as found in the model, the recently observed (1970s–2000s) North Atlantic warming and eastern tropical Pacific cooling might presage an ongoing transition to a cold North Atlantic phase with possible implications for near-term global temperature evolution.

1. Introduction

Previous studies have examined epochs in which the global surface temperature observed in the past century has undergone periods of accelerated warming and hiatus periods with little warming (Delworth and Knutson 2000; Easterling and Wehner 2009; Katsman and van Oldenborgh 2011; Meehl et al. 2011). Some studies

(Meehl et al. 2013; Trenberth and Hurrell 1994) have suggested that the accelerated warming in the last third of the twentieth century was largely due to a combination of greenhouse gas (GHG) warming and internal variability.

How global temperature will evolve over the next decade or so remains unclear (Knutson et al. 2016), although the most recent warming hiatus, observed in surface temperature records over the period 1998–2014, has challenged the scientific community in terms of consistency of models versus observations and in the attribution of the phenomena (Kosaka and Xie 2013; England et al. 2014; McGregor et al. 2014; Fyfe et al. 2012). Further, it has triggered discussions of the impacts of related unforced (Chen and Tung 2014) and additional unmodeled forced contributions (Schmidt et al. 2014) on observed climate changes. Recent studies (Kosaka and Xie 2013; England et al. 2014; Meehl et al. 2011, 2013) have attributed the slowdown to a negative

Denotes Open Access content.

Supplemental information related to this paper is available at the Journals Online website: <http://dx.doi.org/10.1175/JCLI-D-16-0443.s1>.

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DOI: 10.1175/JCLI-D-16-0443.1

interdecadal Pacific oscillation (IPO) phase, which has caused anomalous surface cooling over the equatorial eastern Pacific. On the other hand, the model hindcast experiments of Chikamoto et al. (2012, 2015) suggest an important role of the Atlantic multidecadal oscillation (AMO) in predicting the recently observed cooling and associated La Niña SST pattern over the equatorial eastern Pacific.

While model-based results (Meehl et al. 2011) suggest that during hiatus periods the heat is stored in deeper water layers of the Pacific, a recent analysis of observational records (Chen and Tung 2014) points to the Atlantic and Southern Oceans as being important regions for heat storage.

Concerning quasi-oscillatory multidecadal variability, observational studies of SST (Folland et al. 1984, 1986; Schlesinger and Ramankutty 1994; Z. Wu et al. 2011) as well as modeling studies (Ting et al. 2011; Zhang et al. 2007; DelSole et al. 2011) have previously reported on pronounced multidecadal-scale variability (~ 50 – 70 -yr time scale), with a key center of action over the northern Atlantic, contributing substantially to global SST anomalies. Multivariate analysis in Mann and Park (1996) associated these low-frequency SST variations with changes in large-scale atmospheric circulation. Wyatt et al. (2012) and Kravtsov et al. (2014) argued that the propagation (stadium wave) of the observed multidecadal signal through several climate indices can be explained with atmosphere–ocean teleconnections. Scafetta (2013) suggested that several periodic signals in observed global temperature, including a 59–62-yr mode, are caused by periodic astronomical cycles.

A multimillennial preindustrial proxy record of the AMO has been inferred from Greenland ice core records, which are used as a proxy for Greenland surface air temperatures (Chylek et al. 2012). The time scales identified, while multidecadal, were often much shorter than the 70-yr time scale we find in the 150-yr historical record. A similar-scale oscillation, inferred from an analysis of tree-ring reconstruction of air temperature and the instrumental record (Minobe 1997), was suggested to be due to a natural variability of the coupled ocean–atmosphere system. Delworth and Mann (2000) found that a near 70-yr time-scale oscillatory mode, with key centers of action located over the Atlantic, is present in proxy-based reconstructions as well as in simulations of a GFDL coupled atmosphere–ocean model. The relative roles of internal climate variability and radiative forcing in causing the multidecadal variations in the North Atlantic and Northern Hemisphere since the late 1800s remain under debate (Booth et al. 2012; Zhang et al. 2013).

In this study, we compare spatiotemporal fingerprints of low-frequency components dominating

global multidecadal climate variability, represented with recent century observations and a long control climate simulation. The components are extracted with multichannel singular spectrum analysis (MSSA; Allen and Robertson 1996), which, in contrast to the standard principal component analysis, can separate signals by time scale. Here MSSA is used as a spatial extension of the univariate singular spectrum analysis (Ghil et al. 2002; Ghil and Vautard 1991) to extract spatiotemporal climatic patterns. Furthermore, its joint application to surface temperature, pressure, and winds facilitates investigation of the ocean–atmosphere interactions.

In the section 2, we provide information about data and methods applied in the study. In section 3, we present the results of observational (sections 3a–3c) and model-based (sections 3d and 3e) analysis. Results are interpreted, discussed, and summarized in section 4.

2. Data and methods

The observational sea surface temperature (SST) reconstructions used in this study are the Hadley Centre Sea Ice and SST (HadISST, version 1.1; Rayner et al. 2003), the NOAA Extended Reconstructed Sea Surface Temperature (ERSST, version 4; Huang et al. 2015), and Kaplan's extended SST (Kaplan SST; Kaplan et al. 1998) monthly means. The NOAA–CIRES Twentieth Century Reanalysis (20CR, version 2; Compo et al. 2011; available online at http://www.esrl.noaa.gov/psd/data/20thC_Rean/) provides monthly mean estimates of past sea level pressure (SLP) and wind components (U and V). Preprocessing of variables (i.e., SST, SLP, U , and V) involves computing annual and seasonal means for December–February (DJF) and linear detrending using the least squares fit.

Velocity potential is computed from the wind components of 20CR. Linear regression analysis was performed on variables standardized to zero mean and unit variance using F -statistic significance tests. The annual mean AMO index (available online at <http://www.esrl.noaa.gov/psd/data/timeseries/AMO/>) is computed by averaging the monthly values.

A 500-yr control simulation of the CSIRO Mk3.6.0 model (hereafter CSIRO model; Rotstayn et al. 2010), with all forcings fixed at preindustrial (year 1850) levels is analyzed in this study. The model has $1.875^\circ \times 1.875^\circ$ latitude–longitude horizontal atmosphere grid spacing and 1.875° longitude $\times$ 0.9375° latitude ocean grid spacing. The model has 18 vertical levels for the atmosphere and 31 levels for the ocean.

Multidecadal variability of the observed and simulated datasets was analyzed with MSSA (Allen and

FIG. 1. Time series of the linearly detrended global mean SST ($^{\circ}\text{C}$): HadISST, ERSST (ERSv4), and Kaplan SST, version 2 (Kap) and their reconstructions (RC Had, RC ERS, and RC Kap) using the first multidecadal component (RC60). Shown is also a reconstruction derived without prior detrending (RC Kap nodet). SST time series in the figure (but not for the analysis) were smoothed with a 2-yr running mean filter.

Smith 1996; Vautard et al. 1992). MSSA is an extended version of the singular spectrum analysis, searching for spatially coherent temporal patterns. Under an assumption that physical mechanisms have a preferential time scale, this approach is further assumed to extract a signal representing a single, dynamically meaningful mode of variability. MSSA decomposition is based on diagonalizing a matrix, created with vector time series and their M -lagged time series. The lag window applied to the observations is $M = 70$ yr (half length of dataset), and in modeled data $M = 90$ yr, to enable extraction of statistically significant signals with temporal variability on a multidecadal time scale. Sensitivity of the results was tested for the length of the lag window $70 < M < 100$ yr. MSSA was applied jointly to the SST and U , V , and SLP fields interpolated to a $10^{\circ} \times 10^{\circ}$ horizontal grid.

Because of the relatively short length of the time series, compared to the number of spatial channels (grid boxes multiplied with variables), the dimension of the dataset was reduced to the $N = 25$ leading principal component analysis (PCA) components. MSSA was applied to the derived PCA basis, which explains more than 85% of the variance in the data. The significance of the derived components compared against red noise was tested using a chi-squared test. Prior to the PCA analysis, all detrended variables were standardized to zero mean and unit variance. Interannual variability in the model can cause low signal-to-noise ratios; therefore,

variables were additionally smoothed with a 15-yr running mean filter.

3. Results

a. Decomposition of the observed multidecadal-scale climate variability

In this section, we investigate multidecadal SST and atmospheric circulation variations derived from the instrumental record. For this purpose, we have applied MSSA jointly to all linearly detrended and normalized variables: SST, SLP, and wind vectors. This approach has enabled us to extract physically consistent global-scale components, represented by unique spatiotemporal fingerprints. Annually based and seasonal (DJF) analyses of SSTs provide very similar results. The mid-latitude SLP signal is coupled with SSTs mostly in the DJF season, as will be shown below (see the supplemental material for annual means analysis).

Figure 1 shows the first, multidecadal component of the SST variability in the 140-yr record. This component emerges from each analyzed dataset (i.e., HadISST, ERSST, and Kaplan SST), regardless of the detrending method applied. However the peak-to-trough magnitude of variations is sensitive to the choice of dataset and varies between approximately 0.1°C in HadISST and approximately 0.2°C in ERSST. The amplitude tends also to increase over time [e.g., compare the Kaplan SST (version 2) reconstructions with and without prior detrending (RC Kap and RC Kap nodet)], when MSSA (applied to nondetrended data) is allowed to implicitly separate the secular trend.

The first component shows variability on a near 65-yr time scale (RC60). RC60 dominates over the remaining two multidecadal components, varying on about 30–40-yr and 13–15-yr time scales (RC40 and RC15 components). RC60 accounts for approximately 31% of global mean SST variance (smoothed with a 3-yr running mean filter), compared to RC40 and RC15, which together explain only approximately 6% of variance (Fig. S1 in the supplemental material).

The RC60 global mean time series accounts for most of the prominent multidecadal detrended global SST swings seen in Fig. 1. With its near 65-yr period, the component captures two cycles that comprise two cooling periods in the 1880s–1910s and 1940s–70s and two warming periods in the 1910s–40s and 1970s–2000s. From the late 1990s–early 2000s onward, SST warming noticeably stagnates. The RC60 index peaked around 2008, 2002, and 2010 in the Kaplan SST-, ERSST-, and HadISST-based analyses, respectively, and has begun to decline since then in Kaplan SST and ERSST.

RC40 (see supplemental material) modulates global SST changes to a lesser extent (Fig. S1). It intensifies warming and cooling rates in the early and midtwentieth century (1910–40 and 1940–70). It also reduces the warming rate in the 1990s, contributing to the recent observed global SST warming slowdown. The impact of RC15 on decades-long SST changes is negligible in our analysis.

Overall, RC60 emerges as the most prominent multidecadal component in all analyzed SST datasets, regardless of prior detrending approach. Nevertheless, the sensitivity of the RC60's amplitude to detrending approaches reinforces the notion of uncertainties that can arise while attempting to separate long-term variability components in a relatively short dataset (Zhou and Tung 2013; Z. Wu et al. 2007).

RC60 relatively dominates the global SST multidecadal variability (apart from a long-term trend component) and thus substantially contributes to the three decadal-scale hiatus periods in the SST record. The recent stagnation phase, which RC60 features since the late 1990s, could be indicative of an ongoing transition to a cooling phase, provided that RC60 represents a true mode of internal climate variability and its evolution over the coming decade or two mirrors that of previous such variability periods in the record.

Thus, it is of great interest to assess the physical significance of the RC60 component. Many previous studies have already reported distinct multidecadal variability in global climate (e.g., Schlesinger and Ramankutty 1994; Z. Wu et al. 2011; S. Wu et al. 2011; Wyatt et al. 2012; Scafetta 2013; Kravtsov et al. 2014). However, different views on the physical nature of the identified phenomena have yet to be reconciled. Therefore, in the remaining sections we will investigate the spatiotemporal features, associated mechanisms, and possible origin of RC60.

b. Spatiotemporal fingerprints of the dominant multidecadal climate variability

In this section, we show that the derived multidecadal component, RC60, describes a physically consistent and spatially coherent temporal pattern of coupled SST and atmospheric circulation variability. The quasi-oscillatory nature of RC60 allows us to describe it in a frame of four typical phases, which depict contemporaneous changes in SST, SLP, and wind vectors. To illustrate the regional evolution of the various variables related to RC60 in a way that emphasizes correlated behavior, as opposed to relative magnitudes in different regions, we present the reconstructed phases in terms of decadal changes in data normalized to unit variance (for reconstructions in physical units, see Fig. S2 in the

supplemental material). Fingerprints derived from annual mean and winter (DJF) analyses are very similar. For the latter one, however, the midlatitude atmospheric signal (SLP) has a more distinguishable structure, as will be shown below (for annual data analysis, see Fig. S3 in the supplemental material).

Figure 2 shows the spatial pattern of the four phases of RC60's cycle, featuring predominantly positive and negative SST changes over the Northern Hemisphere (Fig. 2, phases A and C) and two intermediate phases (Fig. 2, phases B and D). Reconstructed tropical/subtropical changes for SST and SLP during peak phases emphasize the primary importance of a coherent pattern formed by anomalies over the tropical Atlantic and tropical–subtropical Indo–western Pacific and opposite-sign triangular anomalies over the eastern tropical Pacific. The percentage of decadal change in the wind field analysis depicts the tropical Atlantic, the eastern tropical Pacific, and the extratropical Atlantic and eastern Pacific as main centers of action. During intermediate phases, a large region of the tropical ocean is covered with the same-sign SST anomalies, cool in phase B and warm in phase D.

Reconstruction of the RC60 component in physical units (Fig. S2) accounts additionally for spatial differences in overall variance. This reconstruction emphasizes mid-to-high-latitude SLP variations and SST variability over the North Atlantic, with maxima in the vicinity of Greenland and the tropical Atlantic.

During the warming phase over the Northern Hemisphere (Fig. 2, phase A, referred to here as a positive phase), SSTs over the eastern tropical Pacific show a cooling tendency, centered near 120°W. Warming SSTs in the tropical Atlantic and western Pacific develop along with cyclonic circulation tendencies, while cooling SSTs in the tropical eastern Pacific (TREP) are accompanied by anomalous anticyclonic tendencies. Consistent with anomalous cooling in the eastern tropical Pacific, surface wind fields show strengthening divergence anomalies [easterly (westerly) anomalies west (east) of about 120°W].

Concurrent with these anomalous circulation features are pronounced changes over the Southern Hemisphere, featuring intensified cyclonic and westerly anomalies along the polar jet stream belt (at 60°S). However, this region has generally poorer data coverage over the twentieth century than the Northern Hemisphere mid-latitudes and so is relatively more dependent on a model to fill in missing information.

Phase B in Fig. 2 illustrates the intermediate phase between warming and cooling in the Northern Hemisphere. Principally, cold anomalies extend over most of the tropical ocean. At this stage, the circulation (SLP) anomaly tendencies form dipolelike structures over the

FIG. 2. (top)–(bottom) Four phases (A, B, C, and D) of RC60 based on DJF data. Shown are decadal changes [$\times 100\%$ decade $^{-1}$] in (left) SST (shaded) and SLP [contours (contour interval: 3% decade $^{-1}$), with solid (dashed) lines for positive (negative) values] and (right) zonal wind component (shaded), wind vectors, and wind speed (contours; contour interval: 3% decade $^{-1}$) anomalies at the model 0.995-sigma level. Values are represented with trend coefficients derived from data normalized to unit variance for 10-yr data blocks and are multiplied by a factor of 10 to signify change over the decade.

North Atlantic and North Pacific. In the North Atlantic are weakening midlatitude westerlies and northeasterly trade winds. The weakening tendencies of trade winds over the North Atlantic extend westward into the eastern Pacific. The circulation in the Southern Hemisphere shows pronounced changes, featuring a weakening polar jet stream and strengthening subtropical westerlies, denoting an equatorward shift of the westerlies.

Phases C and D describe phases with tendencies generally opposite to those described in the phases A and B, respectively, and are shown for completeness in Fig. 2.

The above reconstructed phases of RC60 variability depict physically consistent relationships between SST and atmospheric circulation centered over the North

Atlantic and global tropics. In brief: changes of SST and SLP over the North Atlantic influence the meridional SLP gradient, and the corresponding location and intensity of midlatitude westerlies. Changes of SSTs in the tropical and extratropical North Atlantic are mirrored by changes throughout the western Pacific and Indian Oceans, but with opposite-signed changes in the eastern tropical Pacific. The apparent tropical SST seesaw in phases A and C of Fig. 2 is synchronized with anomalous changes in a pantropical circulation, discussed below.

As the spatiotemporal patterns (Fig. 2) of the extracted component are complex, we will summarize its tropical evolution in Fig. 3a using regional SST and atmospheric circulation time series, reconstructed in the

FIG. 3. (a) Time series of the normalized HadISST and zonal winds U anomalies (%), and the regional SST, SLP, and U reconstructions with RC60. Reconstructed SST (solid lines) and SLP (dashed lines) are shown for the tropical Atlantic (TR Atl: 0°–10°N, 50°–30°W; blue lines) and the tropical eastern Pacific (SST TREP: 0°, 140°–90°W, and SLP TREP: 20°S–20°N, 150°–120°W; red). Reconstructed U is shown for the tropical central-eastern Pacific (U TREP: 0°–10°S, 170°–150°W; dashed black). Time series show changes standardized to zero mean and unit variance. (b) Time series of SST (°C) from HadISST over the North Atlantic (HADISST NA; black line) and its reconstruction with RC60 for the NA (40°–50°N, 20°–50°W; blue), NP (30°–40°N, 170°–190°W; green), and TREP (0°, 130°–90°W; red). Also shown is the AMO index (light blue).

original time space. Consistently with Fig. 2, changes in the tropical SST and SLP are locally anticorrelated. Reconstructed warming (cooling) observed in the 1920–40s and 1970–90s over the North Atlantic (tropical eastern Pacific) corresponds to the strengthening of cyclonic (anticyclonic) circulation and zonal wind changes in these regions. The positive SLP anomalies in the tropical eastern Pacific are clearly associated with strengthening of easterlies (westerlies) eastward (westward) from 120°W. The multidecadal changes in the zonal winds account for 21% of the observed zonal wind variance (using a 5-yr running mean filtered dataset). An apparent relationship between reconstructed SST and zonal winds is also seen in the original datasets (Fig. 3a), with a correlation of 0.67, suggestive of a wind–evaporation–SST (WES) feedback.

In Fig. 4, we examine changes in observed DJF velocity potential from 20CR associated with the RC60 evolution. Changes in the inferred large-scale tropical convection anomalies and large-scale tropical divergent circulation are shown via a regression of the seasonal anomalies of velocity potential at the 850- and 200-hPa level on the RC60 time series reconstructed for the North Atlantic SSTs. Warming observed in the tropical North Atlantic is physically consistent with the anomalous large-scale low-level convergence and high-level divergence tendencies, indicative of strengthened convection in this region. Cooling in the tropical central Pacific is associated with a relative subsidence tendency or suppressed convection tendencies in that region. The global-scale multidecadal climate variations shown here suggest a tropical teleconnection between the Atlantic

FIG. 4. Regression of DJF velocity potential at (left) 850- and (right) 200-hPa levels on the index of reconstructed SST with RC60 over the North Atlantic (30°–70°N, 60°W–0°). Shown are values significant at the 10% significance level using an F test.

and Pacific maintained through an atmospheric bridge mechanism. This is consistent with several recent studies (Kucharski et al. 2011; Li et al. 2016; McGregor et al. 2014; Zanchettin et al. 2016), which have suggested such a link between the tropical Atlantic and eastern Pacific as an important component of global SST low-frequency variability.

Relationships between SST indices, reconstructed for the North Atlantic, North Pacific, and tropical Pacific, are depicted in Fig. 3b. SSTs in the North Atlantic region almost replicate the AMO index (correlation coefficient of 0.94) and account for a large portion of the analyzed SST variance (26%, or 46% of 3-yr moving average filtered data) in this region. Evolution of the SST reconstructed over the central North Pacific (30°–40°N, 170°–190°W) shows similar tendencies but lagged approximately 2–5 yr. The tropical eastern Pacific index is roughly opposite in phase to the North Atlantic (NA) and North Pacific (NP) region tendencies.

The lag relationship between the North Atlantic and North Pacific multidecadal SST variability has been investigated, and to a large extent reproduced, using GFDL CM2.1. Zhang and Delworth (2007) prescribed an AMO-like signal over the North Atlantic, which led to a 3-yr lagged response in the North Pacific SST. The response was obtained mainly through an atmospheric Pacific–North American (PNA) teleconnection pattern. Their proposed explanation was that enhanced northward oceanic transport during the warming AMO (warm North Atlantic) phase weakens and shifts poleward the midlatitude westerlies over the North Atlantic. This leads to the positive PNA pattern with the positive SLP anomalies in the Aleutian low region, which shifts the Kuroshio northward and warms SST in the central and western North Pacific. This explanation is also consistent with the reconstructed (RC60) changes in atmospheric circulation (i.e., weakening of midlatitude westerlies and weakening of Aleutian low during the warming phase, phases A and B in Fig. 2).

The second component from the MSSA analysis, RC40, is shown in the supplemental material (Fig. S1). It has notably different spatial features than RC60 and modulates observed climate variability to a lesser degree. RC40 manifests itself in the Pacific Ocean, with main action centered (see Fig. S4 in the supplemental material) along the Kuroshio Extension and in the eastern tropical Pacific. Reconstructed SST variations form a spatially coherent “horseshoe” pattern, identified also in many previous studies (Newman et al. 2016; Nakamura et al. 1997; Power et al. 1999; Mestas Nuñez and Enfield 1999; Barlow et al. 2001; Seager et al. 2004; Deser et al. 2004; Vimont 2005; Alexander et al. 2008; Chen and Wallace 2015). These SST features,

accompanied by changes in atmospheric circulation, resemble prominent patterns of Pacific climate variability, such as IPO (Power et al. 1999; Deser et al. 2004) or PDO (Newman et al. 2016; Zhang et al. 1997; Mantua et al. 1997). The RC40 component extracted here represents, however, a narrow spectral band of Pacific variability, and its impact on the global SST changes is less prominent, compared to the RC60 component. Hence, we will focus our primary attention on the RC60 component in this study.

c. Regional contribution of the low-frequency components to the observed hiatus periods

In the following section, we discuss the relative importance of RC60 for global SST changes and its regional contributions to the historical hiatus periods.

As shown in Fig. 1, the RC60 SST reconstructed component accounts for most of the major low-frequency (nontrend) changes in global SST, including all three major temperature stagnation periods (1880–1900s, 1940–60s, and 1990–2010s). Regional analysis of the component (Fig. 3) points to the North Atlantic as a major contributor to these changes. RC60 over this region (10°–50°N, 60°–10°W) explains approximately 31% of global HadISST variance (linearly detrended and smoothed with 3-yr moving average filter). The RC60 SST index for the eastern tropical Pacific is approximately in antiphase with Atlantic SSTs and also shows a relationship with global SST. For example, during the first two hiatus periods (1880s–1900s and 1940s–60s, Fig. 3b) the RC60-reconstructed strong cooling tendency over the North Atlantic was accompanied by an SST minimum in the tropical eastern Pacific (see Fig. S5 in the supplemental material and Fig. 3a, dat SST TREP and SST TREP). In the current hiatus period (2000–10), SST records and their RC60 reconstruction show predominantly strong cooling over the eastern tropical Pacific (1980s–2010s) but close-to-zero trend over the North Atlantic. These results suggest that climate variability originating from both the Atlantic and Pacific regions influences multidecadal changes in global SST and can help account for the global warming slowdown periods.

The statistical links between the tropical North Atlantic and eastern tropical Pacific, as shown by the RC60 analysis, points to a possible remote influence of the North Atlantic on the eastern Pacific via an atmospheric bridge or teleconnection pattern. Interactions between these two basins suggest that eastern tropical Pacific multidecadal variability, although often described with a PCA-based IPO index, is modulated to some degree by the North Atlantic multidecadal variability.

FIG. 5. Time series of the CSIRO model SST ($^{\circ}\text{C}$): (left) global mean (60°N – 60°S ; blue) and CSIRO model SST with the RC CSIRO80 component removed (CSIRO SST – RC CSIRO80; black) and its reconstruction with RC CSIRO50 (red). (right) Regional mean SST for the North Atlantic (SST NA 30° – 70°N ; black) and its reconstruction with the RC CSIRO50 component (red). The time series of CSIRO SST NA 30° – 70°N is also shown with centennial-scale variability removed.

The intrinsic time scale of RC60 as well as its spatiotemporal pattern over the North Atlantic, which strongly resembles the AMO features, suggests that it might originate partly from internal climate variability. Such an assumption would further suggest an interpretation that the RC60 component is currently undergoing a transition from warming or intermediate phase (phase A or B) to the cooling (phase C) phase, which will feature a negative shift in tendencies over the North Atlantic and North Pacific.

The derived oscillatory components could potentially have some predictive utility, for example suggesting that the multidecadal cooling region over the eastern Pacific may last for the next decade. However, the relatively short length of the analyzed datasets makes it very difficult to infer mechanisms of the derived oscillation or make confident predictions. The physical significance and the origin of the multidecadal component will be further explored in the next section using a control run of the CSIRO model.

d. Reconstruction of multidecadal-scale climate variability in the CSIRO model

In this section, we analyze multidecadal internal climate variability, as simulated with the CSIRO model. The 500-yr control simulation climate with greenhouse gases and aerosol components held fixed at preindustrial levels is analyzed with MSSA, as was done with the observations. The model output (including all months) was additionally smoothed with a 15-yr moving average filter prior to the analysis. As the result, the method extracted two multidecadal components of coupled SST and atmospheric circulation

variability. These components are statistically significant (at the 95% confidence level) and almost insensitive to the values of $80 < M < 100$ yr.

The spatiotemporal fingerprints of the derived annual components closely resemble the observations-based components. However, in contrast to the observations, both modeled components have a substantial contribution to global SST variations. The first (Fig. 5, left) reconstructed mode of variability, with a time scale of 48–53 yr (RC CSIRO50), accounts for $\sim 29\%$ of global SST variance. The second component shows variability on a longer time scale (77–83 yr; RC CSIRO80), and explains about 18% of variance. Subtracting the second component from the global SST (CSIRO model SST – RC CSIRO80) illustrates the smaller influence of that mode (Fig. 5, left).

These modeled components, similar to the observations, differ in respect to their regional contributions. Action of RC CSIRO50 is centered over the North Atlantic. RC CSIRO50 clearly dominates SST variability in this region (Fig. 5, right), explaining about 40% of SST variance (30° – 70°N , 50° – 20°W). It manifests also over the eastern tropical Pacific, accounting for about 18% of SST variance in this region (20°S – 0° , 130° – 90°W), which is a similar fraction, compared to RC CSIRO80 (23%). Nevertheless, regarding the whole tropical Pacific (20°S – 20°N), RC CSIRO50 accounts for a much smaller fraction of variance (19%) compared to RC CSIRO80 (35%).

The Pacific region is clearly dominated by RC CSIRO80 (Fig. S7 in the supplemental material) and shorter-time-scale activity. These components resemble to a large extent the pattern of the IPO-type component

FIG. 6. (top)–(bottom) Four phases (A, B, C, and D) of the near 50-yr oscillatory component (RC CSIRO50) in CSIRO model. Shown are trend coefficients derived from normalized to unit variance [$\times 100\%$ decade $^{-1}$]: (left) SST (shaded) and SLP [contours (contour interval: 3% decade $^{-1}$), with solid (dashed) lines for positive (negative) values; Pa decade $^{-1}$] and (right) zonal wind component (shaded), wind vectors, and wind speed at 925 hPa (contours; contour interval: 3% decade $^{-1}$). Trend coefficients are derived from 10-yr data blocks and are multiplied by a factor of 10 to signify change over the decade.

(Fig. S4) and together substantially contribute to the global SST variance. However, the observations-based results indicate a clear dominance of the AMO-type component, for global and North Atlantic temperature variability, which motivates us to focus on its model-based counterpart (i.e., RC CSIRO50).

Figure 6 shows the spatial pattern of four phases of RC CSIRO50's cycle, described with anomalous SST variability and associated large-scale atmospheric circulation (for reconstruction in physical units, see Fig. S6 in the supplemental material). Analogous to observational analysis (Fig. 2, phase A), phase A in Fig. 6 describes the warming phase, featuring warming SSTs in

the Northern Hemisphere and cooling SSTs in the eastern tropical Pacific. These anomalies are accompanied by development of positive SLP anomalies in the vicinity of Greenland and the Aleutian low in the North Pacific and, correspondingly, weakening and poleward shift of midlatitude westerlies.

The space–time evolution of RC CSIRO50 (Fig. 6) in general shows physically consistent patterns of SST and atmospheric variability, which closely resemble those of observations-based RC60 (Fig. 2). Prominent features of the component include strong SST and atmospheric variability over the tropical Atlantic and meridional modulation of midlatitude westerlies over

the North Atlantic. A second major feature of the component is an apparently coupled tropical ocean–atmosphere connection between the Atlantic and Indo–western Pacific and the eastern Pacific regions. Consistent with observations, changes in SST and atmospheric circulation over the Atlantic and Indo–western Pacific are out of phase with the eastern tropical Pacific. Pronounced SST changes in the vicinity of 120°W are accompanied by anomalous zonal winds in the central and eastern tropical Pacific. The physical linkages making up the derived interbasin connection are discussed in the following section.

Phase B in Fig. 6 depicts the transition between the warming and cooling phases in the Northern Hemisphere and resembles to a large extent observational results (Fig. 2, phase B). This phase features warming SSTs in the tropical Atlantic, in the vicinity of Greenland, and along the Kuroshio Extension. SSTs in the subtropical western North Atlantic and Pacific develop cooling anomalies. Cooling SST tendencies, observed during phase A in the tropical southeastern Pacific, intensify and extend to the eastern North Pacific, but are not as pronounced throughout the tropics as in the observation-based component (Fig. 2, phase B). Similar to the observations, an anomalous atmospheric circulation over the North Atlantic and North Pacific develops with weakening midlatitude westerlies and strengthening northeasterly trade winds.

The strongest cooling tendencies in phase B of Fig. 6 are located in the tropical southeastern Pacific (20°–10°S, 120°–90°W), collocated with intensifying southeasterly trade winds extending over the central and eastern subtropical Pacific (with maximum located in 0°–20°S, 150°–120°W). Concurrently, the midlatitudes of the Southern Hemisphere manifest a strengthening and poleward shift of westerlies. Phase C in Fig. 6 describes, inversely to phase A in Fig. 6, the negative temperature tendency or cooling phase, featuring cooling SST anomalies in the Northern Hemisphere and warming in the tropical southeastern Pacific. These changes are accompanied by anticyclonic circulation tendencies in the tropical Atlantic with weakening southeasterly trade winds in the southeastern Pacific. Phase D in Fig. 6 shows the opposite of phase B in Fig. 6: the transition between negative and positive phase.

Overall, the reconstructed cycle of RC CSIRO50 depicts a coherent pattern of variability between the North Atlantic and North Pacific, with a strong anticorrelation between the tropical and North Atlantic and the tropical eastern Pacific (TREP SST: 10°–20°S, 130°–100°W). Midlatitude SSTs in the North Atlantic (30°–70°N) are lagged by the tropical Atlantic (0°–20°N, 50°–20°W) by 6–7 yr (not shown), while SSTs and atmospheric circulation anomalies in the tropical Atlantic

are anticorrelated (lag = 0) with climate changes in the TREP region. RC CSIRO50 accounts in the TREP region for about 20% of SST variance (amplitude reaches $\sim 0.09^\circ\text{C}$). This is consistent with our observational analysis and further suggests an important role for the North Atlantic in shaping multidecadal-scale climate variability over the tropical Pacific.

e. Regional contribution and physical interpretation of multidecadal component RC CSIRO50

In this section, we discuss possible mechanisms and dynamical pathways associated with the derived RC CSIRO50. Analysis of the component's relationship with the ocean subsurface fields provides additional insights into the dynamical aspects and origin of the component. Regression of the component onto atmospheric fields facilitates physical interpretation of a tropical teleconnection between the Atlantic and Pacific basins. In the previous section, RC CSIRO50 has been described as a global-scale pattern of internal coupled SST–atmosphere variability resembling to a large extent the observations-based RC60 component with strong influence on North Atlantic and global SST multidecadal variability.

Further analysis of the modeled variability, incorporating the Atlantic subsurface fields, suggests a physical connection between RC CSIRO50 and the Atlantic meridional overturning circulation (AMOC). Figure 7 shows that the coupled SST–atmosphere changes associated with RC CSIRO50 correlate to AMOC variability. Figure 7 shows composites of multidecadal changes in the model's AMOC, corresponding to the four phases (Fig. 6) of RC CSIRO50's cycle. The reconstructed Atlantic SSTs are physically consistent with changes in the model's AMOC. The warming phase (Fig. 6, phase A) over the North Atlantic corresponds to an intensified mean overturning circulation, featuring increasing northward flow in the upper levels (0–2500 m) and southward flow in the lower levels (phase A; Fig. 7, top). The intermediate phase (phase B; Fig. 7, middle top) shows anomalous circulation tendencies in the whole water column in the midlatitudes (40°–50°N). This phase evolves further to the cooling phase, which features weakening of the mean overturning circulation (phase C; Fig. 7, middle bottom). Multidecadal changes of the maximum streamfunction exceed 1 Sv decade^{-1} ($1\text{ Sv} \equiv 10^6\text{ m}^3\text{ s}^{-1}$), corresponding to a peak-to-trough amplitude of approximately 2.5 Sv of change. This accounts for a substantial fraction ($\sim 10\%$) of the long-term mean AMOC in the CSIRO model.

Figure 8 shows the regression of tropical North Atlantic surface and subsurface (400 m) temperature anomalies onto the SSTs reconstructed with RC CSIRO50 in the same region. A strong anticorrelation between surface and

FIG. 7. Composites of changes in an annual zonally integrated meridional overturning streamfunction (Sv decade^{-1}) in the Atlantic Ocean (north of 30°S) corresponding to the (top)–(bottom) four phases (A, B, C, and D, as in Fig. 6) of RC CSIRO50. Long-term mean of the model's AMOC maximum streamfunction reaches 23 Sv.

subsurface anomalies as well as the spatial pattern of these anomalies shows a good agreement with observations-based features (e.g., Zhang 2007). These features, as reported in several studies (Zhang 2007, 2010; Wang and Zhang 2013), constitute a distinctive fingerprint of the AMOC and support a central role of ocean dynamics in the AMO (Zhang et al. 2016).

Hence, our observational and model-based results (RC60 and RC CSIRO50) suggest a physical relationship, which synchronizes SSTs, AMOC variations, and SLP circulation anomalies. A linkage between the North Atlantic and North Pacific atmospheric circulation (Fig. 2 for RC60 and Fig. 6 for RC CSIRO50) is depicted as synchronized variability of SLP in the Aleutian and

Icelandic lows. The pattern and variability of SLP over the North Atlantic in the observations-based RC60 component is almost mirrored over the North Pacific. However, in RC CSIRO50 the midlatitude SLP-dipole structure over the North Atlantic is meridionally shifted compared to the observed NAO pattern (Fig. 6, phases B and D), and SLP imprint in the Aleutian low is weaker.

Lagged regression (Fig. 9) of standardized atmospheric surface temperature anomalies (Fig. 9, left, phase A) on an SST index derived for the North Atlantic (30° – 70°N , 70° – 10°W) depicts the warming AMO phase (Fig. 9, phase A at lag = 2 yr, and Fig. 6, phase A), featuring positive SST tendencies extending over the whole Northern Hemisphere. Corresponding SLP anomalies (Fig. 9, left center) show negative SLP tendencies over the tropical North Atlantic, north polar region, and northern Canada and positive SLP tendencies (weakening) of the Aleutian low. A similar pattern was reported by Zhang and Delworth (2007) as a response to the AMO-forced signal prescribed in a GFDL climate model experiment. These results suggest a contribution of the AMO-type variability to the multidecadal-scale changes in the North Pacific via a midlatitude teleconnection maintained through an atmospheric bridge between two basins.

Further results suggest that AMO-type variability may have an important influence on the eastern tropical Pacific climate. An atmospheric bridge, associated with ascending and descending branches of the Walker circulation cell between the tropical Atlantic and Pacific, is the pathway for this teleconnection.

The observed (Fig. 2) and simulated (Fig. 6) anticorrelation between the tropical Atlantic and eastern Pacific climate is physically consistent with large-scale atmospheric features, as represented by low-level and upper-level velocity potential (Fig. 9), water vapor, and precipitation (Fig. 10).

Figures 9 and 10 depict the temporal evolution (with time step of 6 yr) of the atmospheric tendencies between the transition to the warm phase (Fig. 6, phase D) and the transition to the cold phase (Fig. 6, phase B). Figure 9 (lag = 2 yr) shows the warming phase, associated with pervasive warming surface air temperature over the Northern Hemisphere. These tendencies coincide with an anomalous cyclonic circulation, low-level convergence, and high-level divergence, extending eastward from the tropical North Atlantic across North Africa and Europe. Coinciding with these changes are positive anomalies of precipitation and vertically integrated water vapor tendency (Fig. 10) over the tropical North Atlantic, which are indicative of increasing convection and weakening northeasterly trade winds (Fig. 6, phase A).

FIG. 8. Regression of (left) surface ($z = 5$ m) and (right) subsurface ($z = 400$ m) ocean potential temperature anomalies onto the RC CSIRO50 time series over the tropical North Atlantic (0° – 10° N, 50° – 10° W). Prior to the analysis, all variables were standardized to zero mean and unit variance.

At the same time, changes over the tropical eastern Pacific (i.e., anomalous cooling SSTs, anticyclonic circulation, low-level divergence, and high-level convergence) are suggestive of intensifying subsidence. Corresponding to these tendencies are also negative

precipitation changes, which spread from the central-equatorial Pacific toward the off-equatorial southeastern Pacific, along with the strengthening of the southeasterly trade winds. The anomalous large-scale circulation features shown here suggest an atmospheric

FIG. 9. Regression of (left)–(right) surface temperature, SLP, and velocity potential at 850 and 200 hPa on SST reconstructed with RC CSIRO50 over the North Atlantic (30° – 70° N, 60° W– 0°). Regression is based on standardized (zero mean and unit variance) data and for (top)–(bottom) lag = -10 and -4 yr (phase D), 2 and 8 yr (phase A), and 14 and 20 yr (phase B). Values are only shown where they are significant at the 5% significance level using an F test.

FIG. 10. Regression of (left) vertically integrated water vapor and (right) precipitation onto SST reconstructed with RC CSIRO50 over the North Atlantic (30° – 70° N, 60° W– 0°). Regression is based on standardized data (zero mean and unit variance) and lag = 10 yr (phases A and B). Values are only shown where they are significant at the 5% significance level using an F test.

seesaw, which modulates (intensifies) a Walker circulation cell between an ascending air branch over the North Atlantic and a subsiding branch over the tropical Pacific. In the transition to the cooling phase in Fig. 9 (lag = 14 and 20 yr) anomalous low-level convergence and high-level divergence shifts westward, remaining over the tropical North Atlantic region and Central America, corresponding to the neutral state of the Walker circulation cell anomalies. These tendencies evolve further toward weakening of the Walker circulation cell accompanying the cooling phase over the North Atlantic. The transition to the warming phase (lag = -10 and -4 yr) in turn shows a shift toward a strengthening of the Walker circulation cell, as shown in Fig. 9 (lag = 2 and 8 yr).

The analysis presented here is consistent with the recent findings of Li et al. (2016), who designed a model experiment to show that SST changes over the tropical Atlantic can yield a strong anticorrelated response over the eastern tropical Pacific through a tropical atmospheric bridge. Their results explicitly show that Atlantic warming produces anomalous winds over the tropical Atlantic and Pacific, which, through a wind–evaporation–SST effect, modulate the trade winds while a Bjerknes effect leads to a coupled La Niña response and develops into the tropics-wide SST pattern feature.

4. Summary and discussion

This study investigates the main components of global climate variability that contribute to the multidecadal-scale temperature changes, as shown by instrumental records. For this purpose, we performed observational- and model-based analysis using MSSA, which extracts distinct modes of variability based on their spatial and spectral features. Here we summarize our major findings and discuss them in the context of the recently observed global warming slowdown. Application of MSSA to different observational SST records and atmospheric reanalyses allowed us to isolate three spatiotemporal

components shaping observed multidecadal-scale climate variability in the last 140 yr.

The analysis identifies a strong contribution of the first component (RC60) to all three global SST stagnation periods (1880–1900s, 1940s–60s, and 2000s–10s); RC60 also strongly correlates with the AMO index. Primary features of the component (i.e., ~ 65 -yr time scale of variability and a center of action over the North Atlantic) are also consistent with many previous studies (Folland et al. 1984; Schlesinger and Ramankutty 1994; Z. Wu et al. 2011) analyzing SST records. Z. Wu et al. (2011) reconstructed nearly the same mode of variability, with a time scale of approximately 65 yr and with variability concentrated over the North Atlantic, by applying an empirical mode decomposition method (Wu and Huang 2009) to a 150-yr time series of global SST.

The time scale, location of variability, and spatial pattern of this component suggest a link to low-frequency fluctuations of the AMOC. However, the relatively short length of the observed SST records makes it difficult to verify the quasi-oscillatory nature of the derived component. Findings of a similar near 70-yr time-scale mode of variability in longer instrumental records (Tung and Zhou 2013) or proxy-based reconstructions and simulations of surface temperature (Delworth and Mann 2000) support, to some extent, the hypothesis that the derived variability stems from internal processes of the climate system.

The spatial fingerprint of the RC60 component also reveals its contribution to the SST–atmosphere low-frequency variability over the tropical eastern and North Pacific. Its spatiotemporal structure shows that the North Pacific SSTs lag the North Atlantic by several years, while SSTs over the eastern tropical Pacific are in approximate antiphase. Consequently, not only cooling over the North Atlantic but also preceding cooling over the tropical Pacific appears to be related to the three reconstructed global SST stagnation periods (1880–1900s, 1940s–60s, and 2000s–10s). The results suggest that the observed decadal SST stagnation periods

(including the recent pause) stem from more than one climate component (internal variability and/or radiatively forced). Moreover, these components may also have a mutual influence upon each other (e.g., AMO could modulate the IPO and/or PDO by setting the initial stage for their evolution). These findings are in agreement with previous studies (McGregor et al. 2014; Li et al. 2016) highlighting the role of Atlantic warming in enhancing the Walker circulation cell and cooling the eastern tropical Pacific since the early 1990s.

Further analysis shows physical consistency between the SST and atmospheric fields reconstructed with the RC60 component. It also suggests a tropical atmospheric connection as a pathway synchronizing SST variability between the tropical Atlantic and eastern tropical Pacific.

Our model-based analysis demonstrates a substantial agreement between spatiotemporal and physical fingerprints derived from the CSIRO model's internal climate variability simulations and those derived from observations. A multidecadal AMO-type component, derived from the control simulation, is concentrated over the North Atlantic but also extends over the North Pacific and tropical Pacific. The modeled component has also a coupled SST–atmospheric connection between the tropical Atlantic and eastern tropical Pacific. The out-of-phase variability between these regions, found in SST and associated large-scale sea level pressure, high- and low-level velocity potential, surface winds, and precipitation, is indicative of an atmospheric bridge established through a zonally oriented atmospheric Walker circulation anomaly cell.

The proposed mechanism for the AMO–IPO teleconnection, as described here, highlights the importance of the interactive influence of the Atlantic and Pacific climates upon each other. The relationships described here are consistent with recent modeling studies (Wu et al. 2007, 2011; Kucharski et al. 2011; Li et al. 2016; McGregor et al. 2014; Zanchettin et al. 2016) investigating mechanisms causing tropical teleconnections. Kucharski et al. (2011) found a La Niña pattern as a response to a warming imposed on tropical Atlantic SSTs, which was further amplified by coupled ocean–atmosphere processes. McGregor et al. (2014) have shown that recent warming over the North Atlantic strengthened the Walker circulation and led to cooling over the eastern Pacific, as observed in the recent two decades. Li et al. (2016) demonstrated that the warming in the last three decades over the Atlantic induced dipolelike changes with warming over the tropical Atlantic and Indo–western Pacific and cooling over the eastern Pacific. The spatial pattern of SST and atmospheric circulation changes obtained in their study closely

resembles our observations-based and model-based analysis. Kucharski et al. (2016) and Zanchettin et al. (2016) have shown, consistent with our results, that decadal climate variations over the eastern tropical Pacific can be driven by the AMO over the North Atlantic and associated tropical teleconnection between these basins.

The origin of observed multidecadal variability over the North Atlantic and Northern Hemisphere is still a contestable issue and, according to Booth et al. (2012), has been largely produced by time-varying aerosol forcing. Shindell et al. (2015) have shown, based on a suite of CMIP5 simulations, that aerosol forcing may have a strong impact on the air and surface temperature, especially in the Northern Hemisphere. Consistent with this and prior results (Leibensperger et al. 2012), a relatively large time-varying aerosol forcing in the eastern North America and Europe could influence temperatures in the North Atlantic. This regional response could potentially intensify the impact of the warming North Atlantic on the cooling in the eastern Pacific. However, Xie et al. (2010) and Shindell et al. (2010, 2015) have shown that fingerprints of the CMIP5 models' responses to anthropogenic forcing, unlike fingerprints derived from our analysis, have uniform sign over the Atlantic and eastern Pacific. These results do not support the notion of a primarily anthropogenic origin of the multidecadal variability described in our study.

In contrast, our model-based analysis shows a derived near 50-yr variability that is tightly linked to the thermohaline fluctuations over the North Atlantic. Moreover, the relative importance of this component for SST variability over the eastern tropical Pacific is comparable with another, multidecadal-scale component. This further suggests that the AMO/AMOC can indirectly contribute to the low-frequency climate variations in the tropical eastern Pacific region, as suggested in our observational analysis.

Our results suggest considerable importance for the AMOC, as a pacemaker for multidecadal-scale global temperature changes. As shown in our model-based analysis, the derived RC CSIRO50 component has an impact on surface temperatures and hydroclimate over most of the Northern Hemisphere. Because of its time scale, we speculate that it may provide a source for decadal predictability over not only the tropical and North Atlantic but also the tropical Pacific. In this context, Chikamoto et al. (2012, 2015) have found that an initialization in the Atlantic Ocean improves the decadal predictability of the tropical Pacific via atmospheric interbasin coupling.

The RC60 multidecadal component derived from observations shows, in the recent decade (the 2000s),

cooling over the eastern tropical Pacific, local maximum (and thus stagnation) over the North Atlantic, and warming over the North Pacific. Assuming that the observed AMO-type component represents primarily an unforced component of climate variability, we can speculate that the climate system may be encountering a decline in the AMO/AMOC from the maximum in the early 2000s, consistent with that found in a recent study (Robson et al. 2016). The future temporal evolution of global temperature will depend on other factors as well, including long-term trends associated with anthropogenic warming and decadal variations originating from the Pacific, which apparently contributed substantially to the recent global warming slowdown. The role of the AMO/AMOC and associated teleconnections in global climate is a subject worthy of further investigation.

The relative contribution of the leading derived AMO-type component to global temperature variability is much greater in the observations than in the CSIRO model control simulation. According to model-based analysis, both multidecadal components (AMO and IPO type) play comparably important roles. This could be related to the fact (Yuan et al. 2016; Ruiz-Barridas et al. 2013) that most of the CMIP5 models are deficient in simulating AMO variability, especially its tropical branch. Yuan et al. (2016) have concluded that improving the representation of wind speed response and low cloud feedback in climate models would significantly improve their representation of AMO-like variability and associated climate impacts, such as the tropical Atlantic–Pacific teleconnection.

Acknowledgments. We acknowledge support from the Carbon Mitigation Initiative at Princeton University, sponsored by BP. The authors are grateful to Tom Delworth, Liping Zhang, David Paynter, Ka-Kit Tung, and Hans von Storch for helpful comments and discussion. We also thank the three anonymous reviewers for their valuable comments.

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