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The Controlling Mechanisms of the Recent Global Warming Hiatus: A Focus on the Internal Variabilities

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ABSTRACT

A flattening trend of global surface temperature from 1998 to 2013 is generally referred to global warming hiatus. In this review, its basics and controlling mechanisms are the focuses with the latter receiving more attention. The mechanisms for the hiatus are largely derived from internal climate variabilities which could be divided into sea surface temperature (SST) and energy variabilities. The major SST variabilities are Interdecadal Pacific Oscillation (IPO) and Atlantic Multi-decadal Oscillation (AMO). The negative phase of IPO during the hiatus is associated with strengthened Pacific trade winds that enhance subsurface heat uptake, which is generally thought to be the predominant mechanism for the hiatus. Furthermore, AMO influences the global surface temperature at decadal time scales, or even the IPO, which are considered to be the main drivers of hiatus. As for the energy variabilities, vertical uptake and interbasin redistribution of heat are also suggested to be capable of leading to a hiatus period. There was significant warming of global ocean below 700 m during the hiatus as an evidence for the storage of excessive heat in deep ocean. And various heat redistribution patterns like those through ITF or AMOC could also play a significant role in regulating the hiatus.

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was proposed that external forcings are the dominant factor in GMST trend over a century while GMST trend on timescales shorter than a decade is more typically related to internal climate variability. The trend between these two timescales is primarily the result of the interaction between the external forcing and internal climate variabilities (Knutson et al., 2016; Watanabe et al., 2014; Yao et al., 2017).

Miller et al. (2020) utilized a model that makes use of the forcing data over the period from 1850 to 2016 to forecast the next hiatus, and found a multidecadal hiatus between 2023 and 2061, during which the GMST is predicted to grow by only 0.0001°C/yr. The year 2031 and 2061 are respectively identified of the next maximum and minimum of the global SST fluctuation, which is intimately linked to the AMO and caused by the variations of the AMOC (Miller et al., 2020).

THE ROLE OF INTERNAL VARIABILITIES

The oceans are the source of low-frequency variability due to their higher heat capacity, compared to the land and atmosphere. Decadal-scale internal variability can generate GMST trends of about ± 0.25°C and sustain the deviations for decades (Hunt, 2010). Model simulations have shown that internal variability in heat uptake and ocean temperatures could mask the anthropogenic warming trend in GMST over a decade (Palmer et al., 2011).

Nonetheless, the internal climate variability in the model can't be in phase with the observed variability (Risbey et al., 2014), since it is hard to estimate from observations owing to the underlying forced signal and the short record. However, differences between the observations and models can be reconciled if considering the actual internal climate variabilities in the models (Maher et al., 2014; Risbey et al., 2014). But the point to be made here is that an ensemble average of model simulations will, by definition, average out the internal variability leaving only the externally forced response. Therefore, an internally generated signal, such as the strong negative IPO of the early 2000s hiatus, will not show up in an ensemble average of model simulations. However, Meehl et al. (2014, Fig. 1) showed for the CMIP5 model simulations that 10 ensemble members from various models actually, by chance, happened to have their internally generated variability match the randomly occurring internal variability of the observations, with the observed slowdown in global warming during the hiatus comparable to those 10 ensemble members, and the SST signature of those 10 ensemble members showing a negative phase of the IPO as observed. Therefore, the models are capable of simulating hiatus periods with negative IPO, but to actually match what was observed, the model internal variability in a fraction of all ensemble members has to match, by chance, that in the observations. As for the early-2000s hiatus, the primary cause is thought to be internal climate variability rather than external forcings that are quantitatively insufficient to explain the hiatus (Trenberth & Fasullo, 2013; Watanabe et al., 2014; Fyfe et al., 2016).

The hiatus could have continued for another few years due to internal climate variabilities indicated below (Knutson et al., 2016; Roberts et al., 2015). However, the hiatus would have ceased to exist eventually, since those variabilities would reverse phase. More specifically, the warm water subducted through the shallow overturning cells would ultimately re-emerge at the surface of the western Pacific, or the IPO would eventually turn to a positive phase as was the case in 2014.

In a word, the difference of the GMST trend during the hiatus period between CMIP5 models and observations is caused at least in part by internal climate variabilities (Guemas et al., 2013; Meehl et al., 2011; Meehl et al., 2013). And part of the difference is likely the result of the errors in the modeled radiative forcing or the model response to radiative forcing (Santer et al., 2014; Solomon et al., 2011).

SST-RELATED MECHANISM: PACIFIC DECADAL VARIABILITY

AN INTRODUCTION

Except for the global warming trend, leading modes of the unfiltered global SST are ENSO, Pacific Decadal Oscillation (PDO), and Atlantic Multi-decadal Oscillation (AMO). It has been indicated that decadal variability in the Pacific Ocean is largely responsible for this hiatus period in global warming, which is related to a persistent negative phase of the PDO, or more generally the IPO for the whole Pacific, as well as the increase in subsurface ocean heat uptake caused by intensified trade winds associated with the negative phase of the IPO (England et al., 2014).

For example, Dai et al. (2015) performed an EOF analysis for unforced surface temperature variability, including SST over the ocean and surface air temperature over the ocean for 1920 to 2013. The PDO is the leading mode and the fourth mode resembles the AMO. Therefore, the PDO dominates the GMST variability, with a considerable contribution from the AMO. The second and third modes explain more regional variability and therefore do not project onto GMST. The PDO and AMO modes have been used successfully for a reconstruction that reproduced observed GMST, including the hiatus period.

PDO, a mode sometimes called the IPO, is the leading principal component (PC) of low-pass filtered Pacific SST variability (Chen & Wallace, 2015; Zhang et al., 1997). In the following, we will refer to the IPO instead of the PDO. It could also be derived from the leading EOF of decadal global SST variability after the removal of radiatively forced change (Dai et al., 2015). Its tropical climatic signature is a low-frequency El Niño-like pattern that could persist for 2 to 3 decades but much broader in the meridional direction (Zhang et al., 1997). And it modulates the interannual ENSO on decadal time scales.

THE IMPACT FROM THE LA NIÑA-LIKE DECADAL COOLING

The ENSO cycle in the tropical Pacific, capable of influencing GMST, has favored the cold La Niña phase since the 1997/1998 El Niño event. The La Niña-like phase lifts cold equatorial thermocline water to the surface, producing cold SST anomalies in the eastern Pacific persistently.

Meehl et al. (2011) are the first to indicate that the hiatus is related to the La Niña-like cooling pattern representative of the negative phase of the IPO over the tropical Pacific in model simulations and periods of more rapid global warming trends during positive phases of the IPO (Meehl et al., 2013). Models fitting the observed hiatus have depended on La-Niña-like cooling to counteract greenhouse-induced warming (Foster & Rahmstorf, 2011; Lean & Rind, 2008), indicated by an increase of subsurface ocean heat uptake predominantly in the Pacific due to a combination of stronger Pacific subtropical cells, a reduction of Antarctic bottom water formation, and stronger AMOC (Balmaseda et al., 2013; Meehl et al., 2011; Meehl et al., 2013; Watanabe et al., 2013). While the ensemble mean of the CMIP5 models could not simulate a hiatus period because the ensemble mean only represents the externally forced part of the response, examination of each of the CMIP5 ensemble members showed that ten members actually did simulate the hiatus as observed because in those ensemble members the randomly-occurring internal decadal variability happened to match the randomly-occurring decadal variability in the observations (Meehl et al., 2014), though the decadal variability in the tropical Pacific is thought to be somewhat weaker than observed (Drijfhout, 2018).

By prescribing observed SST only over the central to eastern tropical Pacific in a model, Kosaka & Xie (2013) reproduced the GMST remarkably well for 1970–2012, indicating that this hiatus is driven by a La-Niña-like decadal cooling in the tropical Pacific. According to the extra-tropical response to tropical forcings (Seager et al., 2003; Trenberth, 2002), this cooling could have largely impacted GMST, and the phase of the IPO has been shown to directly impact the magnitude of GMST trends (Meehl et al., 2016).

PUTTING FORWARD THE IPO

The phase of the IPO switched from positive to negative around 1999 and began to reverse again after 2012 (Henley et al., 2015). In contrast to global warming periods, the two most recent hiatus both relate closely to the negative phase of the IPO, with strengthened winds and a cool tropical Pacific during its negative phase (Meehl et al., 2016).

Therefore, following the model results of Meehl et al. (2011) and Kosaka & Xie (2013), Trenberth & Fasullo (2013) confirmed with observations that the IPO modulates the global warming rate through changes in ocean heat uptake. The positive phase of the IPO strengthened the surface warming by reducing heat uptake in the deep ocean; and the negative phase of the IPO results in above 30% of heat deposit below 700 m depth mostly over the Pacific, which contributes to the cooling of the ocean surface but overall ocean warming (Balmaseda et al., 2013; Trenberth & Fasullo, 2013).

Observed and simulated global temperature fields have further shown that the IPO was largely responsible for GMST trend since 1920 (Dai et al., 2015; Meehl et al., 2016). And using a numerical simulation since 1900 where tropical Pacific SSTs are forced to follow the observed evolution, Kosaka & Xie (2016) revealed that the tropical Pacific part of IPO is the key pacemaker of the long-term GMST trend that drives the variability in warming rates.

THE ROLE OF INTENSIFIED TRADE WINDS

Associated with the negative phase of the IPO, England et al. (2014) revealed an unprecedented strengthening in the Pacific trade winds that is enough for explaining the cooling in the tropical Pacific during the hiatus. The increased winds caused the enhancing of the subtropical overturning cells, which strengthens the upwelling of the equatorial cold water that enables further cooling in other regions, and subducts a substantial amount of warm surface water into the thermocline thereby enhancing subsurface ocean heat uptake as simulated (Meehl et al., 2011; Meehl et al., 2013; von Känel et al., 2017). Therefore, they confirmed that the ocean heat uptake apart from that corresponding to the cooling, occurred through increasing subduction in the Pacific shallow overturning cells and enhancing heat convergence in the equatorial thermocline.

The La Niña-like decadal cooling is related to these intensified trade winds, indicative of the Bjerknes feedback as in ENSO. Considering this feedback, the pacemaking effect of the equatorial Pacific on the hiatus has been demonstrated by prescribing observed wind anomalies in models (England et al., 2014; Watanabe et al., 2014), instead of restoring SST. Both SST-forced and wind-forced pacemaker experiments reproduce the recent hiatus. The SST restoration generates the intensified trade winds (Watanabe et al., 2014), and similarly the prescribed intensification of the trade wind leads to the cooling in the tropical Pacific. But unlike the SST-restoring method, the wind-forcing method ensures a closed global ocean heat budget (Douville et al., 2015). The fact that the SST-restoring method reproduces the

that this competition is between the anthropogenic warming signal, cooling effect of a strongly negative IPO and slight cooling (or warming) effect of the AMO. Yao et al. (2015) showed more evidence for that the hiatus is the natural result of the interactions between a secular global warming trend largely due to the increase of greenhouse-gas, and internal climate cooling caused by a cool phase of a quasi-60-year oscillation that is closely related to AMO and IPO. Or specifically, Yao et al. (2015) further demonstrated that the AMO and IPO could be recognized as an indicator and a harbinger of GMST trend on multi-decadal timescales, respectively. It was suggested these climate oscillations largely operate without driving longer-term heat sequestration into the deep ocean. Therefore, the drivers of the recent hiatus do not alter the century-scale global warming trend related to the increase of greenhouse gas.

Wu et al. (2019) indicated that both AMO and IPO have a significant effect on modulating GMST trend in the past a century and a half, contributing a combined 30% apart from the residual contributions from greenhouse-gas, with a potential higher contribution from AMO. Moreover, they found that a combined in-phase of IPO and AMO could contribute to global climate significantly larger than greenhouse-gases do, but a combined out-of-phase of IPO and AMO could minimize their contribution to the global climate (Su et al., 2017).

It has thought before that IPO is more responsible for the multi-decadal variation of GMST (Kosaka & Xie, 2013; Meehl et al., 2016; Trenberth, 2015). Nevertheless, it is more recently suggested that on multi-decadal timescale AMO could contribute more to GMST trend compared to IPO, but on decadal timescale IPO leads AMO with comparable contributions to GMST trend. Tung et al. (2019) indicated that IPO consists of different proportions of ENSO, PDO and AMO in the form of linear superposition, relying on the filter threshold. They argued that IPO is mostly AMO as the second EOF of the decadally filtered SST and therefore the contribution to the GMST trend on multi-decadal time scale usually ascribed to IPO is actually by AMO. And extracting the major climate modes with the method of pair-wise rotation of the PCs, Chen & Tung (2017) showed that the Pacific contributes to the GMST trend mostly on interannual timescale through ENSO and the Atlantic contributes significantly on multi-decadal timescale through AMO. However, if the IPO and AMO are mutually interactive as proposed by Meehl et al. (2021b), both would contribute in combination to GMST trends.

THE PERIOD OF THE AMO

Both observations and reconstructions revealed one statistically significant spectral peak in the 50–70 year band of AMO before (Gray et al., 2004; Schlesinger & Ramankutty, 1994; Tung & Zhou, 2013). But a spectral analysis have showed an observed AMO index oscillations in the 70–80 year range in combination with oscillations in the 30–40 year range and shorter periods (Kavvada et al., 2013). It was concluded that models underestimate the period of AMO by increasing variability in the 10–20 year range so that it becomes more dominant than variability in the 70–80 year range.

Ice core data sets have provided observational evidence for two distinct time scales of AMO that are about 20 years and 45–85 year (Chylek et al., 2011). The former time scale is dominant and statistically significant while the latter one is not. It was suggested that the latter time scale may reflect a larger spatial scale mode related to a declined Atlantic meridional overturning circulation (AMOC) or a coupling of the Arctic and Atlantic circulations.

THE MECHANISMS THAT MODULATES THE AMO

In terms of internal climate variability, proposed crucial drivers of the AMO consist of density and salinity fluctuations caused by variations in AMOC (Latif et al., 2004; Medhaug & Furevik, 2011), changes in wind forcing and air–sea interactions (Huang et al., 2011). AMO exhibits a signature of perturbations involving subsurface OHC, SST, salinity and Arctic sea ice.

Long-term observations revealed that the thermohaline circulation variability in the Atlantic possibly causes the AMO (Tung & Zhou, 2013). And several model studies showed that AMOC intensification is followed by a positive AMO phase, albeit with a model dependent lag (e.g. Marini & Frankignoul, 2013). It was proposed that AMO depends on negative feedbacks between the Arctic ice melt responding to the warm SST and the strength of the AMOC that brings warm SST to the North Atlantic (Dima & Lohmann, 2007; Park et al., 2010). The former then slows AMOC after a delay of 20 year with reduced deep-water formation. It has also been simulated a 55 to 80 year AMO arising from the variability of the AMOC (Lohmann & Wei, 2012).

Over the Labrador Sea where deep water forms, fresh water anomalies stratify the ocean layer and thus contributes to the weakening of the deep water formation and AMOC, allowing for the cooling of surface because of the lack of vertical mixing with the warmer subsurface water. Because of this reduction in the heat lost to the atmosphere, this inhibits the deep convection further (Gelderloos et al., 2012). Therefore, generally there are fresh water anomalies and weaker AMOC during the cold phase of the AMO and vice versa. Sun et al. (2015) indicated further that the positive North Atlantic Oscillation (NAO) forces the strengthening of AMOC and induces a basin-wide SST warming that corresponds to the positive phase of AMO, while AMO in turn has a delayed negative effect on the NAO by producing a meridional SST gradient pattern. However, other studies have shown that much of the decadal timescale variability of the AMO is likely externally forced

2014; Kosaka & Xie, 2013; Trenberth & Fasullo, 2013) or the Atlantic (Chen & Tung, 2014) or the Indian Ocean (Lee et al., 2015), or a combination of the Southern, Atlantic, and Indian Oceans (Drijfhout et al., 2014).

FROM THE PACIFIC TO THE INDIAN OCEAN

Considering the effect of the IPO, a significant amount of excess heat is thought to be taken up by the Pacific. Nonetheless, in situ data indicated that heat content in the Pacific has been decreasing (Levitus et al., 2009). Observational data have revealed that the warming in the 100 to 300 m layer of the Western Pacific and Indian Oceans, with the largest contribution in the tropics, is compensated by the cooling in the top 100-m layer of the Pacific (Nieves et al., 2015). Lee et al. (2015) further found that the strengthened heat uptake in the Pacific has been compensated by the increased heat transport from the Pacific to the Indian Ocean through the ITF. They showed heat content in the Indian Ocean has increased significantly, accounting for above 70% of the global ocean heat uptake in the top 700 m over the past ten year. Moreover, Su et al. (2017) demonstrated that the Indian Ocean accounted for around 30% of global ocean heat uptake, playing a particularly important role during the hiatus.

FROM THE PACIFIC TO THE SOUTHERN OCEAN

While numerical simulations, on the other hand, suggested a subsurface warming during the initial phase of the hiatus in the equatorial Pacific (Oka & Watanabe, 2017), enhancing equatorial Ekman transport to subtropical regions in the later phase of the hiatus (after 2002) that causes enhancing the subtropical Ekman downwelling, which further accelerated heat uptake below 700 m in the subtropical Southern Ocean that contributes to the post-2002 hiatus period. These anomalies in the subtropical Southern Ocean have been considered before to have a crucial impact on generating a multi-decadal IPO cycle (Luo & Yamagata, 2001).

Moreover, it was also suggested before that the cold SST anomalies and relevant cooling of the atmosphere in the equatorial Pacific, owing to the negative phase of the IPO, could force extra-tropical stationary waves to strengthen the heat fluxes into the Atlantic and Southern oceans remotely (Trenberth et al., 2014).

TO THE ATLANTIC AND THE SOUTHERN OCEAN

Several studies suggested a westward pathway for the warming signal from the Atlantic to the Pacific through teleconnection, directly intensifying warming in the Atlantic since the early 1990s, with strengthening anomalies of the Walker circulation and La Niña-like Pacific (McGregor et al., 2014; Ruprich-Robert et al., 2017). The robust mechanisms controlling the Atlantic variabilities are still being discussed, salinity driven mechanism is one of the explanations for the increased heat uptake in the Atlantic (Chen & Tung, 2014).

Using updated OHC estimates, Cheng et al. (2017) recently found that the greatest warming during the hiatus is in the Southern Ocean, followed by the tropical/subtropical Pacific Ocean and tropical/subtropical Atlantic Ocean respectively. And by Argo observations, much of the global heat uptake has been accounted for in the Southern Ocean. Besides, as global ocean heat uptake accounted for 75%–99% south of the equator, the Southern Hemisphere Ocean played a significant role in the warming of subsurface layers over the past decade (Roemmich et al., 2015; Wijffels et al., 2016). Specifically, the Southern Ocean is demonstrated to play a secondary role in warming the 100-m to 300-m layer with a steady pace over the past two decades (Nieves et al., 2015).

Chen & Tung (2014) showed by observational data that the hiatus is largely due to heat transported to deeper layers in the Atlantic and the Southern oceans, initiated by a periodic salinity anomaly in the subpolar North Atlantic that affects AMOC. And they showed that the hiatus related to this mechanism of deeper heat-sequestration lasted 20 to 35 years historically. Besides, the increase of OHC (300–1500 m) accelerates in the Atlantic and Southern Oceans but changes little in the Pacific and Indian Oceans. Therefore, their observational results are against the Pacific-centric view (e.g. Hu et al., 2013; Meehl et al., 2011). Chen & Tung (2014) argued that compared with observations, there are too little variability with too high frequency in their model's Atlantic. However, also by observations, Nieves et al. (2015) showed that the Atlantic switched from warming to cooling during the hiatus, but its area was suggested to be too small to contribute to the hiatus significantly.

Using the same observational dataset and analyzing the ocean heat uptake the same way as Chen & Tung (2014) did, Liu et al. (2016) demonstrated that the ocean heat uptake in deep Atlantic and Southern Oceans is not unique to the hiatus but showed the downward penetration of anthropogenic heat through AMOC. It is shown to occur at a similar rate no matter during the hiatus or not and is hence suggested not the dominant factor affecting the GMST trend during the hiatus. Instead, their findings support the Indo-Pacific heat redistribution mechanism (Lee et al., 2015; Nieves et al., 2015).

SUMMARY

The global warming hiatus from 1998 to 2013 is suggested to be largely due to the natural variabilities in the climate system. So this review focused on the proposed mechanisms for the hiatus associated with internal climate variabilities. From the perspective of SST variabilities, the IPO and AMO related mechanisms