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An ongoing cooling in the eastern Pacific linked to eastward migrations of the Southeast Pacific Subtropical Anticyclone

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An ongoing cooling in the eastern Pacific linked to eastward
migrations of the Southeast Pacific Subtropical AnticycloneYoujia Zou¹ and Xiangying Xi²¹ Department of Meteorology and Oceanography, Shanghai Maritime University, Shanghai,
People's Republic of China² Wuhan University of Technology, Wuhan, People's Republic of ChinaE-mail: xxy98982018@163.com**Keywords:** global warming hiatus, ongoing cooling, Southeast Pacific Subtropical Anticyclone, eastward displacement, greater pressure gradient, stronger alongshore windsSupplementary material for this article is available [online](#)

Abstract

Previous studies demonstrate that recent global warming hiatuses are associated with an ongoing cooling in the eastern Pacific. However, the possible driver for this cooling remains vigorously debated. Present theories can be generally categorized into three different frameworks, the most prevailing theory considering the increased heat uptake in ocean interior as a direct trigger in cooling the eastern equatorial Pacific, the next regarding the prolonged solar minimum as a potential driver in producing weak radiative forcing over the Pacific, while another suggesting that changes in atmospheric water vapour and aerosols play an unnegligible role in absorbing and reflecting solar radiation. Most recently, some studies argue that the ongoing cooling in the eastern Pacific is induced by a strengthening of the easterly trade winds. Nevertheless, observational records coming from the monitoring buoys deployed along the equator by NOAA since 1992 indicate that an intensification of the trade winds is only confined to the central tropical Pacific (around 170° E–170° W) during hiatus decades, elsewhere along the equatorial Pacific the trade winds exhibit a stable condition even a slight weakening in the eastern equatorial Pacific, rendering it as a trigger of this cooling in the eastern Pacific unlikely. Here we use a model and long-term observational data to demonstrate that a persistent cooling in the eastern Pacific is directly linked to an eastward displacement of the Southeast Pacific Subtropical Anticyclone (SPSA). Interactions between the Andes and an eastward shift of the SPSA generate greater pressure gradients in the eastern flank, in turn, stronger alongshore winds and more intense upwelling, ultimately contributing to hiatus decades.

1. Introduction

Observations show that global surface air temperature remained an overall upward trend over the last century, with an average warming of 0.7 °C (IPCC 2007). Interestingly, this trend did not rise monotonically but was punctuated by periods of a few weak warmings, even coolings (a.k.a warming hiatus) even if under scenarios of an increasing radiative forcing (Meehl *et al* 2013), reflecting interactions between greenhouse-gas-related forcing and natural internal variability, with the amplitude of the latter occasionally being comparable to, even greater than, that of

the anthropogenic signal. The most recent hiatuses occurred during about 1940–1970 and 2001–2012, respectively, posing great challenges to the prevailing view that the greenhouse gas emissions are the dominant factor in modulating global mean surface temperature (GMST). A number of mechanisms for the observed hiatuses have been proposed, for example, a slowdown in radiative forcing due to the stratospheric water vapour (Solomon *et al* 2010), weakened solar radiation (Hansen *et al* 2011), increased aerosols (Kaufmann *et al* 2011, Solomon *et al* 2011), enhanced ocean subsurface heat uptake (Katsman and Oldenborgh 2011, Guemas *et al* 2013,

England *et al* 2014, Nieves *et al* 2015) and a persistent cooling in the eastern tropical Pacific (Meehl *et al* 2011, Kosaka and Xie 2013), etc, making the characterization and interpretation of recent climate change a challenging, but potentially rewarding task. Through a variety of analyses and evidence presented in previous studies, consensus is building that the observed hiatuses are mainly linked to an ongoing cooling in the eastern tropical Pacific (Kosaka and Xie 2013, England *et al* 2014) which is considered to be closely associated with an intensification of the trade winds in the equatorial Pacific (England *et al* 2014).

Subsequently, some authors (Luo *et al* 2012, Han *et al* 2014, McGregor *et al* 2014, Li *et al* 2016) proposed an alternative mechanism using a variety of numerical simulation models showing that the recent sea surface temperature (SST) warming and the corresponding trans-basin displacements of the main atmospheric pressure centers in the Atlantic Ocean or Indian Ocean were the dominant factors in contributing to the observed Walker Circulation intensification, eastern Pacific cooling and western Pacific sea level rise.

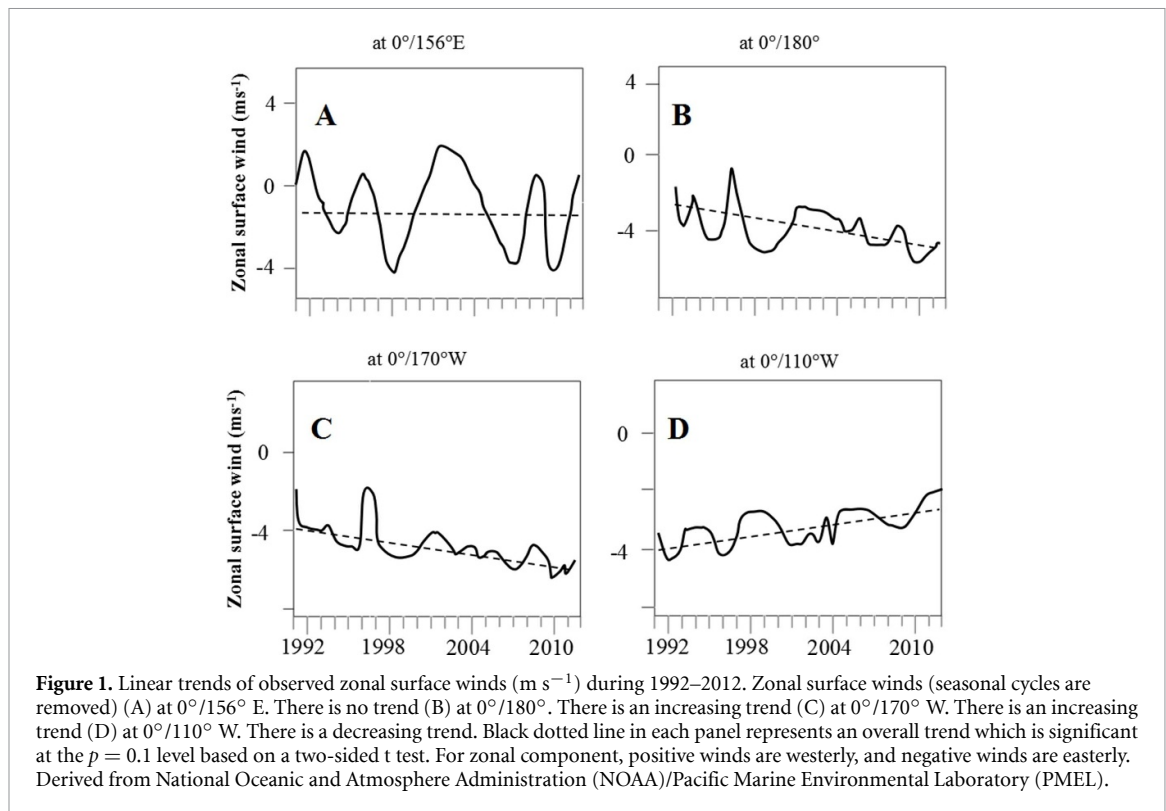
Very recently, a number of authors (Zhang 2016, Zhang and Karnauskas 2017) investigated the role of tropical interbasin SST gradients in forcing Walker Circulation through numerical atmosphere general circulation models (AGCMs) and argued that interbasin warming contrast is able to induce an intensification of the Pacific trade winds, in turn, a cooling in the equatorial Pacific.

To identify the real causes of warming hiatus is of great interest to scientists in order that we can apply the similar principles and take corresponding measures to permanently prevent a repetition of the warming, rather than just seek a few hiatus decades. To this end, we conduct an investigation into the trade winds in the Pacific showing that periods of warming hiatus indeed well match that of coolings in the eastern tropical Pacific, implying a close correlation between them. However, our investigations illustrate that these coolings seem to be less correlated to a slight strengthening of the easterly trade winds (validated in model simulation section), more likely, to be tied with a steadily eastward migration of the Southeast Pacific Subtropical Anticyclone (SPSA) since 1990s. The SPSA is a thermal high system formed by the southern branch of the Hadley Cells, with its center located in the eastern portion of the south Pacific basin, where large-scale subsidence balances strong low-level divergence (Richter *et al* 2008). The SPSA is considered to be the dominant forcing of the subtropical gyre in the south Pacific, which in its right flank is formed by the southeastern Pacific current system, consisting of the Humboldt jet-like stream, Humboldt Current oceanic branch, Humboldt Current coastal branch, Peru–Chile Countercurrent, Peru–Chile Subsurface Current, Chile Coastal Current,

South Pacific Current, and South Equatorial Current (Strub *et al* 1998, Fuenzalida *et al* 2008), and controlling the wind patterns, precipitations and SSTs. Therefore, any variation of the SPSA in position or intensity is most likely to evoke changes of the SPSA-induced meteorological elements.

Indeed, a pronounced intensification of the trade winds is liable to induce a cooling in the central and eastern tropical Pacific due to surface Ekman dynamics which is responsible for about half the total heat transport at the tropical circles in the Atlantic, and nearly all the total transport budget at the tropical circles in the Pacific (Adamec *et al* 1993). Nevertheless, observations *in situ* show that an intensification of the trade winds in zonal component was only confined to the central equatorial Pacific (around 170° E–170° W with an increase of $\sim +0.8 \text{ m s}^{-1} \text{ decade}^{-1}$, partially associated with the migratory anticyclones of the southwest Pacific (Steiner 1980)) whereas the trade winds in zonal component still remained less changed elsewhere along the equator, even slightly weakened in the eastern equatorial Pacific with a decrease of $\sim -0.6 \text{ m s}^{-1} \text{ decade}^{-1}$ during the last two decades (1992–2012) (figure 1). However, some authors argue that the central tropical Pacific zonal wind anomalies can also lead to a strong cooling in the east through inducing oceanic upwelling Kelvin waves, rendering a strengthening of the easterly trade winds in such a confined region as a trigger of the cooling in the eastern tropical Pacific more complicated.

In order to obtain reliable dataset of SST, sea surface level pressure (SLP) and the trade winds in the tropical Pacific, we employ the dataset from the monitoring buoys (total 11, see supplementary figure S1 (available online at stacks.iop.org/ERL/16/034020/mmedia)) deployed along the equator from the western to eastern equatorial Pacific by NOAA since 1992. These buoys with sensitive sensors are able to capture the signals of many meteorological elements and document the timeseries of these variables, such as SST, SLP, sea surface salinity, wind velocity, precipitation, long-wave radiative flux, etc. With these robust dataset, we can make more accurate predictions, model tests and convincing analyses. Our further investigations into the trade winds indicate that although the trade winds in zonal component have not significantly intensified, an overall strengthening of the trade winds in meridional component was pronounced from an average of 1.5 m s^{-1} in 1992 to 4.5 m s^{-1} in 2018 ($+1.1 \text{ m s}^{-1} \text{ decade}^{-1}$) in the eastern tropical Pacific (at 5° S/110° W) (figure 2(B)), suggesting an ongoing increase of southerly winds (strongly supported by subsequent observed data in supplementary figure S2) along South American coast, remarkably consistent with the non-monotonic patterns and timescales of SST cooling in the eastern Pacific (at 5° S/110° W) (figure 2(A)). An ongoing growing of southerly



winds along South American coast is able to result in a persistent increase of the upwelling usually recurring along the equator to feed the South Equatorial Current, cooling the eastern equatorial Pacific. This picture, however, leaves open the question of how the southerly winds along South American coast continuously reinforce during the last decades. Mechanisms proposed to account for the reinforcement involve a persistent intensification of the SPSA (Falvey and Garreaud 2009, Ancapichun and Santiago 2015). Indeed, observations reveal that the intensity of the SPSA has remained an overall upward trend since 1992, from an average of 1021 mb in 1992 to 1025 mb in 2012 (supplementary figure S3). Nevertheless, the magnitude of geostrophic winds is not directly determined by the intensity of the SPSA itself, instead, by pressure gradient (Belmadani *et al* 2017) which is affected by various mechanisms operating on a range of spatial scales, despite their consistency in periods of changes, suggesting that the intensity of the SPSA is unlikely to play a dominant role in inducing a growing southerly wind. This is also supported by the fact that cooler decades still occurred under the scenario of a negligible trend of the SPSA intensity during 1950–1970 (instrumental records available only after 1950) (supplementary figure S3). Even if the magnitude of geostrophic winds is indirectly related to the intensity of the SPSA, the amount of slightly increased intensity is insufficient to account for the notable growing meridional winds in the eastern tropical Pacific. Moreover, the varying patterns of the SPSA intensity do not match that of the

southerly winds throughout the observed periods (supplementary figures S4(a) and (b)). Therefore, an investigation into the SPSA position may be more instructive.

2. Observational data

To examine the ongoing cooling in the eastern tropical Pacific, and identify the relationship between the SST and meridional winds and SPSA position, we start by considering changes of the SST in the eastern equatorial Pacific (monitoring buoy B_{10} , in position $5^\circ \text{S}/110^\circ \text{W}$, see supplementary figure S1). Observations show that the SST in the eastern equatorial Pacific indeed has experienced an ongoing decrease since 1992 (no data available before 1992), but it was not uniform, with a slight rising during 2006–2008 and 2012–2015, respectively, strikingly consistent with the patterns and changes of an overall enhancement of the meridional winds with occasional weakening in position B_{10} during the same periods (figures 2(A) and (B)), manifesting a substantial inherent relation between them.

We subsequently investigate the evolutions of the SPSA position, particularly focusing on changes of the longitudinal position since 1986. Observations indicate that the annual mean longitudinal position (center position) of the SPSA has experienced a substantial eastward migration (from 108°W to 86°W) since 1987, with an overall eastward trend (causes are not clear), except periods of El Niño (figure 2(C)). Although temporary westward

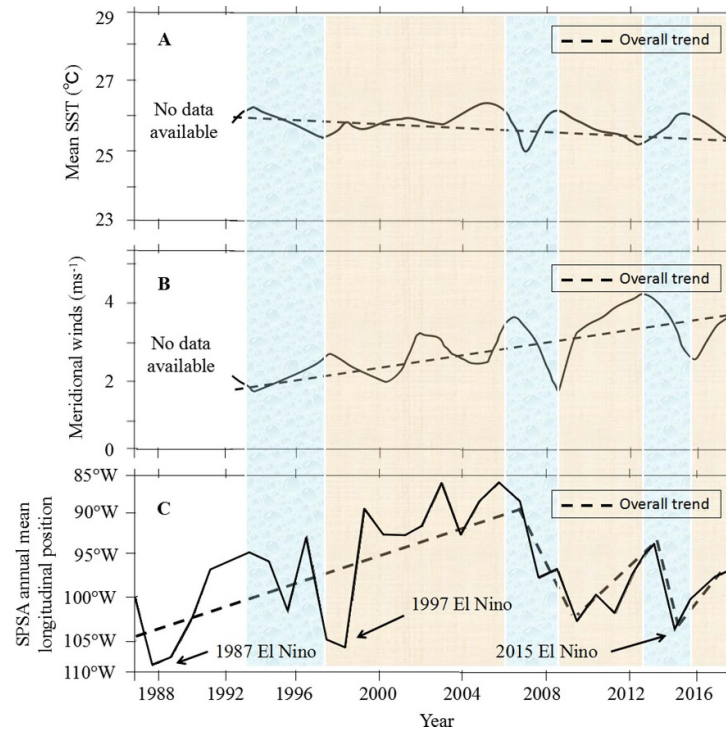


Figure 2. Comparisons between observed trends in SST, meridional winds (seasonal cycles are removed) during 1992–2018 and longitudinal positions of the SPSA during 1986–2018. (A) Mean SST in the eastern tropical Pacific (at 5° S/ 110° W). (B) Mean meridional winds (at 5° S/ 110° W). (C) Annual mean longitudinal positions of the SPSA. Black lines are observed trends in different timescales and dotted lines are overall trends which are significant at the $p = 0.1$ level according to a two-sided t test. Discontinuous areas are data missing while transmitting from the monitoring buoys to land-based stations. EN represents El Niño. The data in figures (A) and (B) from NOAA/PMEL and figure (C) from National Weather Service (Dirección Meteorológica de Chile).

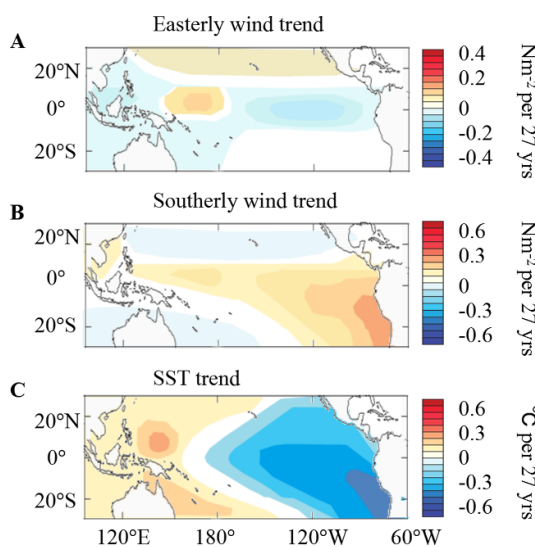
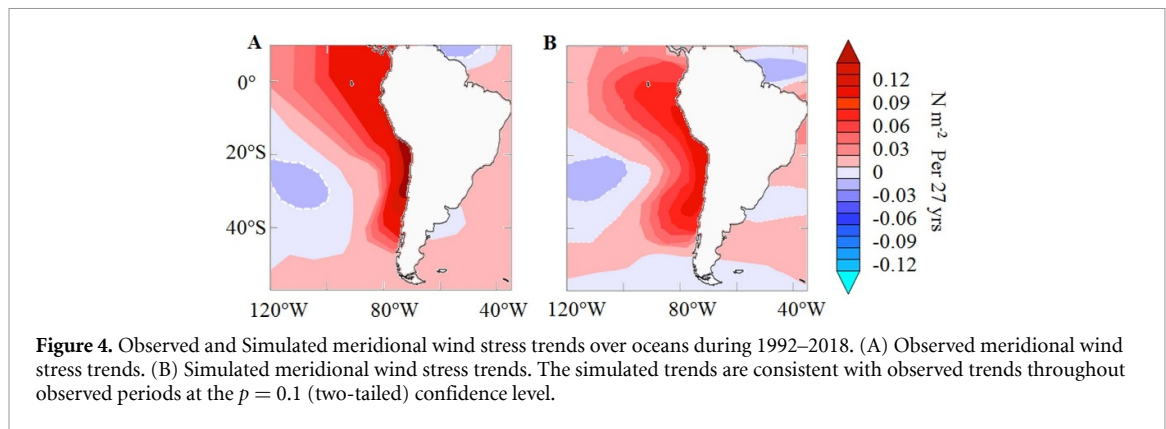


Figure 3. Simulated wind trends over oceans and SST trends during 1992–2018. (A) Easterly wind trends. (B) Southerly wind trends. (C) SST trends. All simulated trends are consistent with observed trends throughout observed periods at the $p = 0.1$ (two-tailed) confidence level.

hampered due to sparseness of the wind-related observational data before 1992. However, intensifications of the meridional winds in B_{10} corresponded closely to eastward migrations of the SPSA while temporary weakenings of the meridional winds in B_{10} well agreed with temporary westward shifts of the SPSA during 1992–2018 (figures 2(B) and (C)), implying that an ongoing strengthening of the southerly winds in B_{10} is directly correlated to an eastward displacement of the SPSA, thus leading to a persistent cooling of the SST in the eastern equatorial Pacific. This conclusion is also backed up by synchronicity of the last warming hiatus (1940–1970) and an ongoing eastward displacement of the SPSA (1950–1965, no data available before 1950, GMST usually lags 3–5 years behind SST). In addition, the meridional pressure gradients driving semi-geostrophic southerly winds near the west coast of South American continent are likely to be stronger with an ongoing eastward displacement of the SPSA (Falvey and Garreaud 2009, Belmadani *et al* 2017), conducive to a growing of the alongshore southerly winds as well.

We have examined not only the prescribed monitoring buoy B_{10} but also the others (supplementary figure S1) deployed by NOAA along the equator, and found that all observational records in the eastern tropical Pacific exhibited an ongoing increase

displacements occurred during 2005–2010, an eastward trend resumed soon in 2010. An assessment of the long-term relationship between the meridional winds in B_{10} and the SPSA position is seriously

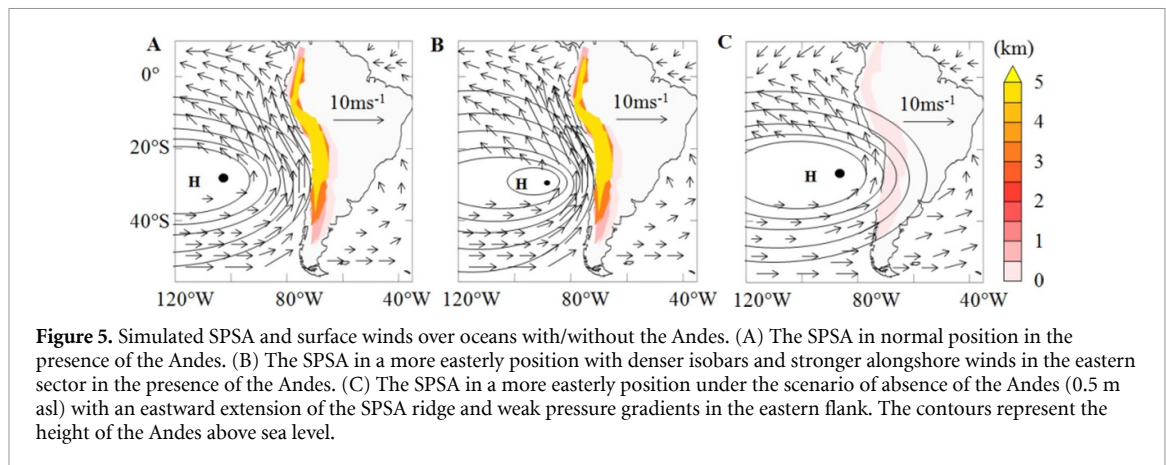


trend in the meridional winds and a persistent cooling trend in SSTs, respectively, with the zonal winds less changed even slightly weakened during 1992–2018 (figure 2(A) and supplementary figures S5 and S6), contrast to the previous studies (L'Heureux *et al* 2013, England *et al* 2014). Their consistency in all monitoring buoys suggests that these observational data are reliable and robust. Based on the theories of the atmospheric and oceanic science, an eastward migration of the SPSA tends to intensify the pressure gradients in the eastern sector of the SPSA, resulting in stronger southerly winds (figures 4(A) and (B)), in turn, more intense wind-driven upwelling along the coast of South America and vast cooling in the eastern Pacific due to an intensification of the offshore Ekman transport and Ekman pumping, and ultimately hiatus decades. Meanwhile, increased southerly winds are also thought to be able to cause a decrease in SST owing to turbulent fluxes, especially latent heat fluxes (Ancapichun and Santiago 2015).

3. Model simulations

To test our hypothesis, a dynamic approach is required. We first simulate the response of the surface winds to the position anomalies of the SPSA using a state-of-the-art coupled general circulation model (GFDL-ESM2G) participating in the CMIP5 (Bracegirdle *et al* 2013, Kumar *et al* 2015) (see Methods). The anomalies for the observed variables are defined as the deviations from the 1950 to 2012 climatological mean, and calculated by removing the long-term monthly climatology over the entire period available for the model. For this study, we use a configuration with 152 grid points in longitude, 108 in latitude and 32 vertical layers, with the first six layers contained within the first kilometer above the surface. Topography of the Andes is derived from a 10 min U.S. Navy data set and spatially interpolated to the model grid. A control experiment is performed using a preindustrial run, with boundary conditions remained at preindustrial levels. A horizontal convergence is set between 30° and 45° S and a divergence

between 0° and 25° S. This model is forced by the historical forcing and position anomalies of the SPSA. For simplicity, the surface wind stress is assumed to be linearly related to pressure gradient in the eastern flank. In this context, two experiments have been performed: one forced with zonal position anomalies of the SPSA, the other with meridional position anomalies of the SPSA. Other drivers, such as GHGs, ozone, aerosols and solar variability, are supposed to change in climatological monthly mean. In order to highlight the regional features of geography and topography in South American continent, a consideration of the presence of the Andes is necessary. Previous studies indicate that the influence of the Andes on the southerly winds has been largely underestimated (Xu *et al* 2004, Sepulchre *et al* 2009) possibly due to a failure of considering 'venturi effect' between the SPSA and the Andes. In a bid to overcome this issue, it is assumed that the southerly winds are horizontally convergent/divergent before/after passing through the 'gateway' (the horizontal line with width of several latitudes linking the center of the SPSA and the Andes acts as a 'gateway'), although this assumption cannot completely reflect the 'venturi effect' between them. When the air coming from the south along the isobaric lines (gradually narrowing in the south of the 'gateway') pass through the 'gateway', the Bernoulli's principle is applied, with an instantaneous acceleration of the air. The more eastward the SPSA, the narrower the 'gateway', the stronger the alongshore winds. As expected, the southerly winds in the eastern tropical Pacific sharply follow the SPSA in zonal position anomalies ($r = 0.98$, see the scatter plot in supplementary figure S7) while the meridional position of the SPSA and its intensity remain unchanged, with the southerly winds less changed elsewhere, consistent with observations indicating a significant upward trend of the meridional winds in the eastern Pacific during 1992–2018 (figure 2(B)). Likewise, we run the model for testing the response of the zonal winds in the eastern tropical Pacific to the SPSA in position anomalies by altering the latitude of the SPSA alone subject to historical changes. As anticipated, the simulations demonstrate that the zonal winds in the



eastern tropical Pacific well track the variations of the SPSA in meridional position anomalies ($r = 0.91$), but do not seem to be as pronounced as the meridional winds due largely to lack of the ‘venturi effect’ in the northern sector of the SPSA, consistent with observations showing a small trend of the zonal winds over the last 27 years (supplementary figure S5). The model experiments suggest that the magnitude of the trade winds in zonal component is mainly determined by the latitudinal anomalies of the SPSA, with the SPSA in longitudinal anomalies playing a minor role, consistent with observations indicating that the trade winds in zonal component in the eastern Pacific remained steadily weakened while a slight southward shift of the SPSA took place during 1992–2018 (supplementary figures S3 and S5). Similarly, the model experiments corroborate that the longitudinal anomalies of the SPSA are the dominant factor for the southerly wind anomalies, with the SPSA in meridional position anomalies playing a negligible role (a similar scatter plot has been performed but not shown here).

An eastward shift of the SPSA is likely to result in two prominent consequences: a stronger pressure gradient in the eastern flank of the SPSA and an intensification of the migratory anticyclones in the southwest Pacific. Our simulations capture these major characteristics of the surface winds, involving a strengthening trend of the zonal winds ($+0.8 \text{ m s}^{-1} \text{ decade}^{-1}$) in the central tropical Pacific and around the midlatitudes of the Northern Hemisphere and a slight weakening trend elsewhere ($-0.6 \text{ m s}^{-1} \text{ decade}^{-1}$) (figure 3(A)), while a significant intensification trend of the meridional winds in the eastern Pacific ($+1.1 \text{ m s}^{-1} \text{ decade}^{-1}$), particularly in the southeast Pacific over the past 27 years (figure 3(B)). All simulated trends are consistent with observed trends in corresponding basins throughout observed periods at the $p = 0.1$ (two-tailed) confidence level, i.e. differences between modeled and observed trends are within the 5%–95% range expected from the control variability. Model simulations also illustrate that a failure of

considering ‘venturi effect’ would lead to a loss of $\sim 10\%$ – 15% in meridional wind intensity off central Chile coast.

We subsequently test the ocean SST response to the surface wind anomalies using a global ocean model subject to historical changes in radiative forcing coupled to a simple energy-moisture balance atmosphere forced by prescribed zonal and meridional wind anomalies (Weaver *et al* 2001) (see Methods). In this model, the radiative forcing is identical to the GFDL-ESM2G, the surface wind stress is a combination of the dataset provided by ECMWF interim reanalysis and observed anomalies along the west coast of South American continent. Wind stress trends during the simulated periods are also applied to the ocean-atmosphere latent and sensible heat fluxes. An imposed upward wind stress trend in the eastern Pacific is continued until 2012, and then remaining constant onwards until the end of the model run. Prior to the calculations, a 3 month binomial filter is applied to all wind stress data (including both the observed and CMIP5 modeled) in order to reduce month-to-month noise. This has a distinct advantage over the other methods in that it can directly simulate the oceanic response to the prescribed wind trends without atmospheric feedbacks. The simulation results demonstrate that the ocean model SST response to the prescribed meridional wind anomalies well reproduces the current patterns of the ocean warming and cooling in the tropical Pacific (supplementary figure S8), with slight cooling ($-0.29 \text{ }^{\circ}\text{C decade}^{-1}$) in the central, strong cooling ($-0.444 \text{ }^{\circ}\text{C decade}^{-1}$) in the eastern and moderate warming ($+0.333 \text{ }^{\circ}\text{C decade}^{-1}$) in the western tropical Pacific (figure 3(C)) as the response of the tropical Pacific to interplays of the anthropogenic forcing and the regional climate variability.

Model simulation also shows that observed zonal wind anomalies in the central equatorial Pacific are able to create very limited SST anomalies, however, stronger-than-observed zonal wind anomalies in the central Pacific can produce equivalent SST anomalies

observed, but this is inconsistent with observed scenarios, implying that zonal wind anomalies may play a role in partially contributing to the cooling over the past decades.

An eastward migration of the SPSA is apt to intensify the pressure gradients in the eastern flank of the SPSA due to interactions between the SPSA and the Andes, in turn, produce intense southerly winds along the west coast of South American continent, thus driving strong wind-induced upwelling with cooler waters from deep sea cooling where it passes through, including the west coast and vast areas of the eastern tropical Pacific, consistent with observed SST pattern. As the cool waters (mean climatological SST 24°C – 25°C) in the eastern tropical Pacific move westward along the equator under the strong solar radiation, the SST will rise by about $\sim 3.5^{\circ}\text{C}$ – 4.5°C , attaining about 30°C in the western tropical Pacific after considering heat exchange between the atmosphere and sea. The warming pool in the western Pacific, however, exhibits a growing tendency during the past decades due to interactions between the anthropogenic forcing and the internal variability with the amplitude of the former larger than that of the latter, consistent with observed SST pattern.

To test the response of the alongshore wind stress to the eastward anomalies of the SPSA, the regional oceanic modeling system (ROMS) is employed. The ROMS is a hydrostatic, primitive equation model that has achieved great success in previous simulations on the relationship between the alongshore wind stress and the position of the SPSA (Haidvogel *et al* 2000, Shchepetkin and McWilliams 2005) using a terrain-following vertical coordinate and a split mode technique to efficiently solve for baroclinic and barotropic variables within the domain of 120° – 40° W and 10° N– 60° S. The surface forcing for the southeastern Pacific Ocean circulation model is derived from the AGCM model in the form of monthly mean energy fluxes. Open boundary conditions and surface forcing are linearly interpolated at each time step between the monthly averaged values to guarantee smooth variations in time. The ROMS model grid has a horizontal resolution of $1/2^{\circ}$ and 30 non-uniform vertical levels, with clustering near the surface. The ROMS forced by eastward anomalies of the SPSA alone well captures the main features of the surface meridional wind stress in the southeast Pacific during 1992–2018, with peaking stress near central Chile coast (figure 4(B)), despite a more zonal extension at midlatitudes, excellently in agreement with observational records (figure 4(A)). A parallel experiment forced by the Andean uplift indicates that the response of the surface winds to the Andean altitude is sensitive, with a corresponding reduction of 11%, 18%, 29% and 61%, respectively, in wind strength off central Chile coast (at 30° S), if the elevation were reduced by 1 km, 2 km, 3 km and 4 km, respectively, qualitatively consistent with the previous conclusion

(Sepulchre *et al* 2009). A complete removal of the Andes (0.5 m asl) would result in a decrease of the southerly winds from an average $\sim 10\text{ m s}^{-1}$ (Rahna and Garreaud 2014, supplementary figure S9) to ~ 3.2 – 3.5 m s^{-1} near central Chile coast and a significant thinning of the stratocumulus deck, with strong upwelling along the west coast of South America no longer existing due to combined effects of a vanishing of the ‘venturi effect’, an eastward extension of the SPSA ridge towards inland regions and a significant diminishing of upwelling-favorable winds (the Chilean coastal area would be no longer the eastern edge but the internal area of the SPSA with much smaller pressure gradients) (figures 5(A)–(C)), concurrently allowing a westward intrusion of warm air from South American continent, in turn, significantly raising the SSTs with anomalies of 3.3°C – 3.5°C in the eastern Pacific (for details of the mechanisms, see Sepulchre *et al* 2009).

4. Discussions and conclusions

The Andes, characterized by world’s longest mountain range along the west coast of South America and world’s steepest cliffs rising up to an average height of $\sim 4500\text{ m}$ above mean sea level (Xu *et al* 2004), acts as an important natural barrier in isolating the atmospheric zonal circulation in the Southern Hemisphere, thus forming an invisible north-south oriented ‘tunnel’ between the Andes and the center of the SPSA for the alongshore winds to pass through. The interactions between the Andes and the zonal migrations of the SPSA have largely modified the atmospheric dynamics, in turn, the ocean circulations in the south Pacific (Sepulchre *et al* 2009). Various model experiments have shown that the role of the Andes in the formation of stratus and/or coastal winds has been largely underestimated by most current general circulation models (GCMs) (Ma *et al* 1996, Xie 1996, Yu and Mechoso 1999). As a significant eastward displacement of the SPSA occurs, the ‘tunnel’ becomes narrow with much more denser isobars in it, producing stronger pressure gradient forces, in turn, more intense southerly geostrophic winds after an accelerating in the ‘tunnel’ (following Bernoulli’s theorem), thus advecting more cooling waters equatorward as well as westward along the equator to feed the South Equatorial Current, and finally contributing to hiatus decades. Despite an enhancement of the meridional winds occurring in the eastern Pacific and along the west coast of South America as well, its influence can widely spread out over entire eastern equatorial Pacific even part of the central equatorial Pacific through the circulations of the wind-induced upwelling. Furthermore, the Andes tends to enhance the stratus cloud deck that can effectively reflect and block the incoming solar radiation and largely shrink the duration of the southern intertropical convergence zone (ITCZ) in

a warm season (Xu *et al* 2004), hence facilitating a stronger cooling in the southeast Pacific.

The unique geography and topography of the Andes in South American continent has at least in part shaped the contrast between the south Pacific and the south Atlantic (Inatsu and Hoskins 2004, Rollenbeck *et al* 2015), despite the presence of the similar Southeast Atlantic Subtropical Anticyclone in the south Atlantic. The finding of an ongoing eastward migration of the SPSA and its ‘venturi effect’ formed along the west coast of South America may be profound because it not only reveals a substantial link between the SST in the eastern Pacific and the zonal position of the SPSA but also suggests a significant influence of the regional climate variability in the southeast Pacific on GMST, particularly highlighting far-reaching impacts on global climate. This also offers the scientists new insights into the predictability of the warming hiatus by tracking and projecting the evolutions of the SPSA and assessing the amplitude of interplays between the anthropogenic forcing and the regional climate variability.

The finding of the interactions between the Andes and an ongoing eastward migration of the SPSA and its ‘venturi effect’ formed along the west coast of South America, however, is not to disparage other factors, such as increased aerosols in stratosphere, abated solar radiation, more heat uptake in subsurface, etc, which may also play a role in generating a cooler surface in the eastern equatorial Pacific, rather, a necessary complement. Perhaps, the warming hiatus in the past decade is more likely to be ascribed to a combined effect of all associated factors. Therefore, further exact exploration is required in the future research.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Author contributions

Both authors contributed equally to this work and should be considered co-first authors.

Y J Zou designed this work, prepared the manuscript and figures, and interpreted results. X Y Xi was responsible for laboratory efforts and contributed to the computer programming and the model simulating.

Competing financial interests

The authors declare no competing financial interests.

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