Cover. Pacific Ocean air temperature anomalies found during decades of stalled surface warming in climate models. The pattern shown is the average of all such decades over the past century that are not associated with a volcanic eruption. The model pattern closely resembles observed trends over the past 20 years leading up to the current period of slowed surface warming, matching the negative phase of the Interdecadal Pacific Oscillation (IPO). The IPO is identified as a major driver of hiatus decades over the last century in the paper by Maher et al. [2014] in this issue of GRL [pp. 5977–5985; doi:10.1002/2014GL060527].
Drivers of decadal hiatus periods in the 20th and 21st centuries

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Abstract The latest generation of climate model simulations are used to investigate the occurrence of hiatus periods in global surface air temperature in the past and under two future warming scenarios. Hiatus periods are identified in three categories: (i) those due to volcanic eruptions, (ii) those associated with negative phases of the Interdecadal Pacific Oscillation (IPO), and (iii) those affected by anthropogenically released aerosols in the mid-twentieth century. The likelihood of future hiatus periods is found to be sensitive to the rate of change of anthropogenic forcing. Under high rates of greenhouse gas emissions there is little chance of a hiatus decade occurring beyond 2030, even in the event of a large volcanic eruption. We further demonstrate that most nonvolcanic hiatuses across Coupled Model Intercomparison Project 5 (CMIP5) models are associated with enhanced cooling in the equatorial Pacific linked to the transition to a negative IPO phase.

1. Introduction

While the long-term trend in globally averaged surface air temperature (SAT) is one of warming [Stocker et al., 2013], there has been no significant warming trend in global SAT over the last 10–15 years. Periods of a decade or longer without significant warming or with globally averaged cooling superimposed on the long-term warming trend have been termed “hiatus periods” [Meehl et al., 2011]. The current hiatus is not unique in the historical temperature record (e.g., extended hiatuses occurred in the periods 1937–1950 and 1956–1968); moreover, hiatus periods are a feature in all historical simulations using global climate models [Easterling and Wehner, 2009]. A number of mechanisms have been proposed to explain hiatuses and in particular the most recent hiatus period.

Cowtan and Way [2013] argue that a lack of data, primarily in the Arctic, may bias the global trend estimate after 1998 relative to the early 1990s; however, a distinct post-2000 warming slowdown is still apparent after a correction is applied [Cowtan and Way, 2013]. Changes in radiative forcing related to changes in solar insolation, volcanic eruptions, and/or anthropogenic releases of aerosols may also be a factor in causing hiatus periods. Kaufmann et al. [2011], for example, suggest that declining solar insolation may have partially offset greenhouse warming.

Large volcanic eruptions release substantial amounts of sulphate aerosols into the stratosphere, that reflect incoming radiation resulting in a net cooling [Harshvardhan, 1979; Rampino and Self, 1984; Robock and Mao, 1995]. A number of studies have suggested that small volcanic eruptions over the last decade may have had a significant cooling effect; however, this forcing alone is insufficient to explain the hiatus [e.g., Santer et al., 2014; Fyfe et al., 2013; Haywood et al., 2013]. Volcanic eruptions may also affect the Pacific circulation, which can in turn influence SAT. Based on a single model, McGregor and Timmermann [2011] found an enhanced probability of a La Niña within 1 year of a large eruption. They suggest that in response to an eruption an enhanced equatorial Pacific zonal sea surface temperature (SST) gradient occurs, as areas with deeper mixed layers take longer to respond to volcanic cooling, resulting in a La Niña-like cooling. In contrast, Ohba et al. [2013] found an increased likelihood of an El Niño 1 year after a major eruption, due to a weakening of the Walker circulation and reduced equatorial upwelling. As such, there is as yet no consensus on how El Niño–Southern Oscillation (ENSO) might evolve following a volcanic eruption.

Changes in the emission rate of anthropogenic aerosols and greenhouse gases have also modulated SAT over the twentieth century. During the period 1940–1975 large increases in anthropogenic aerosols gave rise to a net cooling in SAT [Wilcox et al., 2013; Stott, 2000], post–World War II [e.g., Estrada et al., 2013]. Estrada et al. [2013] suggest that both increases in tropospheric aerosols and reductions in the emissions of chlorofluorocarbons and methane may have contributed to the recent hiatus.
Changes in SAT are also affected by internal variability, in particular through the redistribution of heat in the climate system. Over decadal timescales additional heat entering the deep ocean, at the expense of the surface ocean, can help explain the recent [e.g., Guemas et al., 2013; Katsman and van Oldenborgh, 2011] and past [Palmer et al., 2011; Meehl et al., 2011; England et al., 2014] hiatus periods. Indeed, previous studies suggest that despite the recent hiatus, the heat content of the whole system has continued to rise [e.g., Nuccitelli et al., 2012; Cazenave et al., 2014], with the top 2000 m of the ocean warming more or less monotonically over time [Levitus et al., 2012] and a significant portion of the warming occurring below 700 m [Balmaseda et al., 2013]. As such, SAT is a relatively poor proxy for the heat content of the climate system as a whole.

Pacific Ocean variability has recently been flagged as particularly important for decadal changes in global mean SAT, particularly via the Interdecadal Pacific Oscillation [e.g., Meehl et al., 2013; Watanabe et al., 2013; Kosaka and Xie, 2013; England et al., 2014]. Both the negative Interdecadal Pacific Oscillation (IPO) and La Niña are associated with the drawdown of heat from the atmosphere into the subsurface ocean that can be conducive for hiatus periods [England et al., 2014]. Kosaka and Xie [2013] show that the evolution of observed decadal varying SAT can be largely reproduced in a coupled climate model if the equatorial eastern Pacific SST is restored to observed values. Coincident with the recent hiatus period has been an increase in the strength of the Walker circulation [L’Heureux et al., 2013] and Pacific trade winds [England et al., 2014] consistent with a negative phase of the IPO. During the period 1940–1975, wind-driven cooling of the Pacific associated with a negative phase of the IPO has also been found to be a significant factor in cooling the globe, in combination with enhanced anthropogenic aerosol loads [England et al., 2014].

Based on a single climate model Meehl et al. [2013] found that hiatus decades were related to increased deep ocean heat uptake and decreased surface ocean temperatures across the Pacific, coinciding with a negative IPO phase. They also found that changes in the Atlantic Meridional Overturning Circulation and Antarctic Bottom Water formation played a detectable role in hiatus periods. The mechanism behind the decadal redistribution of heat in the Pacific was examined by England et al. [2014], who used ocean and coupled model experiments forced by observed tropical wind trends to show that changes in the Pacific trade winds lead to a cooling of the eastern and central Pacific and an accumulation of heat in the subsurface western Pacific Ocean. The increased winds lead to a strengthening of the subtropical overturning cells, which increases the upwelling of cool water at the equator and subducts a large amount of warm surface water into the thermocline.

Our study extends the work of Meehl et al. [2013] to examine a large suite of models taking part in the Coupled Model Intercomparison Project 5 (CMIP5). We consider volcanic eruptions, anthropogenic aerosols, and natural variability as drivers for historical hiatus decades and examine how the probability of hiatus periods is likely to evolve under a high-emission scenario and one where greenhouse gas levels stabilize by 2100.

2. Methods

This study uses SST and SAT output from a single ensemble member of 31 climate models taking part in CMIP5 (Table S1 in the supporting information). The analysis includes the historical simulation, which covers a period from approximately 1860–2006, as well as two future emissions scenarios: Representative Concentration Pathways 4.5 (RCP4.5), in which atmospheric greenhouse gas levels stabilize by 2100 at a carbon dioxide equivalent concentration of 538 ppm, and a high-emission scenario (RCP8.5), in which carbon dioxide equivalent levels keep rising at an increasing rate over the 21st century to a value of 936 ppm by 2100 [Meinshausen et al., 2011].

Following Meehl et al. [2013], decadal hiatus periods are identified by their central year and defined as any 10 year period with a negative trend in global average SAT. Hiatus decades are characterized into three types: volcanic, all nonvolcanic (largely IPO), and those nonvolcanic hiatuses that occurred during the period 1940–1975 when anthropogenic aerosol emissions were increasing rapidly [Lean and Rind, 2008]. Note that the third category is a subset of the second.

Volcanic hiatus periods are defined as the strongest hiatus decade (if any) within 5 years on either side of one of the four largest historical volcanic eruptions: Krakatau (1883), Santa Maria (1902), Agung (1963), and Pinatubo (1991).
Accelerated decades are defined as any 10 year period with a positive trend much larger than the underlying long-term trend. Accelerated decade trend thresholds are different for each scenario to reflect the differing long-term trends (0.48°C/decade for both historical and RCP4.5 and 0.85°C/decade for RCP8.5; see supporting information for threshold calculations).

Composites of both hiatus and accelerated decades are found by first taking the mean of all hiatus decades or accelerated decades respectively for an individual model, then averaging across models. The ENSO and IPO time-series are calculated using an empirical orthogonal function analysis (EOF) (this analysis is outlined in the supporting information). This is performed for 27 of the 31 CMIP5 models due to data availability.

The two future emission scenarios do not include volcanic eruptions. To determine how a volcanic eruption might affect future SAT, modified future global average SAT time-series are constructed (for both future scenarios) that include volcanic eruptions toward the beginning (2032) and end (2087) of the 21st century. Two eruption sizes are considered with annual peak radiative forcing of $-3.3 \text{ W m}^{-2}$ (similar to Krakatau) and $-1.5 \text{ W m}^{-2}$ (similar to Santa Maria) and an e-folding timescale of 1.1 years (the average e-folding timescale of historical eruptions). The SAT response to the volcanic forcing is estimated using a multiple linear regression (MLR) over the historical period (the supporting information contains the MLR methodology).

3. Historical Hiatus Decades

Figure 1a shows the historical global average SAT anomaly for both observations and the interquartile range of 31 CMIP5 models. Figure 1b shows the probability of a model having a hiatus decade centered on a given year. In the absence of any long-term trend in SAT or external forcing such as volcanoes and aerosols, we would expect a probability of around 0.5, as internal variability is not coherent across different models. Concurrent changes in radiative forcing associated with key drivers affecting SAT are shown for the historical simulations, related to the following: volcanic aerosols (Figure 1c), anthropogenic forcing (Figure 1d), and solar forcing (Figure 1e). In addition, the time-series of both ENSO and the IPO indices are shown in Figure 1f. While the probability of a hiatus across the model ensemble fluctuates over time, certain periods show strong model agreement of the occurrence of a hiatus. These periods are generally coincident with major volcanic eruptions.

We now discuss hiatus decades related to three key drivers: (1) volcanic eruptions, (2) the trend in the phase of the IPO, and (3) hiatus decades in the presence of large anthropogenic aerosol releases.

3.1. Volcanic Hiatus Decades

During the Krakatau, Agung, and Santa Maria eruptions (the three largest eruptions between 1860 and 1980) almost all (93% for Krakatau, 77% for Santa Maria, and 90% for Agung) models simulate a hiatus decade (Figures 1b and 1c), irrespective of the details of their internal variability. Figure 2a shows the composite of the SAT trends across models that simulate a hiatus around the time of one of the four major volcanic eruptions. The three earlier volcanic eruption hiatuses are characterized by similar SAT responses (Figure S2a), with more cooling over land, the Arctic and the eastern Pacific Ocean and less cooling in the Southern Hemisphere mid-latitudes (Figures S1a–S1c). In contrast, Pinatubo (1991), which took place during a period of much stronger multidecadal surface warming, has a distinctly different spatial trend pattern (Figure S1d). The difference between the multimodel composite of the three earlier eruptions and Pinatubo shows a broad scale warming amplified over land and the Arctic (Figure S2e). Some part of the difference can be related to the increase in background warming (Figure S2g); however, this is not sufficient to fully explain the difference. Unlike the other major eruptions, Pinatubo does not coincide with a hiatus in the observations, and there is only a 58% chance of a hiatus across the models, even though Pinatubo was the second largest of the four.

In addition, previous work has suggested that ENSO may also be affected by large volcanic eruptions [McGregor and Timmermann, 2011; Ohba et al., 2013] and could act as a feedback to modify SAT trends. We evaluate how ENSO evolves in response to a large eruption across the models by examining ENSO indices relative to the time of volcanic eruptions. These are averaged across all major eruptions and models. The multimodel mean ENSO index (see supporting information for calculation) becomes significantly negative (i.e., La Niña-like conditions) on average 2.5 years after the peak in the volcanic forcing (not
Figure 1. (a) Historical observed SAT anomaly relative to 1961–1990 (blue line) [Hansen et al., 2010], with the interquartile range from 31 CMIP5 models temperature anomaly superimposed (pale blue). (b) The percentage of 31 CMIP5 models that have hiatus decades centered on the middle year. (c) Annual radiative forcing due to volcanic aerosols from two volcanic datasets [Sato et al., 1993; Ammann, 2003]. (d) Total anthropogenic forcing (black) split into the greenhouse gas (blue) and other (red) components (http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=spatial). (e) Solar forcing of CMIP5 models (http://solarisheppa.geomar.de/solarisheppa/sites/default/files/data/Calculations_of_Solar_Irradiance.pdf), (f) Observed ENSO and IPO, computed using the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) dataset [Rayner et al., 2003], see methods for details. The shaded grey bands correspond to observed hiatus periods (defined by their central year).

shown), resulting in the eastern tropical Pacific cooling seen in the composite SAT trends for volcanic hiatus decades (Figure 2a).

3.2. IPO-Related Hiatus Decades

Most models simulate eastern Pacific cooling and warming in the northwest and southwest Pacific associated with the negative phase of the IPO (using the preindustrial control runs) (Figure S3). However, the strong temperature signal in the central to eastern tropical Pacific often extends too far into the western
Figure 2. Composites of decadal surface air temperature trends (°C/yr) for (a) four major volcanic events: Krakatau (1883), Santa Maria (1902), Agung (1963), and Pinatubo (1991), with the hiatus decade chosen manually for each model. (b) Hiatus decades during a period of high anthropogenic aerosol emissions (1940–1975). (c) Hiatus decades during the historical scenario, excluding the four major volcanic events. (d) Accelerated decades (i.e., decadal trend >0.048°C/yr) in the historical scenario. (e) Hiatus decades in the RCP4.5 scenario. (f) Accelerated decades (i.e., decadal trend >0.048°C/yr) in the RCP4.5 scenario. (g) Hiatus decades in the RCP8.5 scenario. (h) Accelerated decades (i.e., decadal trend >0.085°C/yr) in the RCP8.5 scenario. The area mean value subtracted from the hiatus/accelerated plots is shown in the title (Figures 2c–2h). The number of CMIP5 models (n) included in each composite is also shown in the title; a total of 31 models were used. Stippling is shown when 80% of the models agree on the sign of the trend.
Figure 3. (a) Observed IPO pattern calculated using the HadISST data set [Rayner et al., 2003]. (b) Multimodel mean IPO, calculated using the preindustrial control scenarios from 27 models (see supporting information for a model list and methodology). (c) Observed ENSO pattern calculated from HadISST data. (d) Multimodel mean ENSO calculated for the historical scenario from 27 models. Stippling is shown when 80% of models agree on the sign of the SST pattern.

The equatorial Pacific, and the southwest Pacific warming can be too weak. The multimodel mean IPO spatial pattern is shown in Figure 3b with the observations shown in Figure 3a.

A composite of the SAT trend for all nonvolcanic hiatuses from the historical simulations shows a clear negative IPO spatial pattern (Figures 2c and 3), while accelerated decades exhibit a positive IPO spatial pattern (Figure 2d). Of the nonvolcanic hiatuses 62% occur while the IPO is transitioning into a negative phase, with this number increasing to 67% when a subset of models with a more realistic IPO spatial pattern is used (i.e., pattern correlated at greater than 0.7 with the observed IPO, see Table S1).

3.3. Mid-Twentieth Century Hiatus Decades

During the period 1940–1975, large increases in anthropogenic aerosols gave rise to a net cooling in SAT [Wilcox et al., 2013; Stott, 2000]. A composite of simulated hiatus decade trends occurring between 1940 and 1975 exhibits widespread cooling, with a negative IPO/La Niña-like spatial pattern in the tropical Pacific (Figure 2b). Hiatuses composited during this period show a different pattern to those composited throughout the entire historical time-series with the difference between the 1940–1975 nonvolcanic hiatus decades and all nonvolcanic hiatuses exhibiting a broad pattern of cooling over the majority of the globe (Figure S2f). This suggests an important role for aerosols in cooling the surface climate at this time. The net cooling due to aerosols increases the likelihood of a hiatus as does a negative IPO transition (58% of 1940–1975 hiatuses is found when the IPO phase is trending negative), resulting in the pattern of widespread cooling superimposed on the negative IPO.
4. Future Hiatus Decades

Here we consider two future emission scenarios over the period 2006–2100: the RCP4.5 and RCP8.5 scenarios (described in section 2). We extend the historical analysis to future scenarios and use the 31 models as an ensemble to assess the probability of a hiatus decade occurring into the future.

4.1. IPO Hiatus Decades

The RCP scenarios do not include volcanic forcing. As for the nonvolcanic historical hiatus SAT trend composites, the RCP composites clearly show enhanced SAT cooling in the eastern tropical Pacific associated with a negative IPO phase transitions (Figures 2e and 2g), with the opposite response shown for accelerated decades (Figures 2f and 2h). The strength of the IPO-like spatial pattern anomalies becomes considerably stronger for the RCP8.5 scenario (Figure 2g) in comparison to the historical scenario, indicating that the IPO phase transitions need to be stronger to overcome the larger background warming associated with this scenario. As in the historical simulations, accelerated warming decades tend to be associated with a positive IPO spatial pattern.

For the RCP4.5 scenario, 73% of hiatuses occur while the IPO is transitioning into a negative phase. Moreover, by selecting a subset of models that have more realistic IPO structure (i.e., pattern correlated greater than 0.7 with the observed IPO, see Table S1) this value increases to 80%. A composite of hiatus decades that do not occur during a transition to a negative IPO phase still shows a weak cooling in the eastern tropical Pacific (figure not shown), suggesting that changes in the Pacific are still an important factor affecting the hiatuses. In the RCP8.5 scenario those few hiatuses that do occur (only five hiatuses between 2017 and 2087 across 27 models) are all associated with a strongly negative trending IPO phase (Figure 2g). We find no significant change in either the frequency or amplitude of the IPO in either scenario when compared to the historical period.

These results extend those of Meehl et al. [2013], who examined an ensemble of five RCP4.5 simulations, from a single CMIP5 model, namely, CCSM4. They composited decades of both cooling and accelerated warming and found that hiatus decades were largely related to a transition to a negative IPO phase, with accelerated decades occurring when the IPO was transitioning to a positive phase. They found that cooling due to a negative IPO phase could overcome background warming and result in the occurrence of hiatus decades. Here we have demonstrated that a similar mechanism appears to be at play in most climate models and that the state of the equatorial Pacific Ocean is a major factor in controlling global SAT trends on decadal timescales, including controlling the occurrence of future hiatuses.

4.2. Frequency of Future Hiatuses

Based on historical and future scenarios the probability of a hiatus occurring is dependent on the gradient in anthropogenic forcing, which in turn affects the rate of temperature increase, with a decreasing probability of a hiatus as the multidecadal gradient of background warming increases (Figure 4a). Outliers are related to volcanic eruptions.

The occurrence of hiatus decades is very sensitive to the emission scenario. Figure 4b shows that under the high-emission scenario (RCP8.5) the probability of a hiatus quickly becomes small, with only one hiatus, in just one of the 31 models, occurring after 2032. Under the lower emissions scenario (RCP4.5), the probability of a hiatus decade initially decreases, but climbs again in the second half of the 21st century toward the 50% level. This occurs as the radiative forcing stabilizes, leading to a leveling of SAT in the latter part of the century.

The occurrence of volcanic eruptions has had a large influence on the likelihood of hiatuses in the past. The RCP scenarios do not, however, include future volcanic eruptions. Given that it is likely that some major eruptions will occur over the 21st century, we have artificially added the effect of two different eruptions to each RCP scenario at 2032 and 2087. For convenience these are referred to as large (Krakatau size) and medium (Santa Maria size) eruptions, respectively. The medium volcanic eruption, when occurring at 2032, increases the probability of a hiatus to 22% in RCP4.5 and 15% in the RCP8.5 scenario, while the larger eruption increases the probabilities to 63% and 50%, respectively. The imposed eruptions at 2087 increase the chance of a hiatus in the RCP4.5 simulation to 89% in the case of the medium volcanic eruption and 96% in the case of a larger eruption. In contrast, even a large eruption is unlikely to result in a hiatus under the RCP8.5 scenario late in the twentieth century, with a probability of only 10% for a large eruption and 0% for a medium eruption.
5. Summary and Conclusions

We show that across the CMIP5 models, hiatus decades are often associated with a transition into a negative IPO phase. This corroborates the finding of Meehl et al. [2013] who used a single model assessment. This result applies to the historical, RCP4.5, and RCP8.5 scenarios, where cooling due to this transition can overcome the background warming on decadal timescales. When considering a subset of hiatus decades within the period 1940–1975, we also find that they are often related to the IPO, with the influence of anthropogenic releases of aerosols causing an additional widespread cooling.

Easterling and Wehner [2009] showed that multiyear periods of no warming or cooling occur in both observations and the CMIP3 models and concluded that there is a 5% chance of such a period occurring in the 21st century under the A2 (similar to RCP8.5) scenario. Based on the two scenarios considered here we find that the occurrence of hiatus decades will be highly dependent on future emission trajectories. Few hiatus decades are likely to occur into the future in the RCP8.5 scenario as the rate of long-term anthropogenic warming overwhelms short-term changes due to low-frequency internal variability. In the RCP4.5 scenario, while the likelihood of a hiatus drops rapidly over the start of the 21st century, by the end of the century the probability of hiatuses begins to approach 50%. Here despite a large increase in temperature, stabilization of greenhouse gas concentrations in the latter half of the century mean that the rate of warming becomes small and low-frequency internal variability dictates whether a hiatus will occur.

Furthermore, this study has shown that large volcanic eruptions dramatically increase the likelihood of hiatus periods in the historical record pre-1980. For Krakatau, Agung, and Santa Maria, the likelihood of hiatus was increased to between 77 and 93% across the models, and indeed, hiatus periods accompanied these eruptions in observations. In the 1990s the background warming acted to partially offset the cooling effect of Pinatubo, with a slightly elevated chance of a hiatus across the models and no observed hiatus. Future RCP scenarios with adjustments made to include the effect of volcanic forcing show an extremely high chance of a hiatus in the RCP4.5 scenario at the end of the 21st century in the event of a volcanic eruption. In contrast there is virtually no chance of a hiatus decade in the RCP8.5 scenario at the end of the century. As such, if we follow a high-emission trajectory, hiatus periods will soon become a thing of the past.
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