A multidecadal oscillation in the northeastern Pacific

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ABSTRACT
The internal modes of the North Pacific can lead to climatic oscillations through ocean–atmosphere interactions and induce global climate responses. The best example is the Pacific Decadal Oscillation, but this fails to explain many climate phenomena. Here, another multidecadal variability over the North Pacific is described, found by analyzing reconstructed data covering the past 140 years. It is named the Pacific Multidecadal Oscillation (PMO), with anomalously high/low SSTs over the northeastern Pacific, and a quasi-60-year cycle. Related to this low-frequency variability of SST, the global mean temperature and precipitation present significant interdecadal differences. More importantly, the PMO index leads the global mean surface air temperature and SST by one to three years. The Arctic Oscillation pattern and atmospheric circulations are shown to change substantially with the transition of the PMO mode from positive to negative phases. This multidecadal oscillation improves the prospect for a long-term forecast of the global warming trend, since the PMO bears a remarkable relationship with global temperature.

1. Introduction
The Pacific Decadal Oscillation (PDO) has been proposed in previous studies as the most significant interdecadal mode in the North Pacific (Mantua et al. 1997; Zhang, Wallace, and Battisti 1997), having significant impacts on the North Pacific and global climate. Fluctuations in the PDO mostly occur over two periodicities: 50–70 and 15–25 years (Mantua and Hare 2002). Independent studies have determined the 50–70-year climate oscillation from instrumental data over the North Pacific and North America (Minobe 1997), and the landing of fish data over the Pacific (Hare 1996; Mantua et al. 1997). Schlesinger and Ramankutty (1994) also indicated that the global climate system has an oscillation period of 65–70 years.

Previous studies have shown three apparent changes (in the 1920s, 1940s and 1970s) that have been labeled as regime shifts; and most studies (Mantua et al. 1997; Schlesinger and Ramankutty 1994) have attributed the regime shifts to the PDO and its impact on marine climate variability. However, the phases of related indices (e.g. the atmospheric circulation index (ACI) and global air temperature presented in Figure 1 of Chavez et al. (2003), as well as the Washington streamflow and Pacific salmon catch records in Figure 5 of Mantua et al. (1997)) do not match the PDO, especially from 1900 to 1945. During this period,
changes occurred in the phases of all the related indices from 1900–1924 to 1925–1947, but the phase of the PDO was the same during 1900–1945. The PDO is related to the overlying Aleutian low; however, the same distinction can also be seen between the North Pacific Index (NPI), which depicts changes in the intensity of the Aleutian low (Trenberth and Hurrell 1994), and the PDO (Mantua et al. 1997). According to Minobe (1997) and Klyashtorin (1998), another important regime shift in the related indices occurred in the 1890s, but the PDO did not change at this time. The landings of sardines vary synchronously off Japan, California, Peru, and Chile (Chavez et al. 2003). However, it remains unclear as to why sardines increase off Japan when the local waters are cool and become more productive, while they increase off California and Peru when those regions are warm and become less productive (Chavez et al. 2003; McFarlane et al. 2002). All of these questions have not yet been answered.

To investigate whether there is another multidecadal mode over the North Pacific that can explain these regime shifts, we examine SST data using EOF analysis, and find that the second mode has a certain multidecadal signal. This mode is similar to the North Pacific Gyre Oscillation (NPGO), or Victoria mode, at interannual timescales (Bond et al. 2003; Di Lorenzo et al. 2008), which possess no such multidecadal oscillation characteristics. Further analysis reveals that the multidecadal signal comes from the area north of 50°N over the North Pacific, rather than NPGO region; and then we define the Pacific Multidecadal Oscillation (PMO) region and index. In terms of the role of the PMO at multidecadal timescales in global climate change, this remains largely unknown. After proving the existence of the PMO, this study focuses on the impacts of the PMO on the global climate system, and the global atmosphere and SSTs.

2. Datasets and methods

The datasets used in the current study include ERSST.v3b, for the period 1871–2010, and with a horizontal resolution of 2° latitude/longitude (Smith and Reynolds 2003, 2004; Smith et al. 2008). The monthly mean SLP data for
1871–2010 are from the Hadley Centre website (http://www.esrl.noaa.gov/psd/data/gridded/data.hadslp2.html), with a horizontal resolution of 5° latitude/longitude (Allan and Ansell 2006). The monthly mean geopotential height, air temperature at 2 m, and precipitation rates, are from the twentieth century reanalysis V2 (Compo et al. 2011), provided by NOAA. Surface air temperatures (CRUTEM3v) are also from NOAA (http://www.esrl.noaa.gov/psd/). The monthly mean SSTs from the Hadley Centre (HADSSST, Rayner et al. 2003), NOAA (KAPSSST, Kaplan et al. 1998) and COBESST, Ishii et al. 2005; Hirahara, Ishii, and Fukuda 2014) and the ECMWF (ERASST, Poli et al. 2013), are also used to support our results, as are near-surface temperatures from the CRU (Harris et al. 2014).

Several climate indices are also used in this study, including: (1) The ACI, also known as the Vangengeim–Girs index, calculated based on atmospheric activity in the Atlantic–Eurasia region (Girs 1974; Hoy et al. 2013; Klyashtorin 1998); (2) The NPI, defined by Trenberth and Hurrell (1994) as an area-weighted SLP average over (30–65°N, 160°E–140°W); (3) The southern oscillation index (SOI), defined as the leading principal component (PC) of winter SLP anomalies over (40°S–20°N, 90°E–140°W) (this SOI is similar to that defined by Trenberth (1984), as the Tahiti pressure minus the Darwin pressure, and the correlation coefficient between the two is as high as 0.81 during 1871–2003); (4) The eastern Pacific wave train (EPW), defined as the volume average of the seasonal vertical wave activity flux in the domain (30–60°N, 170–120°W; 950–500 hPa). This definition of the EPW describes the strength of both the vertical and horizontal fluxes well (Sun and Tan 2013).

In order to obscure the greenhouse warming signal, we assume that the relationship between greenhouse gas (GHG) concentrations and global temperature is linear. We remove the global warming signal of CO2 gas (GHG) concentrations and global temperature is assumed to be a function of time only; cov is the temporal covariance between \( Z \) and \( \xi \); and var is the variance. This method removes the long-term trend of global warming efficiently (figures omitted). To obtain the interdecadal variation of the climate signals, data are low-pass filtered using an 11-year running mean in a convolutional way (Trauth et al. 2007), and the result of the original data minus the low-pass filtered data is used as high-pass filtered data. The same data are also low-pass and high-pass filtered using an FFT filter, and similar results are obtained. Note that the reduced effective degrees of freedom, due to the low-pass filter, have been considered when computing the statistical significance based on a Monte Carlo test. All the data are the original data, unless otherwise indicated as high-pass or low-pass filtered data.

3. Characteristics of the PMO

Consistent with previous studies (Mantua et al. 1997; Zhang, Wallace, and Battisti 1997), the first EOF mode — by applying the EOF to the winter SST anomalies (SSTAs) over the North Pacific (20–65°N, 110°E–110°W) — is the PDO, which explains 22.2% of the total variance. The second EOF mode is similar to the Victoria mode, or NPGO (Bond et al. 2003; Di Lorenzo et al. 2008; Liu 2012), accounting for 17% of the total variance of the winter SSTAs. The global warming signal has been removed from the computation. Both the second EOF (EOF2) mode and the PC related to EOF2 (PC2) are shown in Figure 1. Following the low-pass filtered result of PC2, a number of multidecadal signals are found. Using the high-pass filtered data and low-pass filtered data of PC2 separately to perform correlation analyses with SST, we find that the most dominant interdecadal signal is from the area north of 50°N, and the most dominant interannual signal is from the area south of 50°N over the North Pacific; namely, the NPGO region (Figure 2). The pattern in Figure 2(a) exhibits a northeast–southwest-oriented dipole, which is very similar to the SST regression pattern associated with the NPGO index (Di Lorenzo et al. 2008). And this also proves that the interannual signal is the NPGO. However, the distribution of correlation coefficients between the low-pass filtered PC2 and SST is different to the NPGO pattern, which indicates the interdecadal signal is not the NPGO. Considering the fact that the NPGO has no such long-term cycle about 60 years (Di Lorenzo et al. 2008), and the regions of this interdecadal signal and the NPGO are different from one another, we define this multidecadal signal as the PMO. And the most relevant areas ((50–65°N, 160°E–145°W) and (40–65°N, 145–130°W)) of the low-frequency signal are together defined as the PMO region. The PMO index is then defined as the area-averaged SST over the PMO region. Furthermore, from the time–latitude cross section of the 160°E–140°W zonally averaged SST, we reach the same conclusion that the multidecadal signal of the North Pacific SSTAs lies in the change of SST in the area north of 50°N (Figure 3), which differs from the NPGO.
these four datasets are very similar to the PMO index of ERSST.v3b (Figure S2). All of the datasets yield the same PMO over the northern Pacific, which indicates that the PMO is a real mode in the North Pacific and primarily depicts the variation in SSTs in these regions. The center of the PMO mode is located in the northeastern Pacific, near the Alaska Current and Bering Strait. It can be seen from the corresponding time series that the PMO has a quasi-60-year oscillation during 1871–2010, which appears significant in the power spectrum of the PMO index (Figure 4). Roughly, the periods of 1871–1897, 1923–1948, and 1979–2003 were positive phases, and 1898–1922 and 1949–1978 were negative phases.

The PDO index is defined as the corresponding time series of the first mode (Figure 5(b)) using the method of Mantua et al. (1997). Lead–lag correlation analysis, between the PMO and PDO, yields no significant relationship, suggesting that the PMO and PDO are two relatively independent modes over the North Pacific. Large differences in periodicity exist between the PMO index and PDO index (Figures 5(a) and (b)). The former has only one relatively stable cycle, of around 60 years, while fluctuations are much shorter and less pronounced.

To further distinguish the PMO from the NPGO, correlation analysis is separately performed between the NPGO index (Di Lorenzo et al. 2008, http://www.o3d.org/npgo/npgo.php) and the PMO index and PC2. The results show that only PC2 bears a significant relationship with the NPGO during 1950–2010 (correlation coefficient of −0.6), while between the PMO and NPGO the value is −0.08 (figures omitted). Furthermore, we analyze the differences in the relationships of the PMO and NPGO with atmospheric circulations. The regression maps of PMO and PC2 with geopotential height and horizontal wind (850 hPa) are shown in Figure S1, revealing a significant difference between them. The former exhibits a northeast–southwest-oriented wave train, while the latter is a north–south-oriented dipole that is very similar to the regression map of the NPGO index and SLP, in which the NPGO index defined by Di Lorenzo et al. (2008). All the differences demonstrate that the PMO and NPGO are two different modes.

We also examine the low-pass filtered SSTs of four other datasets over the northeastern Pacific by calculating the area-average of the PMO region. The results obtained from these four datasets are very similar to the PMO index of ERSST.v3b (Figure S2). All of the datasets yield the same PMO over the northern Pacific, which indicates that the PMO is a real mode in the North Pacific and primarily depicts the variation in SSTs in these regions. The center of the PMO mode is located in the northeastern Pacific, near the Alaska Current and Bering Strait. It can be seen from the corresponding time series that the PMO has a quasi-60-year oscillation during 1871–2010, which appears significant in the power spectrum of the PMO index (Figure 4). Roughly, the periods of 1871–1897, 1923–1948, and 1979–2003 were positive phases, and 1898–1922 and 1949–1978 were negative phases.

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The difference between the cycles also proves that the PDO and PMO are two independent modes. Importantly, previous studies (Gershunov and Barnett 1998) have documented that the PDO and ENSO are closely related to one another. They can result in similar climate patterns in the North Pacific (Mantua and Hare 2002). In its positive (negative) phase, the PDO is able to enhance canonical El Niño (La Niña) events (also known as the eastern Pacific (EP) pattern, i.e. EP-type ENSO) (Gershunov and Barnett 1998). Conversely, the PMO bears no significant relationship with EP-type ENSO events; and the patterns related to ENSO and the PMO are totally different, as shown by the correlation between the PMO index and SSTs (Figure S3a), in which there are no large areas of significance in the relationship (like there are for the PDO) over the eastern tropical Pacific (Gershunov and Barnett 1998; Mantua and Hare 2002). Figure S3a shows that the PMO has a significant effect on global SSTs, especially over the west coast of North and South America, the North Atlantic, and the tropical western Pacific. Under the modulating effects of the PMO, the global SSTs present a near uniform distribution pattern, and this may be the reason why the landings in the PDO mostly occur over two periodicities: one of 50–70 years, and the other about 15–25 years. These features are consistent with the results of Mantua and Hare (2002). The difference between the cycles also proves that the PDO and PMO are two independent modes.

Figure 3. Time–latitude cross section of the 160°E–140°W zonally averaged SSTA using (a) the original data and (b) the low-pass filtered data, in which the global warming signals have been removed from the SST data. Note: The black dashed line indicates the 50°N.

Figure 4. Power spectrum of the PMO index shown in Figure 5(a) (line-filled). Note: The red dashed line indicates the 95% confidence level and the PMO index has a significant 60-year period.
of sardines vary synchronously off Japan, California, Peru, and Chile, which cannot be explained by the PDO (Chavez et al. 2003). During the warm (cool) periods of the PMO, the global SSTs increase (decrease), so the interdecadal variability of the landings of sardines is consistent with the PMO over these four places.

4. Evidence of the PMO

The PMO has a strong periodicity, with a cycle of around 60 years. For 25–30 years, the North Pacific SSTs are warmer than average, and in the following 25–30 years they shift to being cooler than average. Minobe (1997) analyzed instrumental data and found that there was a 50–70-year oscillation over the North Pacific and North America (see Figure 1 of Minobe (1997)). It is known, however, that the speed of atmospheric signal dispersion is very fast. As such, the signal generally cannot sustain for 50–70 years. Instead, the ocean has long ‘memory’ characteristics, and the cycle of 50–70 years may be a result of air–sea interaction. Furthermore, the interdecadal variability of temperature over the west coast of North America fits the PMO very well (Minobe 1997). These phenomena prove, to some extent, that the PMO does exist, and has a relationship with climatic oscillations, including the spring air temperatures in western North America, the spring SSTs in the eastern North Pacific, the winter–spring SLPs in the central North Pacific, the spring–summer SSTs at Enoshima, Japan, and the annual mean SSTs in the Indian Ocean Maritime Continent.

There is increasing evidence that marine climate variability can strongly affect populations of Pacific salmon (Beamish and Bouillon 1993; Francis et al. 1998). Furthermore, the landing of salmon also fluctuates markedly — on the interdecadal timescale, with a cycle of about 60 years (Hare 1996; Mantua et al. 1997). Previous studies (Chavez et al. 2003; Mantua et al. 1997) suggest that the PDO might be the reason for the fluctuations in
the landings of these fish, modulating the populations by changing large-scale atmospheric and oceanic patterns. Further examination (see Figures 5 and 6 of Mantua et al. (1997), and Figure 1 of Chavez et al. (2003)) indicates that the phases of the indices and records do not match with the PDO, especially from 1900 to 1945. However, they do match the PMO very well, which demonstrates that the PMO is another key internal mode, as well as the PDO, and can modulate large-scale atmospheric and oceanic patterns.

Other climate indices, including changes in northern hemispheric summer precipitation, also present the same oscillation as the PMO (Figure 6). Based on analysis of the ACI (the anomalies of which show the relative dominance of zonal (positive anomalies) and meridional (negative anomalies) transport in the Atlantic–Eurasia region), SOI (commonly used to monitor the seesaw of surface air pressure over the eastern and western tropical Pacific), NPI (mainly reflects the change in the Aleutian Low), and summer precipitation index, it is interesting to see that, when the PMO varies from one polarity to another, coinciding with this, all of these indices also modify from one phase to another. This further proves that the PMO is indeed a multidecadal mode that is independent from the PDO over the North Pacific. Moreover, it has important relationships with several key indices and records of climate change.
After the PDO and AMO, the PMO may be another important internal factor that can modulate near-surface temperatures, especially when (before the 1920s) the PDO and IPO indices do not match the global temperature curves. Figure 7 shows that the variation in global temperature may be explained by the PMO in conjunction with the greenhouse effect. When the PMO changes from a positive to negative phase, the cooling effect of the PMO is superimposed on the warming effect of GHGs. As a result, the increase in global temperature becomes slower; the effect of the PMO may even be more dominant than the GHG effect, and cause global temperatures to decrease. In contrast, when the PMO turns from a negative to a positive phase, the warming associated with the PMO is superimposed on the warming effect of GHGs, and warming then accelerates.

After 2000, the PMO turned to a negative phase, and thus there has been a lull in global warming in recent years. Furthermore, according to the cycle of the PMO, it may be anticipated that the lull in global warming will continue to around 2025. After this point, the global temperature will probably increase again, because of a change of the PMO into a positive phase. Moreover, using the PMO index to perform a lead–lag correlation with the low-pass filtered global-mean near-surface air temperature (AIR), SSTs, and the combined SST + AIR index, we find that the PMO leads all of these indices by between one to three years (Figure S4b). This makes the PMO more important to global climate change. Also, based on lead–lag correlations between the PMO and regional SST indices (Figure S3c), similar results are obtained; the PMO leads global SSTs.

The Arctic Oscillation (AO) and ENSO are among the most important climate systems over the Northern Hemisphere in winter (December–February). The question therefore arises as to whether the PMO can influence the AO and ENSO systems. Figure 8 shows the correlations between the AO and northern hemispheric 850-hPa geopotential height, during five different positive and negative phases of the PMO (1871–1897, 1923–1948, 1979–2003, 1898–1922, and 1949–1978). The results show that, during the three PMO positive phases, the distributions of geopotential height anomalies related to the AO are zonally symmetric. In the meantime, the AO influences not only the North Atlantic but also the North Pacific. In contrast, the AO has little influence over the North Pacific during the two negative phases of the PMO.

5. PMO effects and possible mechanisms

Several studies have shown the impacts of internal and external factors of oscillations, such as the Atlantic Multidecadal Oscillation (AMO) (Delworth and Knutson 2000; Mann, Bradley, and Hughes 1999; Schlesinger and Ramankutty 1994) and solar radiation oscillation (Beer, Mende, and Stellmacher 2000; Marcus, Ghil, and Ide 1999; Tett et al. 1999), on near-surface temperatures. Recent studies (Dai et al. 2015; Tollefson 2014) indicate that the PDO and Interdecadal Pacific Oscillation (IPO) may explain the recent hiatus in global warming, demonstrating that oceans play an essential role in the interdecadal fluctuation of global temperature. Figure S4 shows that the fluctuations of the PMO and global temperature are remarkably similar. Over the past century, the primary cause of global warming has been GHG emissions, produced by human activity. However, despite the continuous increase in GHGs, periods of both increasing (20–30 years) and decreasing global temperatures have occurred. This means that other factors must also change global temperature, and the latest curve is affected simultaneously by all factors.
anomalous SST patterns related to the two different types of El Niño are different. Ashok et al. (2007) showed that El Niño Modoki is represented by the second EOF mode of SSTs, and explained that the recently more frequent El Niño Modoki might be caused by the flatter thermocline in the tropical Pacific. As shown in Figure S3a, a positive PMO phase can result in warm SSTs near the eastern and western edges of the tropical Pacific, but cool SSTs in the central tropical Pacific. These changes modify SST gradients and, subsequently, the thermocline. Therefore, it can be speculated that the PMO is able to modulate El Niño Modoki events, by exerting a change in the thermocline.

Figure 9 shows the second EOF modes of the SSTs in 110°E–70°W and 30°S–30°N, during the different phases of the PMO, corresponding to the three warm phases (a, b, and c) and the two cool phases (d and e) of the PMO. It is shown that the El Niño Modoki mode appears on the second EOF mode during the positive phases only of the PMO. The possible mechanism underpinning this phenomenon is that, when the PMO is positive, the SSTs in the northeastern Pacific are warmer than average. This generates strong EPW, which in turn influences the Aleutian low–Icelandic low (AL–IL) seesaw, and the AO pattern. During negative PMO phases, the northeastern Pacific SSTs are cooler than average, which causes a weak EPW. The Pacific center of the traditional AO pattern thus disappears, when the AL–IL seesaw is absent.

Canonical El Niño and El Niño Modoki are two coupled ocean–atmosphere phenomena in the tropical Pacific (Ashok et al. 2007; Rasmusson and Carpenter 1982). The anomalous SST patterns related to the two different types of El Niño are different. Ashok et al. (2007) showed that El Niño Modoki is represented by the second EOF mode of SSTs, and explained that the recently more frequent El Niño Modoki might be caused by the flatter thermocline in the tropical Pacific. As shown in Figure S3a, a positive PMO phase can result in warm SSTs near the eastern and western edges of the tropical Pacific, but cool SSTs in the central tropical Pacific. These changes modify SST gradients and, subsequently, the thermocline. Therefore, it can be speculated that the PMO is able to modulate El Niño Modoki events, by exerting a change in the thermocline.

Figure 8. Correlation coefficients between the AO and northern hemispheric geopotential height at 850 hPa, during different phases of the PMO: (a) 1871–1897; (b) 1923–1948; (c) 1979–2003; (d) 1898–1922; (e) 1949–1978. Note: The black dots mark the grid points for which the correlation coefficients exceed the 95% confidence level.
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the modulating effect of the PMO, global SSTs present a near uniform distribution pattern. During PMO positive phases, global SSTs are higher than average. At the same time, there is more rainfall in summer in the Northern Hemisphere, the Aleutian low strengthens, the Southern Oscillation weakens, and zonal atmospheric transport is relatively dominant in the Atlantic–Eurasia region. Conversely, during negative phases of the PMO, the opposite features appear.

The relationship of the PMO with the AO and ENSO is examined during boreal winter. It seems that the AO and ENSO can also be influenced by the PMO; during warm PMO phases, the AO influences both the North Atlantic and the North Pacific area. Meanwhile, El Niño Modoki events become more frequent. During cool PMO phases, however, the AO exerts a significant influence over the North Atlantic only, and El Niño Modoki events hardly ever occur.

6. Discussion

This paper examines various aspects of the PMO. The PMO has a strong periodicity, with a cycle of around 60 years, and is fundamentally different to the PDO. There have been three positive and two negative phases of the PMO during 1871–2010. Currently, the PMO lies in a negative phase, which started around 2003 and may persist in total for about 25–30 years, before changing into a positive phase around 2025. The PMO has a significant effect on global SSTs, especially off of North and South America, in the North Atlantic, and in the western tropical Pacific. Under the modulating effect of the PMO, global SSTs present a near uniform distribution pattern. During PMO positive phases, global SSTs are higher than average. At the same time, there is more rainfall in summer in the Northern Hemisphere, the Aleutian low strengthens, the Southern Oscillation weakens, and zonal atmospheric transport is relatively dominant in the Atlantic–Eurasia region. Conversely, during negative phases of the PMO, the opposite features appear.

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Both the PMO (as a natural internal oscillation) and GHGs exert effects on global temperature. When the phase of the PMO changes from negative to positive, the increase in temperature related to the PMO and the effects of GHGs

Figure 9. The second EOF mode of winter tropical Pacific SSTs during different phases of the PMO: (a) 1871–1897; (b) 1923–1948; (c) 1979–2003; (d) 1898–1922; (e) 1949–1978. Panels (a–c) are three positive phases of the PMO, and (d, e) two negative phases.
are significant. In contrast, when the PMO changes from a positive phase to a negative phase, the cooling effects related to the PMO phase offset global warming due to the GHGs. Of greater importance, generally, changes in global air temperature and SST lag the PMO by between one to three years.

While the causes of the PMO are not fully understood at present, two possibilities are proposed: (1) external oscillatory forcing, such as a variation in the solar constant; and (2) an internal oscillation of the atmosphere–ocean system. However, comparison between the PMO index and the sunspot cycle during the last century reveals no significant relationship. Therefore, the internal oscillation of the atmosphere–ocean system is the more likely cause.

Issues related to the global warming hiatus in the last decade have received a great deal of attention; however, the reasons behind the phenomenon are still unclear. The AMOC (Atlantic Meridional Overturning Circulation) has been identified as a factor, according to Smith et al. (2007) and Keenlyside et al. (2008). In contrast, Tollefson (2014) and Dai et al. (2015) claim that the pause is caused by change in the PDO and IPO, from a positive phase to a negative phase. The current study shows that the hiatus in global warming that has occurred in the last decade may be related to the influence of the PMO. If so, this pause in global warming may persist until 2025, after which apparent warming may return. It should be noted that all the results presented in this paper are statistical, and that sensitivity experiments using coupled models are needed to confirm the findings.

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