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An Incursion of Off-Equatorial Subsurface Cold Water and Its Role in Triggering the "Double Dip" La Niña Event of 2011

ZHENG Fei*[1], FENG Lisha[1,2], and ZHU Jiang[1]

[1]*International Center for Climate and Environment Science, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[2]*College of Atmospheric Sciences, Chengdu University of Information Technology, Chengdu* 610225

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ABSTRACT

Based on Global Ocean Data Assimilation System (GODAS) and NCEP reanalysis data, atmospheric and oceanic processes possibly responsible for the onset of the 2011/12 La Niña event, which followed the 2010/11 La Niña even—referred to as a "double dip" La Niña—are investigated. The key mechanisms involved in activating the 2011/12 La Niña are illustrated by these datasets. Results show that neutral conditions were already evident in the equatorial eastern Pacific during the decaying phase of the 2010/11 La Niña. However, isothermal analyses show obviously cold water still persisting at the surface and at subsurface depths in off-equatorial regions throughout early 2011, being most pronounced in the tropical South Pacific. The negative SST anomalies in the tropical South Pacific acted to strengthen a southern wind across the equator. The subsurface cold water in the tropical South Pacific then spread northward and broke into the equatorial region at the thermocline depth. This incursion process of off-equatorial subsurface cold water successfully interrupted the eastern propagation of warm water along the equator, which had previously accumulated at subsurface depths in the warm pool during the 2010/11 La Niña event. Furthermore, the incursion process strengthened as a result of the off-equatorial effects, mostly in the tropical South Pacific. The negative SST anomalies then reappeared in the central basin in summer 2011, and acted to trigger local coupled air–sea interactions to produce atmospheric–oceanic anomalies that developed and evolved with the second cooling in the fall of 2011.

Key words: "double dip" La Niña, subsurface cold water, incursion, off-equatorial process

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1. Introduction

ENSO is the strongest signal of air–sea interaction, which periodically develops in the tropical Pacific and exerts a surprisingly significant influence on short-term global climate change (e.g., Huang and Wu, 1989; Neelin et al., 1998; Alexander and Scott, 2002; Toniazzo and Scaife, 2006; Philippon et al., 2012). The significance of ENSO has been documented by many researchers (e.g., Wang and Picaut, 2004; McPhaden et al., 2006; Wang et al., 2012). Recently, ENSO has been receiving increased attention due to the appearance of a new type of El Niño, the Central-Pacific (CP) El Niño (e.g., Kao and Yu, 2009; Yu et al., 2010), which has maximum SST anomalies centered near the dateline.

As many efforts have been made to develop and enforce the performance of ENSO models (e.g., Ji et al., 1996; Latif et al., 1998; Kleeman and Moore, 1999; Zhang et al., 2003; Zheng et al., 2006a, 2006b; 2007; Zheng and Zhu, 2008; Jin et al., 2008; Zheng et al., 2009; Zheng and Zhu, 2010a, 2010b; Barnston et al., 2012), their skills in predicting ENSO have gradually improved. However, the real-time ENSO prediction skill of models in the past decade has been somewhat lower than the less advanced models of the 1980s and 1990s (Barnston et al., 2012). Additionally, Barnston et al. (2012) suggested an apparent retrogression in skill exists for ENSO prediction in the 2002–11 study period compared with that in the 1981–2010 period. The 9-yr sliding correlation for the hindcasts over the 1981–2010 period has an average score of 0.65 at a 6-month lead time, but the prediction skill of correlation decreases to 0.42 for the 2002–11 period. There are two possible explanations for this abnormal phenomenon in the past decade: one is due to the more frequent occurrences of CP El Niño (Lee and McPhaden, 2010; McPhaden et al., 2011; Xiang et al., 2012); and the other is the appearance of a special kind of La Niña (Zhang et al., 2013; Hu et al., 2014), which follows a previous La Niña event (e.g., the 2011/12 event), and is referred to as "double dip" La Niña hereafter in this paper.

McPhaden and Zhang (2009) argued that there is a ten-

* Corresponding author : ZHENG Fei
Email: zhengfei@mail.iap.ac.cn

dency for some La Niña events to persist and re-emerge for a second cooling year after 1980. However, most ENSO models are unable to successfully predict this kind of second cooling event until now (Barnston et al., 2012). Specifically, among all ENSO prediction models (14 dynamical and 8 statistical) listed on the International Research Institute for Climate and Society (IRI) website at http://iri.columbia.edu/climate/ENSO/currentinfo/SST_table.html, most failed to forecast the Niño3.4 SST anomalies of the 2011/12 event, starting from early-mid 2011, and only one model [an intermediate coupled model (ICM) used by Zhang et al. (2013)] gave a successful prediction of 2011 cold SST conditions over the tropical Pacific one year in advance. This presents a critical challenge to the ENSO prediction community (Barnston et al., 2012) and suggests an imperative demand to understand the physical processes leading to the second-year cooling in 2011. Zhang et al. (2013) demonstrated that thermocline feedback is a crucial mechanism affecting the interannual SST evolution of the "double dip" in 2011, which is specifically represented by the relationship between the oceanic entrainment temperature (T_e) and sea level (SL) in the ICM. At the same time, the persistent and sufficiently strong easterly wind anomaly over the western-central equatorial Pacific, which operates to sustain the large negative subsurface thermal variability off and on the equator to significantly affect the SST evolution during 2010–12 associated with the thermocline feedback, has been demonstrated to be another key process by Zhang et al. (2013). Hu et al. (2014) argued there can be two preconditions responsible for the continuation of a La Niña event: one, which is necessary but insufficient on its own, is that the previous La Niña must be a strong event; and the other is whether there are eastward propagating downwelling warm equatorial Kelvin waves during the decaying phase of the first La Niña. Moreover, it has been suggested that the subtropical–tropical teleconnection is important and cannot be ignored for the occurrence of ENSO events (Vimont et al., 2001; Wang and Yang, 2014). Vimont et al. (2001) proposed a seasonal footprinting mechanism to explain how midlatitude atmospheric variability could lead to tropical ENSO variability via atmosphere–ocean coupling in the subtropics. Wang and Yang (2014) investigated the impact of subtropical Pacific sea surface temperature anomalies (SSTAs) on the equatorial ocean, and proposed a wind–evaporation–SST mechanism as playing the dominant role in equatorial SST changes. However, all previous studies on the 2011/12 La Niña event lack a detailed description of its onset and evolution due to the qualification of observations and oceanic 3D monitoring, which is crucial in order to understand the mechanism causing the second-year cooling during the long-lived 2010–12 La Niña event.

In this work, to elucidate the trigger mechanism of the 2011/12 La Niña event, we examine the atmospheric and oceanic processes related to the evolution of the 2011/12 La Niña in detail, through analyzing the 3D reanalysis fields from the Global Ocean Data Assimilation System (GODAS) and its calculated diagnostic variables. We focus on the roles played by off-equatorial subsurface temperature anomalies in the tropical South and North Pacific through examining the subsurface temperature evolution of isotherms. In order to observe the pathways consistently throughout the basin from the off-equatorial to the equatorial region, isothermal analyses are performed using the 3D temperature fields. Seeing as the subsurface temperature anomalies tend to propagate along isothermal surfaces, an isothermal analysis is necessary and can better characterize the temporal evolution and the 3D structure of the upper ocean. The major finding in this work is that the enhanced southeasterly wind anomalies over the tropical Pacific from March to June in 2011, associated with the negative SST anomalies in the tropical South Pacific that were left behind by the 2010 moderate La Niña event, played a key role in spreading the subsurface cold water over the tropical South Pacific northward. The subsurface cold water then broke into the equatorial region at thermocline depth to activate the onset of the second cooling in summer 2011. In addition, analyzing the temperature anomalies at isothermal surfaces makes it clear that the incursive pathway of cold subsurface water was along the thermocline depth and originated from off-equatorial regions, mostly in the tropical South Pacific.

The remainder of the paper is organized as follows. Section 2 briefly introduces the dataset and analysis method used in this work. Section 3 describes the onset and evolution of the 2011/12 La Niña event in detail. Section 4 is concerned with the incursion process from the extratropical subsurface cold water into the equatorial region. And finally, a discussion and conclusions are presented in section 5.

2. Dataset and analysis method

The monthly mean data for temperature and SL are from GODAS (Behringer and Xue, 2004), which are operationally provided by the National Centers for Environmental Prediction (NCEP). The horizontal resolution in the zonal and meridional direction of GODAS is $1^\circ \times (1/3)^\circ$ and the products have 40 levels with a 10 m resolution in the upper 200 m. The monthly mean atmospheric reanalysis data, including sea level pressure (SLP) and wind stress, are from the NECP–DOE (National Centers for Environmental Prediction–Department of Energy) Reanalysis II (Kanamitsu et al., 2002), with a resolution of $2.5^\circ \times 2.5^\circ$ and a T62 Gaussian grid (192×94), respectively. Both the GODAS products and atmospheric NCEP reanalysis datasets cover the period from January 1982 to December 2011, and the long-term climatological fields are generated based on the period 1982–2004.

It is well known that the dynamic and thermodynamic processes at subsurface layers (e.g., the mixing and entrainment) contribute to interannual SST variations (e.g., Zebiak and Cane, 1987; Wang and McPhaden, 2000). Moreover, the thermocline and its variations play an important role in affecting ENSO evolution, but observation systems for subsurface structure have been very scarce in the past (Wang et al., 2012). The available 3D GODAS products provide a unique opportunity to investigate the 3D structure of the upper ocean and ENSO evolution in more detail. Furthermore, it is also worth mentioning that the 3D structure of the temperature field in the GODAS products—especially the distributions of the subsurface temperature, which play a critical role in ENSO evolution—is highly correlated with that of the Argo dataset over the tropical Pacific. In this study, due to the poor quality of the salinity fields in GODAS, instead of the isopycnal analyses, isothermal analyses are performed using the 3D temperature fields to better characterize the temporal evolution and 3D structure over the tropical Pacific during the 2011/12 "double dip" La Niña event. The thermocline depth is defined as the depth where the 20°C isotherm is located, and the climatological and interannually varying temperature at the thermocline depth are also calculated.

3. Onset and evolution of the 2011/12 La Niña

Various GODAS and NCEP reanalysis data involving the atmospheric and oceanic processes responsible for the onset and evolution of the 2011/12 La Niña event are investigated in this section. Figure 1 shows the temporal evolutions of the interannual variations in SST, SL, zonal wind stress (Taux), meridional wind stress (Tauy), and thermocline depth in the equatorial Pacific in 2011. The development of the 2011/12 La Niña event is quite clear at the equator, and there is a close relationship among these anomalous fields. For the SST anomalies, there is a shift of the cold–warm–cold conditions over the equatorial central-eastern Pacific during the whole of 2011 (Fig. 1a). A second cooling at the sea surface occurs in mid-to-late 2011, following the first cooling in the fall of 2010 (not shown). The 2010 moderate La Niña event seems to end in spring 2011 (Zhang et al., 2013). Then, the equatorial eastern Pacific experiences neutral SST conditions and witnesses this weak La Niña event (i.e., "double dip" La Niña event) in August 2011. The weak La Niña conditions gradually develop to moderate intensity during November 2011. The key feature here is the appearance of the second cooling at the sea surface in the boreal fall of 2011. Corresponding to the characteristics of the SST anomalies, the anomalous SL and thermocline depth show similar variation patterns (negative–positive–negative) over the central to eastern equatorial Pacific (Figs. 1b and e). Meanwhile, the combined data presented in Figs. 1c and d, which depict the easterly and southerly wind anomalies, respectively, demonstrate a predominance of the anomalous southeasterly winds over the whole of the equatorial region. In addition, the depth of the thermocline (Fig.1e), represented by the 20°C isotherm depth, and the SST (Fig.1a), are highly correlated, with a cold SST associated with a shallow thermocline, and vice versa. Moreover, from February to May 2011, the positive oceanic heat anomalies in the equatorial western Pacific ex-

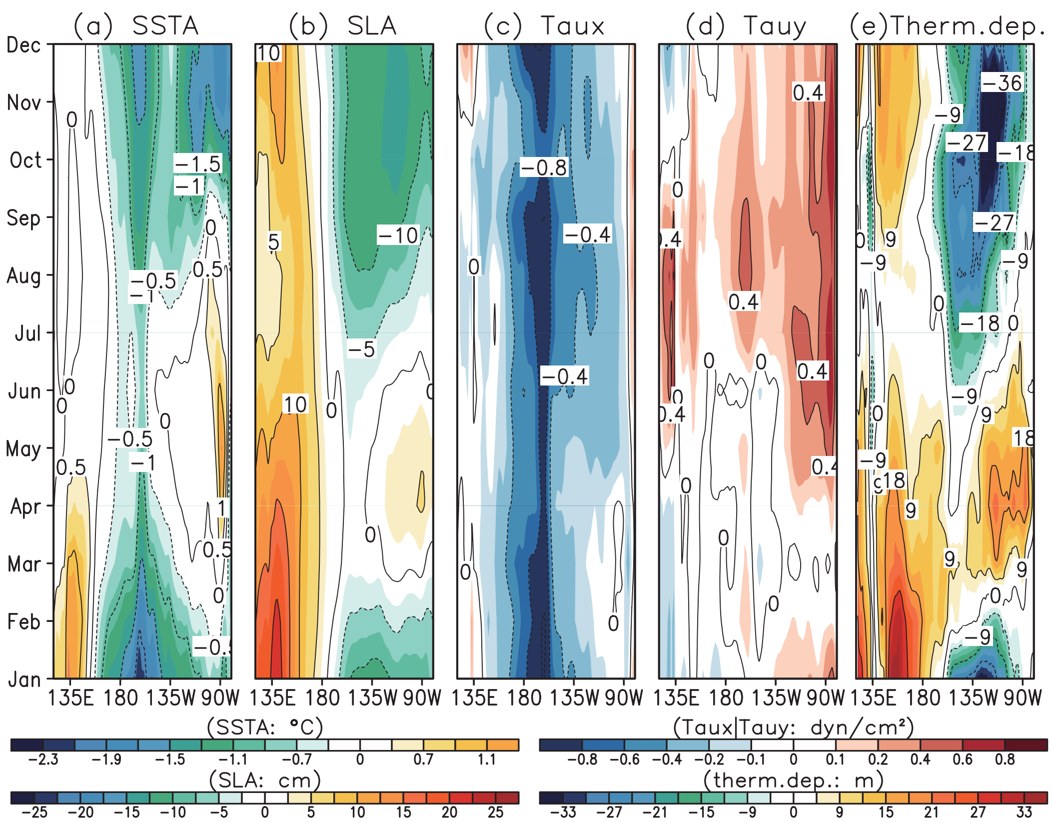

Fig. 1. Temporal evolutions of interannual anomalies along the equatorial Pacific (averaged between 2°S and 2°N) in 2011 for (a) SST, (b) SL, (c) Taux, (d) Tauy, and (e) thermocline depth. The contour interval is 0.5°C in (a), 5 cm in (b), 0.4 dyn cm^{-2} in (c) and (d), and 9 m in (e).

cite a downwelling oceanic Kelvin wave, which are depicted clearly by the thermocline depth anomalies (Fig. 1e). Associated with the eastward propagating Kelvin wave, a pronounced warming process exists in the equatorial central-eastern Pacific during early–mid 2011 (Fig. 1a). However, after the Kelvin wave successfully reaches the eastern boundary of the tropical Pacific, the warming process does not continue afterward and is replaced by a cooling process in the whole equatorial Pacific.

Figure 2 displays the horizontal distributions of the interannual SST anomalies over the equatorial Pacific region in 2011. The vigorous period of the 2010 La Niña persists to January 2011, so the negative SST anomalies prevail extensively in the tropical Pacific, with a minimum of less than -2°C along the equator between 150° and 170°W (Fig. 2a). From March to June, the region of negative SST anomalies shrinks gradually in the equatorial eastern Pacific, while a small-scale warm SST signal appearing in March gradually expands its area and increases its strength during the next three months (Figs. 2b–e). As a result, neutral SST conditions emerge in the eastern equatorial Pacific in mid-2011. During this period, negative SST anomalies persist over off-equatorial regions, being most pronounced in the tropical South Pacific. Thereafter, the domain of positive SST anomalies gradually diminishes and is displaced by negative ones. In particular, the negative SST anomalies reappear in the equatorial central Pacific in August (Fig. 2g), and this cooling condition tends to persist and strengthen in the following months (Fig. 2h), leading to a "double dip" La Niña event. The condition shift of the SST anomalies (i.e., negative–positive–negative) in the central-eastern Pacific is the most direct response to this kind of continuous La Niña event.

In contrast to the variations of temperature at the surface layer, those in the subsurface layers are clearer. Figure 3 presents the horizontal distributions of interannual temperature anomalies at the thermocline depth, associated with the current anomalies. In January, the cold and warm water at the subsurface layers over the tropical Pacific nearly separate at 160°W. The cold subsurface water is located in the eastern tropical Pacific, while the warm subsurface water is located in the western tropical Pacific (Fig. 3a). The positive subsurface temperature anomalies, which previously accumulated at subsurface depths in the tropical western Pacific (Fig. 3a), start to propagate along the equator toward the eastern basin in February and March (Fig. 3b). Simultaneously, pronounced negative anomalies persist in the subsurface layers of the off-equatorial regions, and warm water occupies almost the entire equatorial Pacific. Note that the cold water appears unexpectedly in 145°–155°W and 2°N–2°S and interrupts the eastern propagation of the warm water along the equator in April (Fig. 3c). Then, the region of warm water shrinks gradually in the eastern equatorial Pacific and the area of equatorial cold water expands gradually in the next

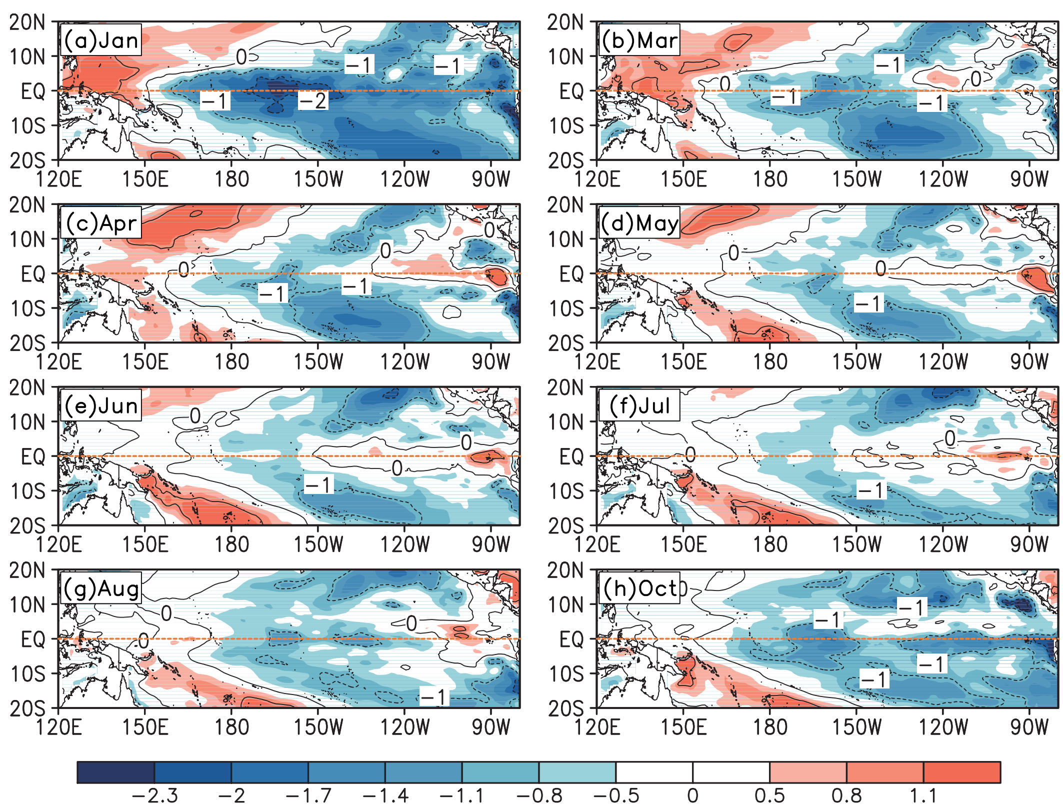

Fig. 2. Horizontal distributions of the interannual SST anomalies over the equatorial Pacific region in some selected months of 2011. The contour interval is 1°C.

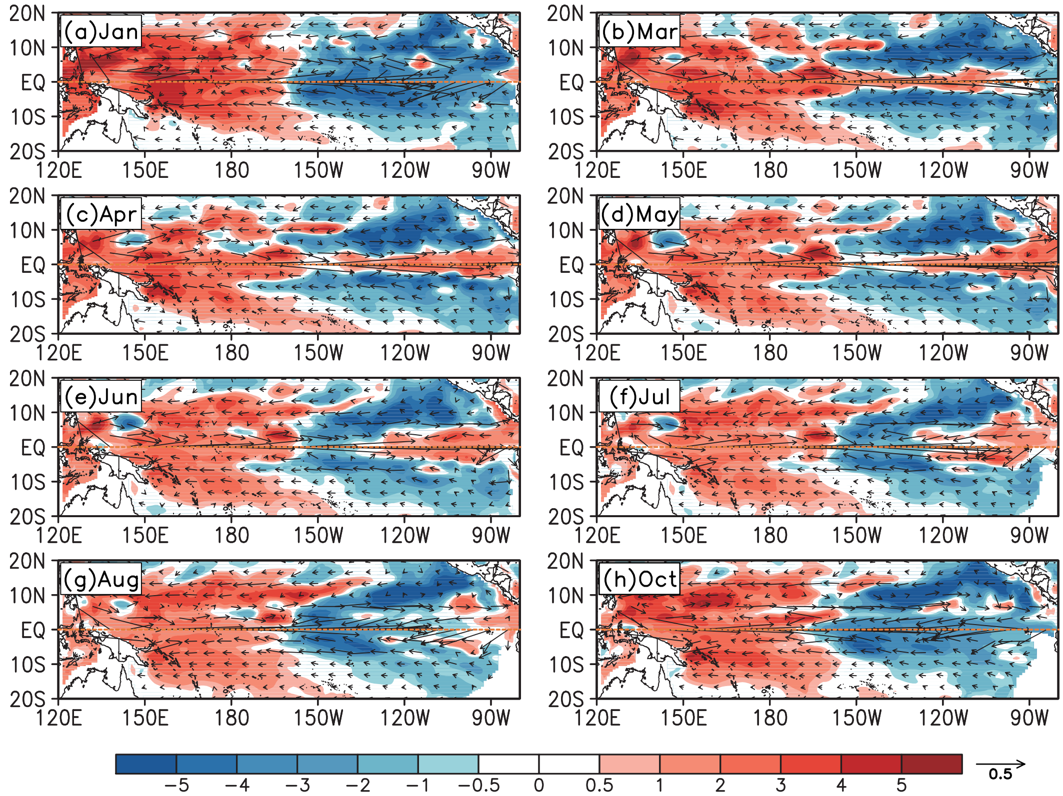

Fig. 3. The same as in Fig. 2, but for the temperature (shading) and ocean current (vectors) anomalies at the thermocline depth. The units for ocean current is cm s^{-1}.

few months (Figs. 3d–h). Finally, the cold water is seen to totally occupy the tropical eastern Pacific again (Figs. 3d and h). The pattern of the subsurface temperature anomalies in October is similar to that in January, only with a weaker amplitude. Obviously, the temperature anomalies at the thermocline depth (Fig. 3) can reflect the evolution of the second cooling event better than the SST anomalies (Fig. 2). For the subsurface current field, a pathway originating from the tropical South Pacific can be clearly seen: the cold water carried by the southeastern currents is eventually transported to the equator (Fig. 3).

Due to the strong interaction between ocean and atmosphere over the tropical Pacific, atmospheric components also play significant roles in the development of the "double dip" La Niña event. Here, the NCEP reanalysis data are used to describe the atmospheric processes closely related to this event. Figure 4 shows the horizontal distributions of the SLP anomalies (shading) and wind stress anomalies (vectors). Consistent with the negative SST anomalies, the center of the positive SLP anomalies exists for several months in the tropical central-eastern Pacific during the 2011 La Niña event, acting to strengthen a southern meridional wind across the equator in early–mid 2011, especially from February to May (Figs. 4b–d). The gradient of the SLP leads to an equatorward transport of cold water, and acts to produce the cross-equatorial southern wind. The cross-equatorial southern wind can make the cold surface water in the tropical South Pacific expand northward to the equator and mix with the cold surface water in the tropical North Pacific, off-equator. At the same time, the southeasterly wind can cause the stratification variation of the thermocline to further spread the cold subsurface water to the equator from the off-equatorial regions.

During the decaying phase of the 2011/12 La Niña, the region of negative SST anomalies gradually shrinks in the equatorial eastern Pacific, but these cooling processes do not persist and develop, perhaps because the off-equatorial cold anomalies (i.e., South and North Pacific) are too weak to provide enough cold water, and the meridional winds also cannot support an equatorward current in 2012 (figures not shown). Finally, the SSTA does not return to the La Niña state, as happened during 2011.

Figure 5 shows the vertical distribution of the interannual temperature anomalies in the upper oceans (i.e., from the surface to 300 m) over the equatorial region. In January 2011, positive temperature anomalies can be observed at the surface in the tropical western Pacific, while negative temperature anomalies are located in the tropical central-eastern Pacific regions at the surface layer. However, positive temperature anomalies and negative temperature anomalies exist in almost equal measure in the subsurface layers, with a sharp temperature front along 160°W. Meanwhile, the thermocline over the equatorial western Pacific is relatively deeper than that in the equatorial eastern Pacific (Fig. 5a). Thereafter, the positive subsurface temperature anomalies, which had pre-

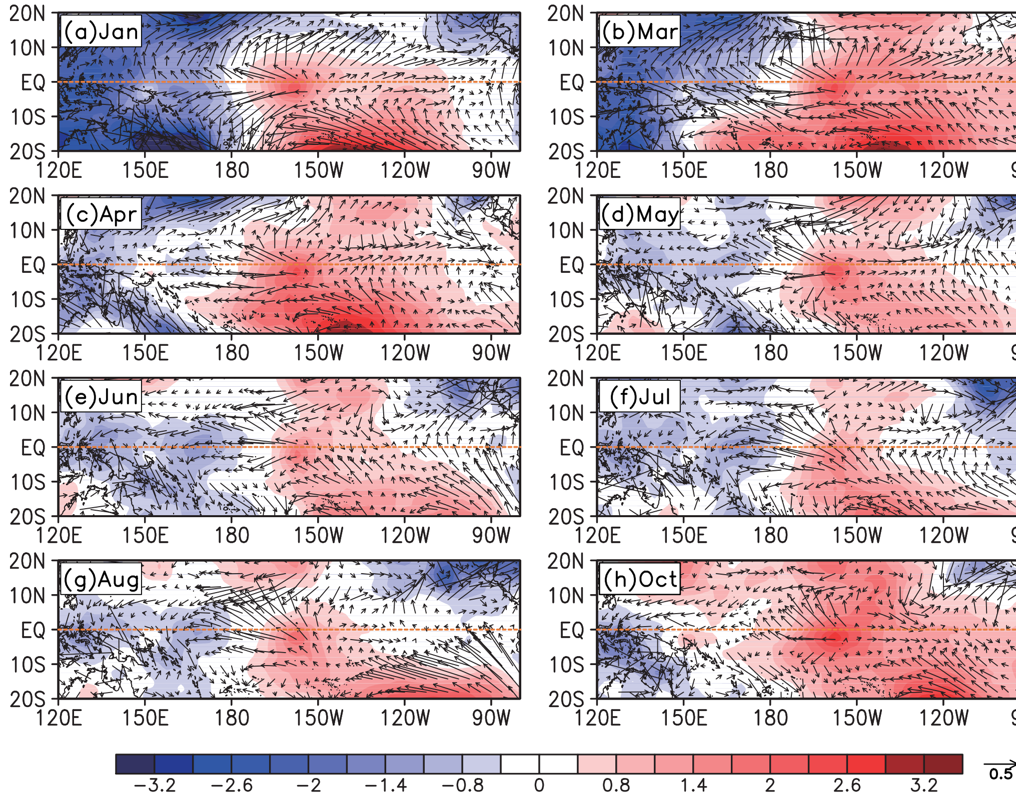

Fig. 4. The same as in Fig. 2, but for the sea level pressure anomalies (shading) and the wind stress anomalies (vectors).

viously accumulated at subsurface depths over the tropical western Pacific, start to propagate toward the eastern basin along the equator, acting to diminish the negative temperature anomalies there, reverse the sign of SST anomalies, and initiate warm conditions (Fig. 5b). In April, the negative temperature anomalies in the equatorial central-eastern Pacific almost totally disappear except for a small surface region between the dateline and 140°W, and the whole surface equatorial Pacific is almost completely occupied by neutral-warm SST conditions (Fig. 5c). In May, a striking feature is evident in the form of a cold water mass unpredictably appearing and persisting at the thermocline depth between 140° and 150°W, when the warm water occupies almost the entire equatorial Pacific both at the surface and in the subsurface layers (Fig. 5d). In the following months, the range of this cold water mass gradually expands and eventually reoccupies the whole equatorial central-eastern Pacific (Figs. 5e–h). Based on these analysis results, we can conclude that this incursion of cold water into the equatorial region took place at the thermocline depth, and the incursion process was the key mechanism preventing the development of a warm event and causing a second-year cooling during the 2010–12 La Niña event. However, it is still difficult to distinguish whether the source of the cold water was from the south or the north, as well as what kind of physical process was able to trigger the incursion of cold water. These questions are further examined in the following section.

4. The incursion process from the off-equatorial subsurface water into the equatorial region

The incursion process is clearly displayed in Figs. 6a–d by showing the horizontal distributions of the interannual temperature anomalies at the thermocline depth in a specifically smaller region (10°S–10°N, 165°W–120°W) and a shorter period (from March to June). In March, the negative subsurface anomalies still prevail over the off-equatorial region, while the equatorial Pacific is occupied by warm water in the subsurface layers (Fig.6a). Note that the cold subsurface water, which is located in the tropical South Pacific, starts to spread northward and break into the equatorial region between 145° and 155°W, successfully interrupting the eastern propagation of warm water along the equator in April (Fig.6b). In May, the incursion of the cold subsurface water from the tropical South Pacific into the equatorial region strengthens, and the cold water tends to move across the equator to the north (Fig.6c). Subsequently, the cross-equatorial cold subsurface water from the tropical South Pacific mixes with that located in the tropical North Pacific, and the off-equatorial negative temperature anomalies converge over the equator (Fig.6d). Furthermore, the cold waters in the tropical South and North Pacific (the two selected specific regions) are previously accumulated at the subsurface depths. Consistent with the surface winds, the subsurface currents,

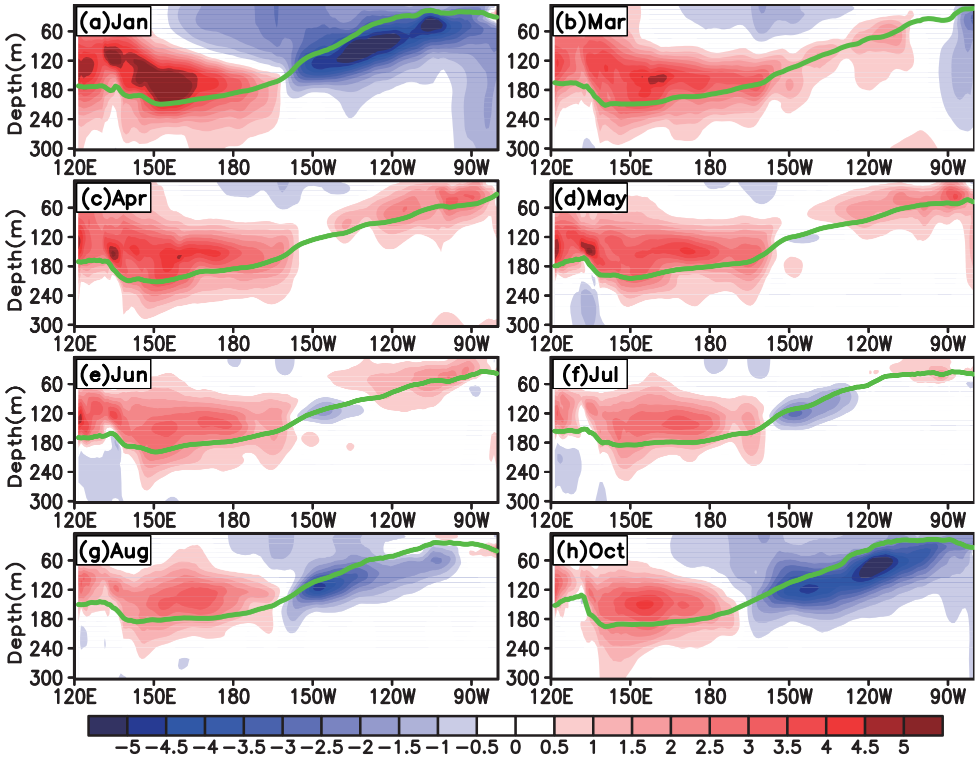

Fig. 5. Vertical distributions of the interannual temperature anomalies in the upper oceans of the equatorial region (averaged between 2°S and 2°N) in 2011 for (a) January, (b) March, (c) April, (d) May, (e) June, (f) July, (g) August, and (h) October. The green line represents the thermocline depth diagnosed by the 20°C isotherm.

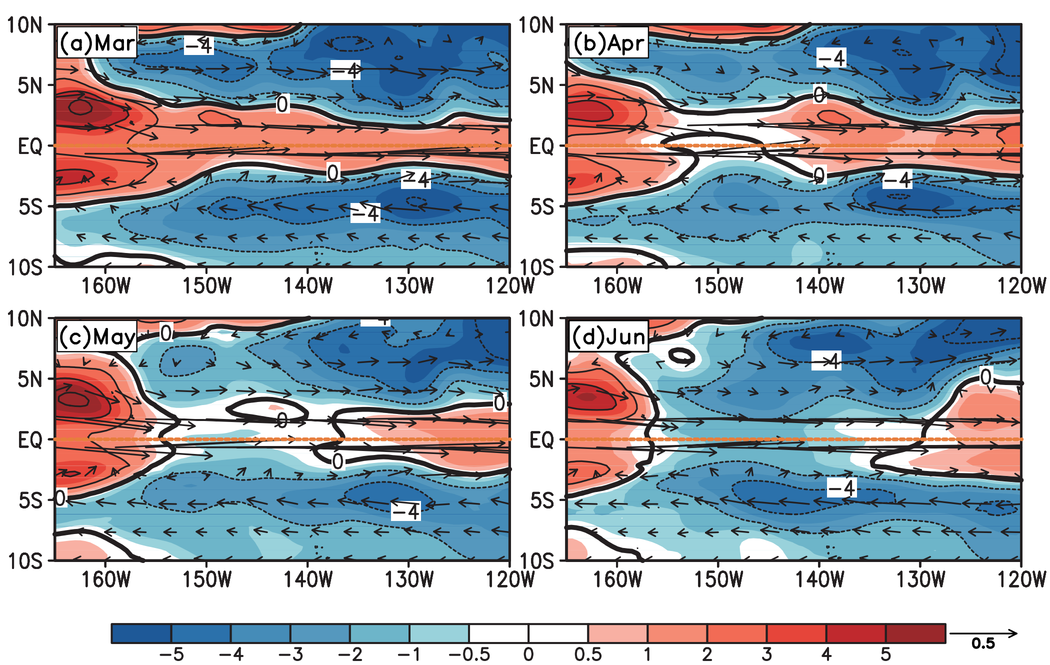

Fig. 6. Horizontal distributions of the interannual temperature (shading) and ocean current (vectors) anomalies at the thermocline depth over the central to eastern equatorial Pacific (10°S–10°N, 165°–120°W) in 2011 for (a) March, (b) April, (c) May, and (d) June. The contour interval is 2°C, and the units for ocean current is cm s^{-1}. The bold black curve represents the zero-line.

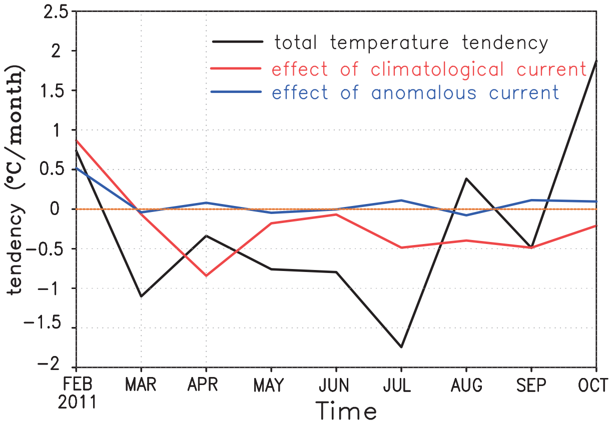

Fig. 7. Temperature tendency in 2011 over the incursion region (150°–140°W, 2°S–0°) at the thermocline depth. The black line represents the total temperature tendency; the red line represents the effect of climatological current with temperature anomalies on the temperature tendency; and the blue line represents the effect of anomalous current with temperature anomalies on the temperature tendency.

combined with the persistent cold water at the subsurface depths over the tropical South Pacific, are active enough to generate a cold water pathway to the equatorial region. The area of the junction gradually expands in the next few months and the cold water can again be seen to completely occupy the tropical eastern Pacific (Fig.3). As depicted above, the cold water in this incursion process is mostly from the off-equatorial regions (i.e., the tropical South Pacific).

Consistent with the demonstrations in Huang et al. (2010), the climatological current with anomalous temperature plays a more important role in affecting the tropical temperature tendency than the anomalous current with temperature anomalies. In 2011, the climatological current associated with temperature anomalies provides a cooling effect on modulating the temperature tendency over the tropical South Pacific at the thermocline depth (Fig.7). Especially during the key MAM-timing (March–April–May timing) for the onset of "double dip" La Nina, the cooling effect is obvious and significant in affecting the temperature tendency. In contrast, over the whole of 2011, the anomalous current has little effect on enhancing the temperature tendency.

In order to investigate the 3D structure of the pathway along which the off-equatorial cold water moves into the equatorial region, we compute an oblique section from (2°N, 150.5°W) to (8°S, 141.5°W). The vertical distributions of the interannual temperature anomalies in the upper oceans (5–300 m) from (2°N, 150.5°W) to (8°S, 141.5°W) are illustrated in Fig.8. It is clear that the negative temperature anomalies during the incursion process almost break into the equatorial region at the thermocline depth (Figs. 8a–d), which has already been discussed based on Figs. 3 and 6. In March, in the subsurface layers, there are negative temperature anomalies over the south of the equator and positive temperature anomalies over the equatorial region (Fig.8a). A northward position of the temperature zero-line in the subsurface depths occurs in April, and the positive temperature anomalies at the equator dissipate at that time (Fig.8b). In May, the negative subsurface temperature anomalies in the tropical South Pacific start to break into the equatorial region along the thermocline via horizontal advection (Fig.8c), and then mix with the negative subsurface temperature anomalies located in the tropical North Pacific region (Fig.8d).

As described in section 3, consistent with the negative SST anomalies over the tropical South Pacific, the positive SLP anomalies over that area act to produce a southern meridional wind across the equator in early–mid 2011. As the interannual variations of the upper ocean over the tropical Pacific are controlled by the surface wind (e.g., Wang and McPhaden, 2000), a potential trigger for the activation of the incursion process of the subsurface cold water can be found in the form of the enhanced southern meridional wind throughout early–mid 2011. Zhang et al. (2013) argued that interannual wind forcing effects were important to SST evolution during 2011. Figure 9 shows the zonal–time sections for anomalous wind stress changes during 2011 to illustrate the key factor triggering the 2011/12 La Niña event. In Fig.9a, the southeasterly wind reappears over the tropical South Pacific (100°–110°W) around March, and spreads to almost the entire tropical South Pacific (160°E–80°W) from April. Moreover, the wind is crossing the equator (Fig.4). On the other hand, southerly anomalies exist over the tropical North Pacific (Fig.9b), which are not conducive to the invasion of the subsurface cold water from the north of the equator. All these phenomena could have contributed to the incursion process of the off-equatorial subsurface cold water having mostly arisen from the tropical South Pacific, indicating significant roles played by the wind in activating the "double dip" La Niña event. It is also worth noting that the subsurface cold water in the North Pacific is also significant. However, the surface cold water over that region is weaker than that in the South Pacific, and there are no corresponding northeasterly winds to cause the stratification variation of the upper oceans to further spread the cold subsurface water from the north to the equator.

5. Discussion and conclusions

The atmospheric and oceanic processes that could have been responsible for the onset of the La Niña event of 2011 have been investigated, and an incursion process of subsurface cold water from off-equatorial regions into the equatorial region has been illustrated by GODAS 3D temperature products and NCEP reanalysis atmospheric datasets. Furthermore, it has been demonstrated that this incursion process of cold subsurface water was the key process in precipitating the "double dip" La Niña. During 2010–12, a prolonged La Niña event arose in the tropical Pacific, with a second cooling at the sea surface following an initial cooling in the fall of 2010. After the moderate La Niña event in 2010, positive subsurface anomalies, which had previously accumulated at subsurface depths over the tropical western Pacific, started to propagate along the equator toward the eastern basin, acting to reverse

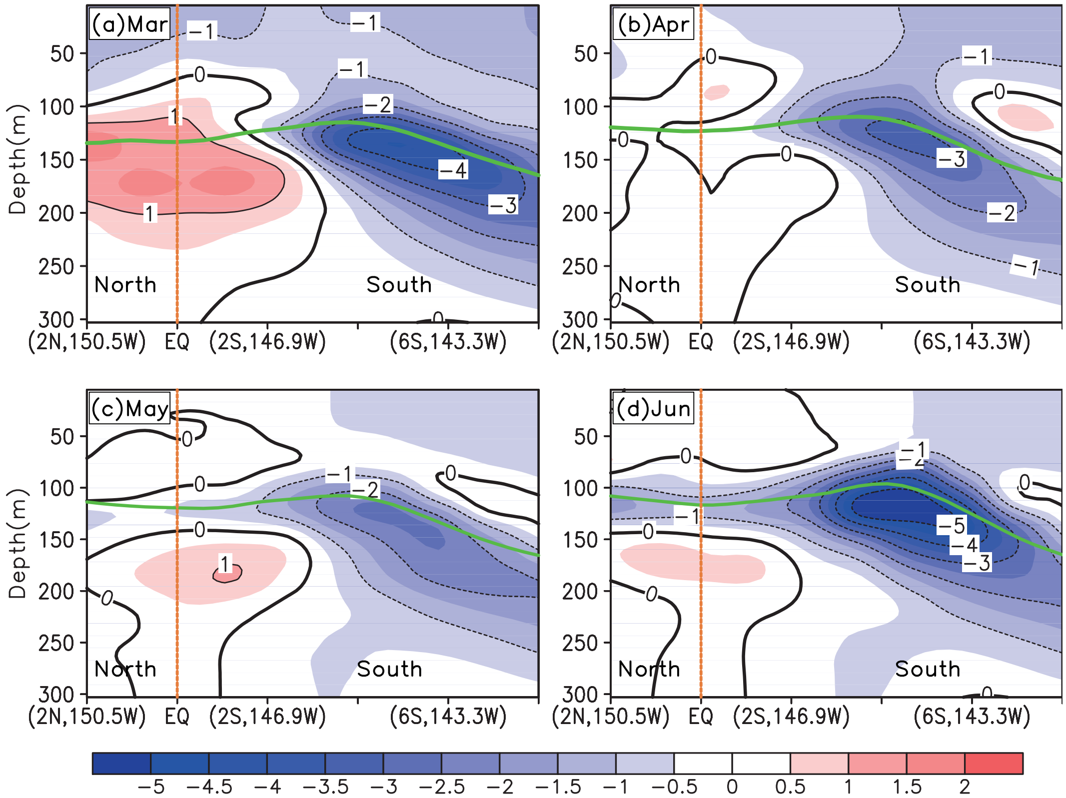

Fig. 8. Vertical distributions of the interannual temperature anomalies in the upper oceans from (2°N, 150.5°W) to (8°S, 141.5°W) in 2011 for (a) March, (b) April, (c) May, and (d) June. The contour interval is 1°C. The green line represents the thermocline depth diagnosed by the 20°C isotherm. The bold black curve represents the zero-line, and the vertical orange line represents the equator.

the sign of the SST anomalies there and initiate warm conditions. Then, in mid-2011, near normal SST conditions were present in the equatorial eastern Pacific. However, throughout early 2011, obviously negative anomalies persisted at the surface and at subsurface depths in off-equatorial regions, being most pronounced in the tropical South Pacific. The negative SST anomalies in the tropical South Pacific acted to strengthen a southern meridional wind across the equator. The subsurface negative temperature anomalies in the tropical South Pacific then spread northward and broke into the equatorial region at the thermocline depth. This incursion process of off-equatorial subsurface cold water successfully interrupted the eastern propagation of the warm water along the equator, and was strengthened as a result of the off-equatorial effects, mostly in the tropical South Pacific. The cold SST anomalies then reappeared in the central basin in summer 2011, and acted to trigger local coupled air–sea interactions producing atmospheric–oceanic anomalies that developed and evolved with the second cooling in the fall of 2011.

The evolution of the 2011 "double dip" La Niña event described in this study is unprecedented, and depended on the obvious negative temperature anomalies that persisted at the surface and at subsurface depths over off-equatorial regions, as well as the triggering mechanism of the atmosphere. During the decaying phase of the 2010 La Niña event, the surface and subsurface cold water persisted over subtropical regions, and the subsurface cold water maintained a stronger negative value and retreated slower than that at the surface (Feng et al., 2015). Moreover, different from the mechanism of subtropical–tropical teleconnection, the off-equator cold anomaly in early–mid 2011 may not have been conducive to the equatorial recharge process, and as a result could have favored the persistence of a cold ocean subsurface temperature anomaly and prevented the transition from La Niña to El Niño (Hu et al., 2014). Two issues have been demonstrated as key conditions responsible for the appearance of "double dip" La Niña. One is subsurface cold water still existing in off-equatorial regions during the decaying phase of the previous La Niña event. Accumulated cold water in the off-equator subsurface layers provides a precondition for the generation of a "double dip" La Niña event. The other is persistent negative SST anomalies in the tropical South Pacific acting to produce and strengthen southern winds across the equator. The enhanced southern wind then plays a triggering role that encourages subsurface cold water in the South Pacific to spread northward and break into the equatorial region at the thermocline depth.

The findings of our work can also partly explain why most models, especially coupled atmosphere–ocean general

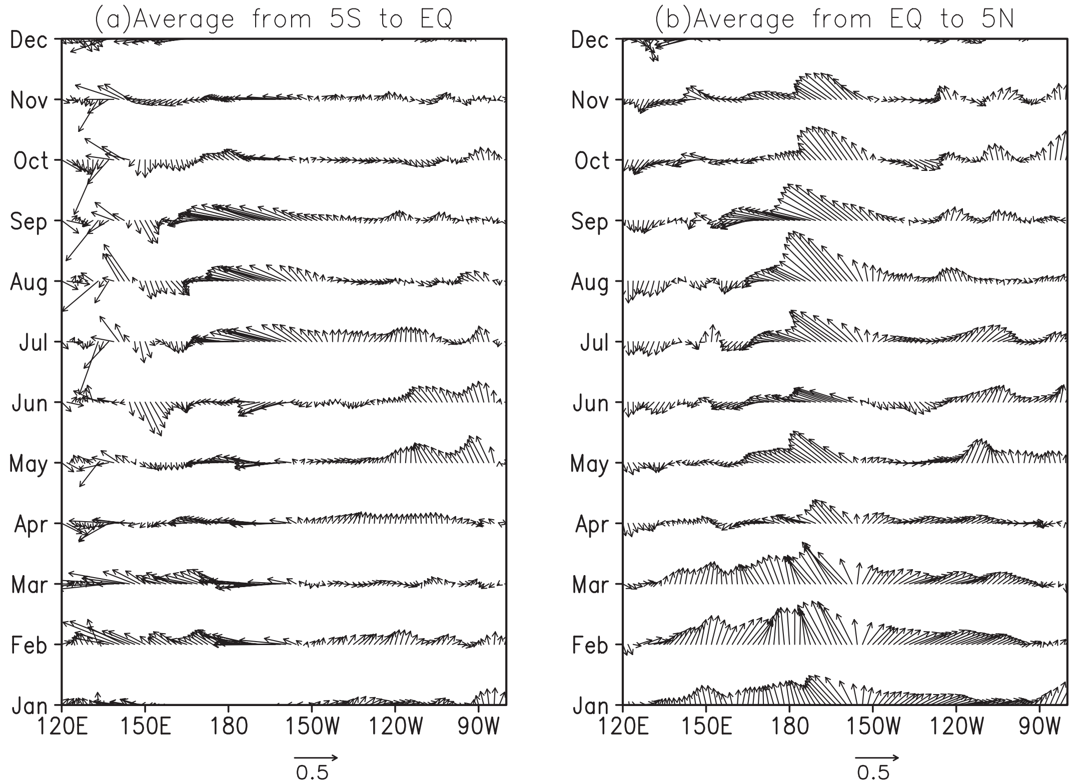

Fig. 9. Zonal–time sections of the wind stress anomalies in 2011: (a) south of the equator (averaged between 5°S and the equator); (b) north of the equator (averaged between the equator and 5°N).

circulation models, failed to predict the "double dip" La Niña event that started from early–mid 2011. The failure possibly resulted from the initialization in such models. In this paper, we indicate that the persistent southeasterly winds and prescribed subsurface cold conditions with an equatorward incursion would have been the key factors for predicting the 2011/12 La Niña. However, for most ENSO models, their initialization methods are based on "ocean-only" assimilation schemes (i.e., only oceanic observations are assimilated into the model, and the initial atmospheric states are kept unchanged). Moreover, due to the limitations of the quality and quantity of ocean current observations, it is very hard to assimilate the observed current directly (Zheng and Zhu, 2010a). Thus, providing more accurate atmospheric and oceanic subsurface information in the initial conditions of models based on more advanced coupled data assimilation methods (e.g., Zheng and Zhu, 2008, 2010a) would clearly benefit seasonal-to-interannual predictions of "double dip" La Niña events.

However, these conclusions have only been drawn based on one "double dip" La Niña case. There are other "double dip" La Niña cases that have happened over the tropical Pacific (e.g., in 2008/09 and 2000/01), and so the similarities and differences among these events need to be analyzed to better describe the nature of these strikingly different ENSO evolutions associated with various physical processes within the Pacific climate system (Hu et al., 2014). For instance—as exemplified by the fact that a similar incursion of subsurface cold water from the North Pacific happened in 2008, while there was no obvious incursion process from the off-equatorial regions in 2000—whether or not the persistent subsurface cold water can break into the equatorial region can differ from one case to the next. Furthermore, the differences in the location and orientation of the incursion process vary and depend on the atmospheric surface conditions (i.e., easterly and equatorward winds).

Moreover, due to the lack of 3D oceanic data in the past, modeling studies are also needed to validate the roles played by the off-equatorial surface and subsurface anomalies in activating "double dip" La Niña events over the tropical Pacific. For example, approximately 15 "double dip" La Niña cases could be simulated by a long-term (i.e., 500 years) pre-industrial control run in a fully coupled atmosphere–ocean model (Zheng, 2014), which could help analyze the key mechanisms favoring the occurrence of "double dip" La Niña events through providing more than 10 samples of the second cooling case.

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