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Potential effects of subduction rate in the key ocean on global warming hiatus

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Abstract

In this study, the possible effects of subduction rate on global warming hiatus were investigated using Simple Ocean Data Assimilation (SODA) data. This study first analyzed the characteristics of the temporal and spatial distribution of global subduction rate, which revealed that the North Atlantic meridional overturning circulation region and the Antarctic Circumpolar Current region are the two main sea areas with great subduction variations. On this basis, four key areas were selected to explore the relationship between the local subduction rate and the global mean sea surface temperature. In addition, the reason for the variations in subduction rate was preliminarily explored. The results show good correspondence of the subduction of the key areas in the North Atlantic meridional overturning the circulation region and the Antarctic Circumpolar Current region to the global warming hiatus, with the former leading by about 10 years. The subduction process may be a physical mechanism by which the North Atlantic overturning circulation and the Antarctic Circumpolar Current act on the stagnation of global warming. Advection effect plays an important role in the variations in subduction in the key regions. In the Antarctic Circumpolar Current region, the magnitude of sea surface wind stress is closely related to the local changes in subduction.

Key words: global warming hiatus, sea surface temperature, inter-decadal variation, subduction rate

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1 Introduction

Since the industrial revolution, the global average surface temperature has risen with the increase in human-related greenhouse gases. At present, global warming has caused concern throughout the world. However, available global surface temperature data have not shown an obvious upward trend since 1998, and some have even stagnated in recent years (e.g., Easterling and Wegner, 2009; Knight et al., 2009; Kerr, 2009; Foster and Rahmstorf, 2011; Met Office, 2013a; Chen et al., 2014). This so-called "global warming hiatus" has gained attention from many climate scientists.

Global mean surface temperature is often used as the main indicator for climate change studies. However, in addition to surface temperatures, some other important variables in the climate system can help explain the current climate status. During global warming stagnation, land surface temperature, sea surface temperature and the heat content of the upper 800 m in the ocean all showed the same hiatus characteristics as global surface temperature (Met Office, 2013a, b). Combined, these data indicate that global warming has stagnated in the last 10 years.

Many scientists have tried to explain the phenomenon since it first appeared. From a large point of view, climate system external forcing and energy redistribution are the two main angles (Wang et al., 2014). The Met Office's report comprehensively analyzed important factors in radiative forcing of the climate system, and argued that it is unlikely to explain the recent pause in global warming based only on a reduction in radiation energy entering the climate system. Although in the global warming stagnation process, the question that which ocean and which natural variability process play a key role is still controversial, but scientists generally agree that excess heat transfer from the atmosphere and the ocean surface to the deep ocean is the main cause of the global warming hiatus (Guemas et al., 2013; Balmaseda et al., 2013; Chen and Tung, 2014; Meehl et al., 2011; Wang et al., 2015). Moreover, various studies have investigated the influence of interannual and decadal natural variability (e.g., PDO, AMO, ENSO) in the oceans (Meehl et al., 2011; Kosaka and Xie, 2013; Trenberth and Fasullo, 2013; Heffernan, 2014; Huber and Knutti, 2014; Trenberth, 2009; Trenberth et al., 2009; Chen and Tung, 2014; Yang et al., 2017), but it is still unknown which specific physical processes in the ocean play key roles in the extra heat transfer from the surface to the deep ocean.

The subduction process can bring the anomalous signal of the atmosphere and mixed ocean layer to the sub surface ocean, which can communicate exactly between the upper and the deep ocean (Liu et al., 2006). Many studies have analyzed the temporal and spatial characteristics of global or regional subduction (e.g., Yu et al., 2015; Liu and Huang, 2010; Chen et al., 2010; Liu and Wang, 2014; Qu et al., 2002, 2016; Suga et al., 1989). Therefore, this study was conducted to investigate the subduction in

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sensitive areas and its relationship with global warming hiatus based on the subduction process.

2 Data and methods

2.1 *Data*

The temperature, salinity and velocity data available in Simple Ocean Data Assimilation (SODA) 2.2.4 (Carton and Giese, 2008) were used in this study. The SODA dataset contains ocean reanalysis assimilation data developed jointly by the University of Maryland and the Texas A&M University. It is the first time for SODA dataset to release data version (SODA 2.2.4) with period over one hundred years, providing abundant and reliable ocean data for long-term climate studies. Long time series data are more suitable for investigations of decadal time scale variations such as global warming, which is why we selected the SODA data. The reanalysis dataset is output in the form of monthly average data, and the horizontal resolution of the model is 0.5°×0.5°. The potential density and mixed layer depth were computed from the monthly average data from 1871 to 2010 for this study.

2.2 *Method*

The method for calculation of the subduction rate described by Huang and Qiu (1994) was used in this study. The method adopts the Lagrange viewpoint, tracking water particles released from the bottom of the ocean mixed layer in late winter from when the mixed layer reaches its maximum depth for a whole year until next late winter. We used the vertical velocity in the SODA data to calculate vertical pumping instead of Ekman pumping and the adjustment term of surface meridional velocity, which differs from the original method mentioned described by Huang and Qiu. This alternative method has also been adopted in other studies (Liu, 2012). The specific equation used is as follows:

$$S_{\rm ann} = -\frac{1}{T}\int_{t_1}^{t_2} w_{\rm mb}\,{\rm d}t + \frac{1}{T}\left(h_{\rm m}(t_1) - h_{\rm m}(t_2)\right), \qquad (1)$$

where $S_{\rm ann}$ is the subduction rate, $w_{\rm mb}$ is the vertical velocity of the water particle at the mixed layer bottom, and $h_{\rm m}$ is the depth of the mixed layer. When calculating subduction, tracking the water particles released from the mixed layer bottom in late winter t_1 for a full year until next late winter t_2, the integration time is one year, T. The first item on the right side of Eq. (1) represents the contribution of vertical pumping at the bottom of the mixed layer, while the second item is the mixed layer depth advection, which is mainly related to the horizontal distribution of the mixed layer depth and the horizontal velocity. The annual mean subduction rate is the water mass that passes through the seasonal thermocline from the mixed layer to the permanent thermocline in an entire year. This value reflects how many water masses are released from the bottom of the mixed layer into the thermocline in the first late winter that do not return to the mixed layer in the next late winter. Therefore, the annual mean subduction rates should all be non-negative values, and the negative values in the calculation result are meaningless. Negative values indicate that there is no effective detrainment, for which case we set the annual mean subduction to zero. In the Northern Hemisphere, we selected March as the late winter time point, while in the Southern Hemisphere, September was selected as the late winter time point. The definition of the mixed layer depth used in this paper was as follows: the depth where the water potential density is 0.125 kg/m^3 larger than that of the sea surface in the vertical direction.

3 The temporal and spatial distribution of global subduction rate

Before exploring the relationship between the subduction rate and global warming hiatus, we analyzed the spatial distribution and temporal variation of global subduction rate in the SODA data.

Figure 1 shows the climatological distribution and standard deviation of global subduction from 1871 to 2009 calculated using the SODA data. Globally, the high values were mainly located in the middle and low latitudes of the North Pacific and North Atlantic, mid-latitudes of the South Indian Ocean, and parts of the South Pacific and South Atlantic. These regions are also characterized by the great standard deviation of subduction. These results are in good agreement with the spatial distribution of the subduction rate calculated by Liu (2012).

We also calculated the time variation of the global mean subduction rate anomaly. As shown in Fig. 2, there was obvious inter-decadal variation in the anomaly curve. In nearly one hundred years from 1871 to 1960, the global mean subduction has maintained negative anomalies, staying at a relatively low level. From the mid-1960s to 2009, the anomaly of the global mean subduction shifted from negative to positive, maintaining a rapid increasing trend.

Figure 3 shows the variations in global mean sea surface temperature anomaly time from 1871 to 2010 based on the SODA data. There was an obvious inter-decadal change over the last

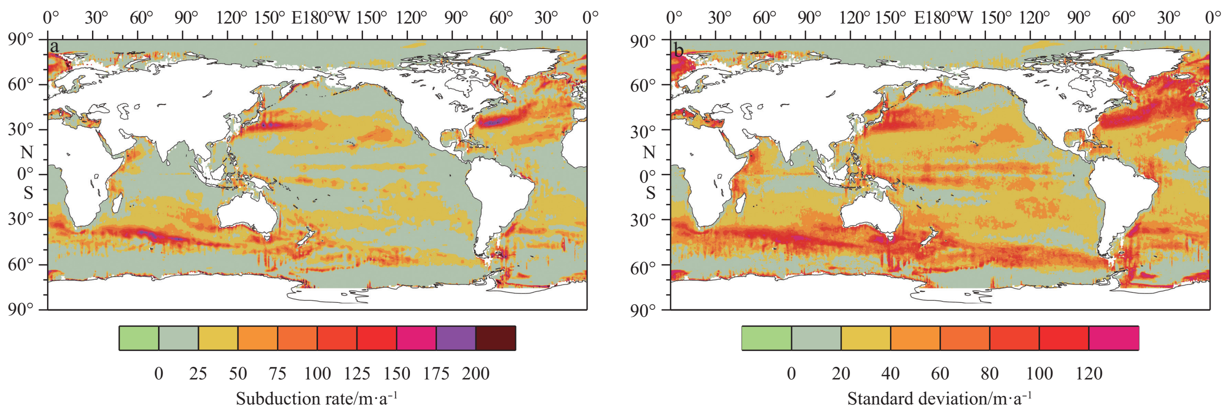

Fig. 1. The climatological spatial distribution (a) and standard deviation (b) of the global subduction rate during 1871–2009.

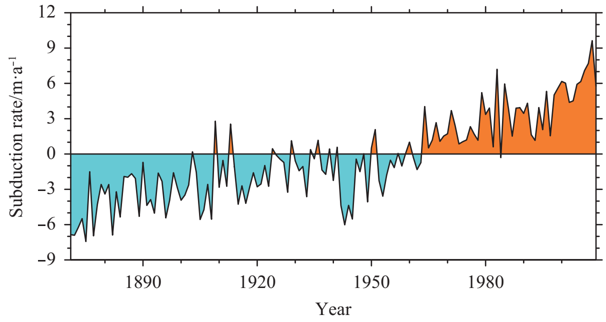

Fig. 2. Variations in subduction rate anomaly during 1871–2009.

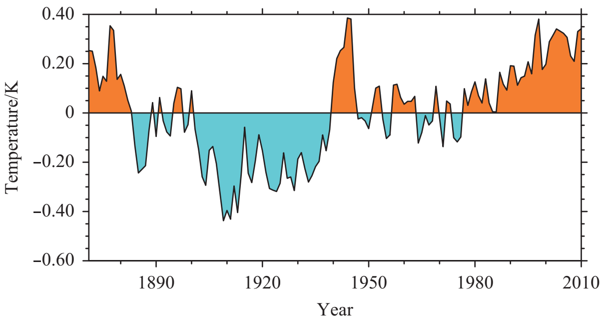

Fig. 3. Variations in global mean sea surface temperature anomaly.

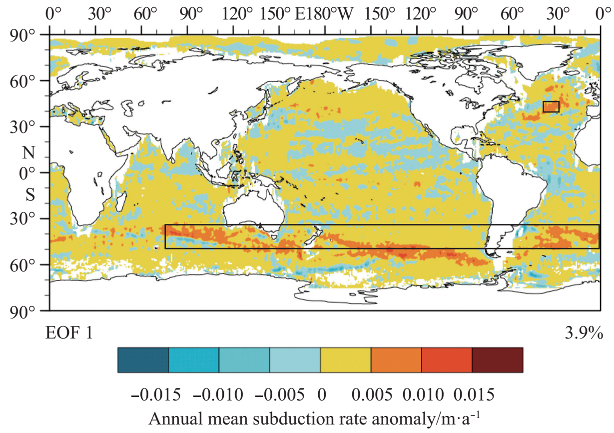

Fig. 4. The EOF first spatial mode of annual mean subduction rate anomaly during 1871–2009.

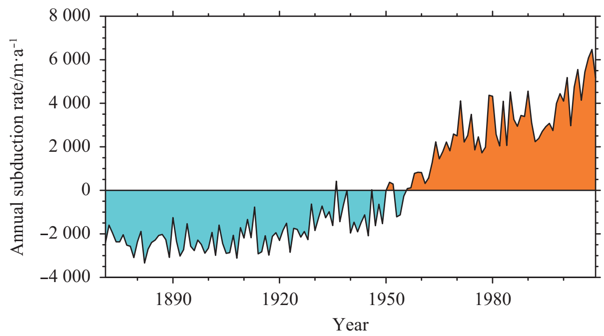

Fig. 5. The EOF first mode time coefficient of annual subduction rate during 1871–2009.

century and a half in time variation, which mainly manifested as a consistent warming trend, i.e., global warming. However, after 1998, the rate of temperature rise decreased, which is known as the so-called "global warming hiatus". Comparison of Fig. 3 and Fig. 2 reveals that both time curves show obvious decadal variations and they both showed a gradual ascending trend after the 1880s. The correlation coefficient between the SST time variation and the subduction rate variation reached 0.38 during 1881–2009, which exceeded the significant level of 99.9%. Hence, it can be assumed that there is a significant correlation between the global mean subduction rate and the global mean sea surface temperature.

4 Key area affecting global warming hiatus

Based on the above analysis, we further focus on the question that the subduction rate in which key area plays a crucial role in global warming stagnation process. To accomplish this, we conducted EOF analysis of the annual mean subduction anomaly from 1871 to 2009. Figures 4 and 5 show the first spatial mode and the corresponding time coefficient of the global annual subduction rate anomaly, respectively.

The spatial distribution of annual mean subduction anomaly primarily mainly manifested on the anti-phase between the sea areas of the subtropical North Pacific, North Indian Ocean, tropical South Atlantic Ocean and other sea areas. Another notable feature is that areas with the largest subduction rate variability are only located in the North Atlantic meridional overturning circulation region and the Antarctic Circumpolar Current region, which may indicate that the two circulation system is closely related to local variations in the subduction rate. The corresponding time coefficient shows obvious inter-decadal variation, especially after the mid-1950s, when the phase converts from negative to positive. During 1871–2009, the correlation coefficient between the global mean sea surface temperature and the first mode time coefficient of annual mean subduction was 0.44, while the correlation coefficient reached as high as 0.56 when the latter led the former by 8 years. This may indicate that the change in global annual mean subduction may precede the change in sea surface temperature; thus, we can predict the global mean sea surface temperature anomaly according to the variation of global mean subduction rate in the future.

According to the EOF first spatial mode of global annual mean subduction rate shown in Fig. 4, we found that the subduction rates in the North Atlantic Ocean (40°–45°N, 35°–25°W) and Antarctic circumpolar area (35°–50°S, 75°–0°E) had relatively large variations (these two regions are marked by black rectangles in Fig. 4). Chen and Tung (2014) and Meehl et al. (2013) also found that heat absorption in these two areas may exert influence over the stagnation of global warming. Therefore, further research will be carried on these two regions.

In addition, to reduce the subjectivity in selecting key areas, we first selected the two regions mentioned above as the maximum range, then traversed all rectangular regions in this range with horizontal resolution as the smallest areal unit, after which we analyzed the correlations between the regional mean subduction rate anomaly of all possible areas and the global mean sea surface temperature. Finally, four regions in which the subduction had relatively larger correlations with the global mean sea surface temperature were selected. These regions were located in the North Atlantic (42.25°–42.75°N, 34.25°–28.75°W), southeastern sea area of Australia (45.25°–51.25°S, 153.25°–153.75°E), the

South Pacific (50.75°–51.25°S, 162.75°–100.25°W), and the South Atlantic (40.75°–46.75°S, 39.75°–4.75°W). The correlations between the subduction rates in the areas mentioned above and the global mean sea surface temperature are shown in Table 1. Good correspondence of subduction in the key regions with the time variation of global sea surface temperature was observed, with the former leading by about 10 years (9–13 years), and all correlation coefficients exceeding the significance level of 99.9%. These findings indicate that the time variations in subduction rate anomaly in these areas had a predictive effect on variations in global mean sea surface temperature; thus, we can infer the changes in global mean sea surface temperature according to the variations in subduction rate in advance. The standardized timelines of subduction rate in the key areas and the global mean surface temperature are shown in Fig. 6.

Table 1. Correlation between the mean subduction of key regions and the global mean sea surface temperature

Key region	Specific range	Lead-lag time with global mean surface temperature	Correlation coefficient
The North Atlantic	42.25°–42.75°N, 34.25°–28.75°W	Leading 9 years	0.40
The southeastern sea area of Australia	45.25°–51.25°S, 153.25°–153.75°E	Leading 12 years	0.49
The South Pacific	50.75°–51.25°S, 162.75°–100.25°W	Leading 11 years	0.48
The South Atlantic	40.75°–46.75°S, 39.75°–4.75°W	Leading 13 years	0.48

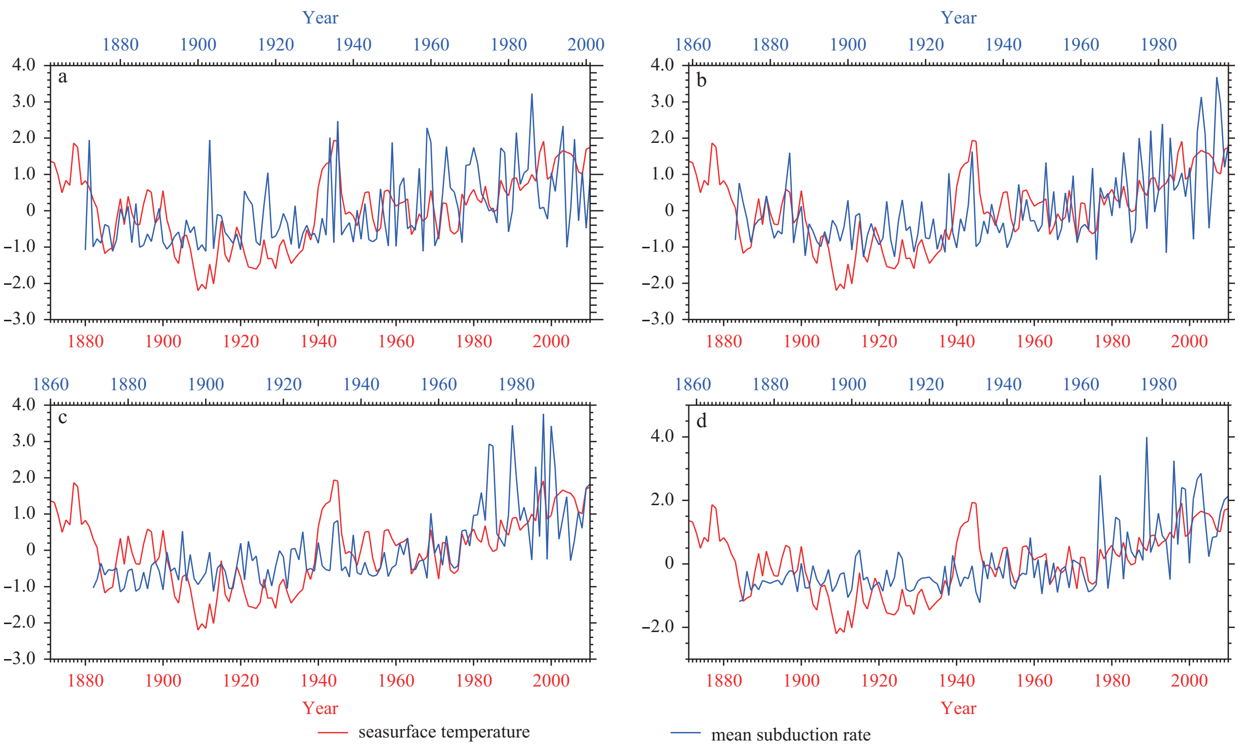

Fig. 6. Standardized time lines of the global mean sea surface temperature (red) and the regional mean subduction rate of key areas (blue) in the North Atlantic (a), the southeastern sea area of Australia (b), the South Pacific (c), and the South Atlantic (d).

5 Reason analysis of the variation of subduction rate in key areas

The formula used to calculate the Lagrange viewpoint of the subduction mentioned above revealed that the subduction is composed of the vertical pumping term and the horizontal advection term. The vertical pumping term is the result of a combination of Ekman pumping velocity and the vertical velocity in the mixed layer bottom, which includes not only the effects of sea surface wind curl, but also the deepening effect on mixed layer induced by heat loss in winter. The advection term was mainly related to the horizontal distribution of the mixed layer depth level and the horizontal velocity.

To determine which processes dominate the variations in the subduction rate in key areas, the temporal variations of the regional mean vertical pumping term and the advection term were further examined. Figure 7 shows the temporal variations of the regional mean subduction rate, vertical pumping term and advection term in the four key sea areas. Both the phase and amplitude of the advection term series were consistent with the subduction rate in all regions, indicating that advection is the dominant factor influencing subduction rate variability in all key sea areas. The vertical pumping in these regions does not play a role in inducing the water particles to enter the seasonal or permanent thermocline from the mixed layer, nor does it make any positive contributions to the subduction in these regions. Therefore, the advection effect is considered the main reason for the variations in subduction rate in the key regions.

The horizontal distribution of the mixed layer depth and the

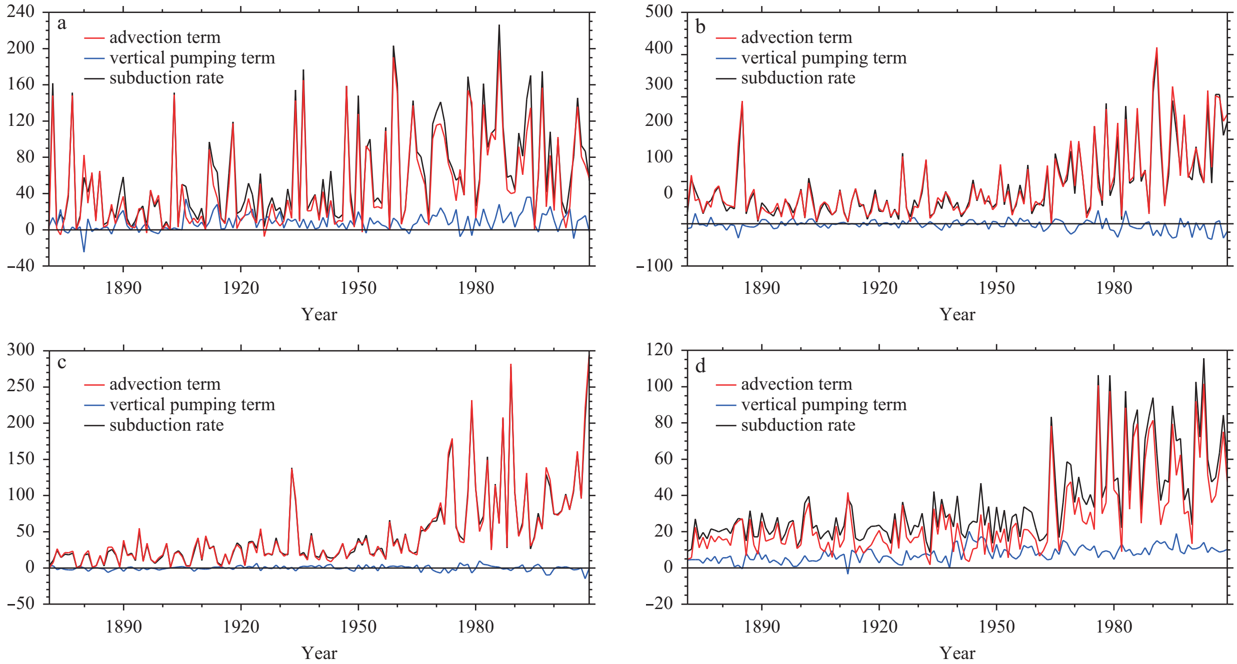

Fig. 7. The time series of regional mean subduction rate (black), vertical pumping term (blue) and advection term (red) of the key areas in the North Atlantic (a), the southeastern sea area of Australia (b), the South Pacific (c), and the South Atlantic (d).

horizontal current velocity are the two important factors affecting the advection term. Liu et al. (2006) pointed out that the sea surface wind can affect variations in the subduction rate by influencing the ocean advection process. Next, we took the key regions in the Antarctic Circumpolar Current region as an example to discuss the effects of the sea surface wind stress on the advection term of subduction rate. Figure 8 shows the standardized temporal series of the regional mean magnitude of sea surface wind stress and subduction rate in the key areas. The correlation coefficients of the three regions all exceed the significant level of 99.9%, indicating that the increase in sea surface wind stress magnitude in these regions had positive effects on the subduction. In other words, the increasing magnitude of the sea surface wind stress under the horizontal distribution differences in the mixed layer depth could partly explain the abnormal changes in subduction rate in these regions, as well as influence variations in the global mean sea surface temperature.

6 Discussion and summary

In this study, the global warming hiatus since 1998 was analyzed from the perspective of global mean subduction rate. The relationship between the global mean sea surface temperature and the subduction rate was specified. The results revealed that the North Atlantic meridional overturning circulation region and the Antarctic Circumpolar Current region were the two main sea areas with great subduction variations in the EOF analysis result. Four key areas were selected from the two regions mentioned above for further analysis, which revealed a good correlation between subduction of the key areas and the global mean sea surface temperature, with the former leading by about 10 years. Further analysis shows that advection plays a leading role in the change in subduction rate in the four key sea areas. In the Antarctic Circumpolar Current region, the increase (decrease) in sea surface wind stress was found to have a positive (negative) effect on the local subduction rate.

Overall, the results indicate that sea areas that are closely related to global warming stagnation are mainly located in the North Atlantic overturning the current region and the Antarctic Circumpolar Current region from the point of view of the subduction rate. The subduction process may be a physical mechanism by which the North Atlantic overturning circulation and the Antarctic Circumpolar Current act on the stagnation of global warming. However, further studies are needed to determine the mechanisms by which the two circulations affect changes in loc-

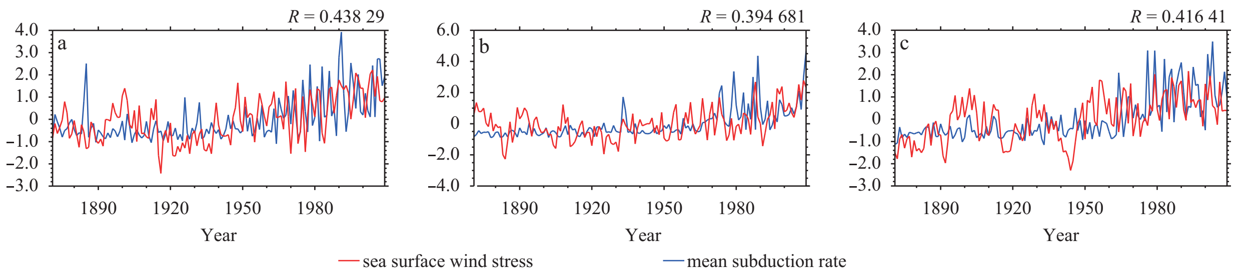

Fig. 8. Standardized time series of sea surface wind stress (red) and regional mean subduction rate (blue) in the southeastern sea area of Australia (a), the South Pacific (b), and the South Atlantic (c).

al subduction rates and how these changes impact global warming stagnation.

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