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Features of the Three Dimensional Structure in the Pacific Sub-surface Layer in Summer

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ABSTRACT

The anomaly of the summer sea temperature is analyzed by a spatial-temporal synthetically rotated orthogonal function (REOF) at three different depths (0 m, 40 m, and 120 m) over the area 110°E~100°W and 30°S~60°N. The spatial-temporal distribution shows that the “signal” of annual anomaly is stronger in the sub-surface layer than the surface layer, and it is stronger in the eastern equatorial Pacific than in the western area. The spatial structure of the sea temperature anomaly at different layers is related to both the ocean current and the interaction of ocean and atmosphere. The temporal changing trend of the sub-surface sea temperature in different areas shows that the annual mean sea temperature increases and the annual variability evidently increases from the 1980s, and these keep the same trend with the increasing El Nino phenomenon very well.

1. Introduction

Since the El Nino phenomenon has brought to the public's attention, the ocean has attracted more and more meteorologists to pay attention to it. There are many important research results on the ocean and the interaction between ocean and atmosphere. However, most of the research is based on the observed sea surface temperature (SST) or the analysis of the single layer ocean. On the whole, there is not only the horizontal, but also the vertical exchange in the ocean. It is indicated that the annual vertical temperature gradient is much larger than that in the horizontal direction. Therefore, vertical structure of ocean should be paid more attention when analyzing the distribution of ocean temperature^[1]. The

mechanism for the various warm-pool anomalies in the western Pacific has indicated that the warm-pool sub-surface sea temperature anomaly in the western Pacific which plays important role in the El Nino event, since it connects closely with the western passing of the northern equatorial current temperature's abnormal signal. It has been proven that the warm-pool abnormal warm water in the western Pacific mainly comes from northern equatorial current, which is aroused by the subduct of surface warm water in the Middle East Pacific along with the thermocline, which can reach up to 120 m in the area of warm pool in the western Pacific. During the period between the end of the El Nino event and the onset of the La Nina event, the sub-surface abnormal warm water in the northern equatorial current area (in the vicinity of 10°N) spreads from

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the Middle East Pacific to the western Pacific warm pool subduct along with the thermocline, and the abnormal warm water signal continually increases and extends, and finally the warm water controls the whole western Pacific, and provides the essential conditions for the onset of an El Nino event^[2]. Results of Chao et al (2002) showed that the initial ocean temperature departure of El Nino or La Nino aroused by the observation mainly appeared in the thermocline at about 150 m in a warm pool; when its intensity reached up to a specific threshold, it would spread to the tropic western Pacific along with climatic thermocline and move up to the sea surface. In the western boundary of the Pacific, the abnormally forced by the atmosphere can arouse sub-surface temperature anomaly, which spreads to the ocean east, mainly with an east-spread Kelvin wave, and arouses the anomaly in the whole ocean^[3]. The sea temperature in the upper layer tropical Pacific Ocean has shown that there is a relationship between the various features of ocean surface in the area of the western Pacific warm pool (0-16°N, 125-145°E) and the sub-surface ocean temperature in the western. It is discovered that there is a remarkable annual anomaly of vertical temperature in the western Pacific warm pool, with the most evident area appears in the sub-surface (120-200 m). The sub-surface change signal of temperature in the western Pacific “warm pool” is clearly earlier than the ocean temperature’s anomaly in the western Pacific sub-surface. The sub-surface ocean temperature in Pacific “warm pool” area has a pronounced inter-annual anomaly, and there was negative departure during the El Nino period and positive departure during the La Nino period in the warm pool area. The sub-surface sea temperature departure in the warm pool area has a distinct decreasing trend and the descending rate of the temperature is -0.2°C/10a. During the process of the ENSO cycle, the anomaly signal of the sub-surface sea temperature in the equatorial western Pacific appears firstly in the warm pool area, and the abnormal signal becomes much stronger and then spreads to the east and the equator, finally it spreads to the surface (under the force of the atmosphere) from the equatorial western Pacific to Middle East Pacific along with thermocline when the intensity reaches up to a specific threshold. The period of diffusion perhaps needs 18 months, in other words, the sub-surface abnormal signal of the sea temperature in warm pool is an important condition for the anomaly of the ocean temperature field in the western Pacific. Therefore, the anomaly of sub-surface ocean temperature in the warm pool area is essential for the occurrence of an El Nino event or La Nina event^[4]. Chao et al thought that the profound mixing layer (which has a large thermal capacity) is connected with the feeble

interaction of atmosphere. Some researches also showed that the sub-surface sea temperature in Pacific orderly come through an evident inter-decadal eruption from up to down in around 1980^[4].

Recently, the sea surface is of increasing interest for meteorologists because the annual signal in the deep layer is stronger than the surface layer. Zhang et al. studied the three dimensional structure of sea temperature at the sub-surface and the characters of decadal evolution of changing rate in the northern Pacific, they suggested that anomaly of sub-surface temperature circumgyrated deasil round the subtropical vortex go with average circumfluence. It is evident that this signal is connected with the subduct of temperature anomaly in the “window” area of middle latitude, and this feature especially reflects the action of the Rossby wave. The analyses on isopycnal surfaces reveals two preferential paths of temperature variability which rounding subtropical vortex on the decadal scales, where one is the southwest subduct path derived from the east of northern Pacific center, and another is the subtropical path derived from the east of subtropical to tropical and boundary towards west^[5-7].

All the above and other research^[8-12] shows that sub-surface sea temperature changes are closely connected with surface temperature change in the Pacific, and the vertical ocean temperature change and distribution are closely connected with El Nino and La Nina^[13-17].

The next section provides information on the data and method. Section 3 mainly discusses the three dimensional spatial character of sea temperature field in Pacific. The temporal evolution of summer sea temperature in Pacific is analyzed in Sections 4. Conclusion and discussion are given in the final section.

2. Data and Method

2.1 Data

The monthly mean sea temperature comes from the ocean laboratory of environmental data analysis center (JEDAC) of American Scripps^[18-19], with the period of January 1995 to December 1998, and the area of 60°S-60°N, 0°-360°. The spatial resolution of the sea temperature is 5°×2°, and the vertical layers are 0 m, 20 m, 40 m, 60 m, 80 m, 120 m, 160 m, 200 m, 240 m, 300 m, 400 m, respectively. The layer used in this study is 0, 40 and 120 m, respectively, and the area is from 110°E to 100°W, and from 30°S to 60°N.

2.2 Method

In order to analyze the three dimensional structure of multi-layer sea temperature, the spatial-temporal integrat-

ed REOF is used in this study. Supposing the data matrix of the average sea temperature departure field at L layer is $F_{N \times M}^L$, N is the number of temporal sample and M is the number of spatial grid. We turn every layer data into a new matrix:

$$F_{N \times M} = \{F_{N \times M}^1, F_{N \times M}^2, \dots, F_{N \times M}^L\}$$

Count its real symmetry matrix:

$$S_{M \times M} = F_{M \times N}^i \cdot F_{N \times M}^j$$

The sub-matrix $S_{ij} = F_{M \times N}^i \cdot F_{N \times M}^j$ is the covariance of i layer and j layer in isobaric surface of monthly mean sea temperature departure field, when $i=j$, S_{ij} becomes surface of monthly mean temperature departure field, when $i=j$, S_{ij} becomes the self covariance matrix of monthly mean sea temperature departure field in i layer, so the real symmetry matrix, not only contents the self distributing information of each layer's temperature anomaly, but also the information of interconnection of each layer's temperature departure. Because of the rationale of EOF, the eigenvector of real symmetry matrix $V_{K_0 \times M}$ composes the basic field of matrix $F_{N \times M}$, and also includes the inter-actional information of each layer's temperature departure.

The original material matrix is analyzed by using the mathematical method:

$$F_{N \times M} = \sum_{K_0} T_{N \times K_0} \cdot V_{K_0 \times M} \quad (1)$$

K_0 is the truncated wave number. If we have the eigenvector of former i, the precision of variance fitting using EOF is:

$$Q_{(K_0)} = \frac{\sum_{k=1}^{K_0} \lambda_k}{\sum_{k=1}^M \lambda_k}$$

(λ_k is the corresponding eigenvalue of the k_{th} eigenvector)

In formula (1), $T_{N \times K_0}$ is the temporal coefficient matrix of EOF, which includes the character of temporal evolution of each layer's whole structure anomaly field, where $V_{K_0 \times M}$ is the eigenvector matrix of EOF, and it can be taken apart in several sub-blocks:

$$V_{K_0 \times M} = \{V_{K_0 \times M}^1, V_{K_0 \times M}^2, \dots, V_{K_0 \times M}^L\}$$

Every sub-block represents the distributing structure of spatial function of some eigenvector in L layer. In this work, $N=45$, $L=3$, $LM=3118$.

In order to highlight the regional feature of sea temperature anomaly, rotating orthogonal analyzing method (REOF) is used to EOF [20], rotating each two spatial vectors in order in the time of rotating, the factors that are rotated are made certain according to astringency (using the former tenth weight in here), the rotating can be repeated, finally making every rotating total variance to get to the maximum. In the actual calculation, we can study the critical value as the end of adjusting spatial function;

we rotate the former tenth vector in our work.

The advantage of this method is that orthogonal function outspread can turn the spatial dot from high dimension down to low dimension, and compress and centralize the spatial-temporal information. Meanwhile, through transforming different elements' field matrix, the matrix includes the information of different elements' field in the temporal and spatial. The eigenvector field obtained using Experience Orthogonal Function (EOF) transformed matrix not only includes the spatial-temporal feature of some elements, but also includes the interaction of the different elements' field. Because the rotating calculation is made on the basis of vector space obtained by the EOF, the RLV of REOF can better reflect the regional feature [21].

3. The Three Dimensional Spatial Character of Sea Temperature Field in Pacific

Table.1 shows that the astringency of summer sea temperature in the Pacific is slow, it carries the complexity of sea temperature annual change in three-dimensional spatial. The eigenvector obtained by REOF mainly centralizes on the first 4 weights, thus only the spatial structures of the first 4 eigenvectors' fields are analyzed in this study.

Because of the area whose absolute value is larger and has more contribution to the variance, the spatial function of each eigenvector only works when analyzing and discussing an area with a large value. In the following sections, our discussion will focus on analyzing the character of spatial distribution and annual change in an area with a large value (which is called the sensitive area, the absolute value $\geq \alpha_{0.01} \approx 0.37$ in this paper).

Table 1. fitting variances of the first 9 eigenvectors of the departure fields

Order number	1	2	3	4	5	6	7	8	9	Σ
RLV	15.0	9.9	7.0	4.4	4.0	3.3	3.0	2.9	2.9	52.4

The sea surface over the middle to east equatorial Pacific is the area where the RLV1 is positive and large. The large value area has more attribution and is the most sensitive area of the annual abnormal change. The positive largest value is at 170°W-140°W, 0-10°N. The RLV1 occupies more than 80% of the annual change variance of the sea temperature in this area, which is the most sensitive area of surface sea temperature annual change in Pacific, and this area is relatively the same as the area where El Nino occurs (Figure 1.a). There are two extreme negative centers; one is centered at the middle to east Pacific (30°N, 170°W-150°W) and another is centered at the zonal area from Indonesia to the northern Australian sea area. The annual change in the area of the east equatorial

Pacific changes oppositely with the sea temperature in the area of the western ocean, which is centered at the warm pool and the middle to northern Pacific.

The sea temperature distribution at the depth of 40 m basically has the same characteristic as the sea temperature's annual change (Figure 1.b). The area that has the largest annual change is basically the same as the surface in the spatial distribution, which shows that the deep sea temperature's change is mainly influenced by the surface.

With the increasing of depth, the influence of ocean surface decrease at the depth of 120 m, and the distribution of sea temperature inter-annual variations is obviously different compared to that at 0-40 m. Firstly, the positive value area of middle to west Pacific in 0 m turns to the southeast, the center is on the sea area of the equatorial south. Secondly, the intersecting area between west wind drift and the ocean current of California is the area which has larger annual various, and so we should pay more attention to the warm pool area of the eastern ocean surface in Philippines which is the sensitive area of opposite interannual change, i.e., there is a negative center in the area 10°N, 140°E-150°E, and which is connected with eastern positive changing area that forms the 'Seesaw' which forms along in a quasi-east-west direction.

By analyzing the three layers' sea temperature change, we discover that each horizontal layer's sea temperature change presents the most sensitive area of interannual anomaly of sea temperature in the area of southeast Pacific and north Pacific, which is similar to the SST distribution of El Nino. At the deeper layer of 120m, the inter-annual anomaly feature has the opposite phase change of northwest-southeast in the equatorial south and north. The annual anomaly of northern west wind drifts and the Californian warm current is another sensitive area that should be paid more attention to. The "signal" of the annual anomaly of Sub-surface sea temperature which a reverse phase change in east - west direction at 120m can transfer upwards under some conditions, but it is not obvious at an under sea level of 120m; that is to say, the "signal" of annual anomaly in eastern Pacific appears earlier in sub-surface than in surface, and the annual anomaly signal of El Nino happens earlier in sub-surface. Hence, in other words, although the area of warm pool has a higher average of sea temperature than any other ocean area in surface, because it is adjusted by factors, such as wind, and exchanges the energy between ocean and atmosphere, it is relatively stable. The annual anomaly in the eastern Pacific is larger. The annual anomaly of surface temperature in eastern area of Pacific is larger at the depth of 120m.

The first eigenvector of REOF frankly reflects the inward relationship of the sea temperature departure field

in different layers (Figure 1). We can restrainedly infer the ocean temperature vertical variations by the spatial distribution of three layers' sea temperature, the physical character of seawater in surface is relatively uniform, and the annual anomaly's spatial difference of sea temperature is also relatively homogeneous. The sea temperature has the character of nearly barotropy in the vertical, while the depth is more than 120 m and the character is a similar baroclinity. The sensitive area of sea temperature's annual anomaly indicates the southern excursion commencing from up to down, the homodisperse decrease, and the change is of an opposite phase change in an east-west direction which reflects the circumfluence of sea water exchange existing in deeper sea temperature.

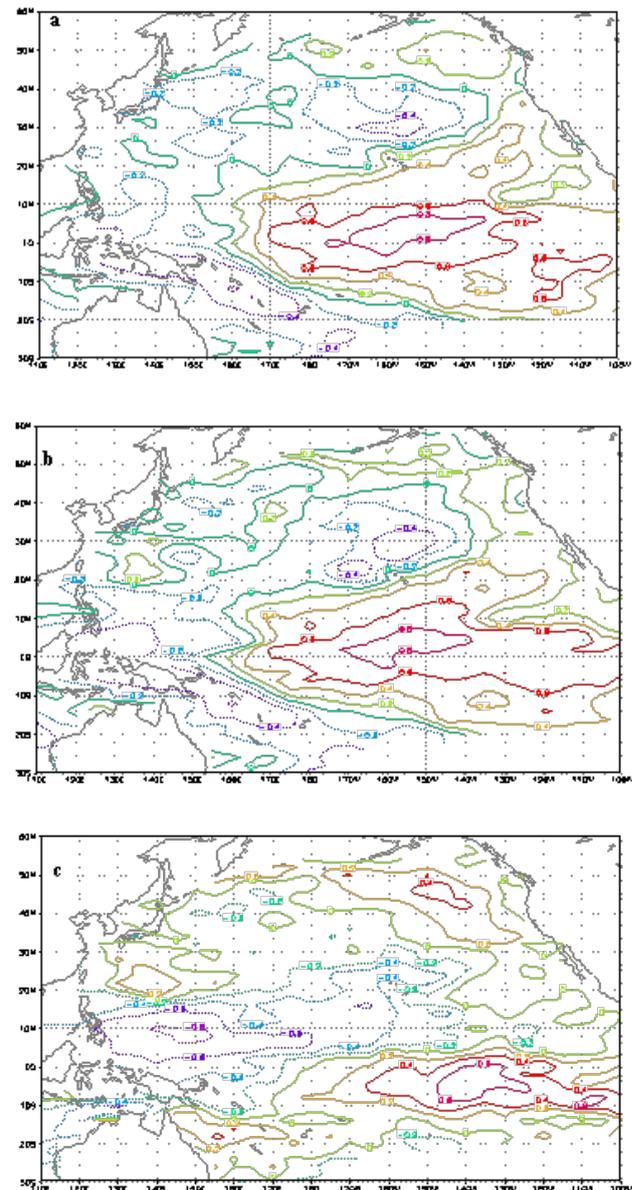


Figure 1. The first eigenvector's distribution (RLV) in (a) 10 m, (b) 40m, and (c) 120 m

Figure 2 shows the spatial structure of every layer's sea temperature corresponding to the second eigenvector. Figure 2.a shows the sensitive area of annual anomaly on surface which has two main waves, the oscillation between the Kuroshio and the west wind drift shows opposite annual phase change in the two areas; another wave transforming along the direction of east-west shows an annual oscillation in the southeastern Pacific and in large areas of middle to east Pacific, the latter is stronger than the former. The transforming direction of wave at 40m is basically the same as that over the surface fig.2b, and the all sensitive area of annual anomaly sea temperature has the same position and distribution as Figure 2.a. It hardly superposes with Figure 2a in the sea area of the equatorial south; the annual anomaly in the area of west wind drift is relatively weaker, its position is further south, and its area relatively decreases, which reflects the shallow feature and the vertical baroclinity of west wind drift. That is, the vertical amplitude of wave in the direction of east west is large and relatively stable. The feature of middle-west Pacific in southern equatorial at 120m is that sensitive area of annual anomaly retreat to the east equatorial Pacific, the area becomes smaller (set the 0.4 as boundary), and the annual anomaly in the region of eastern Pacific and Kuroshio has already become weaker compared with the surface and sub-surface.

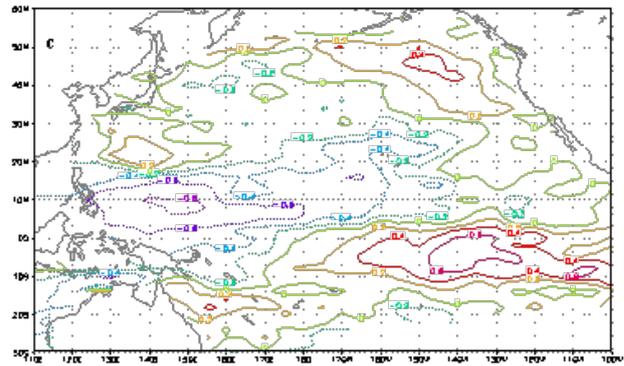
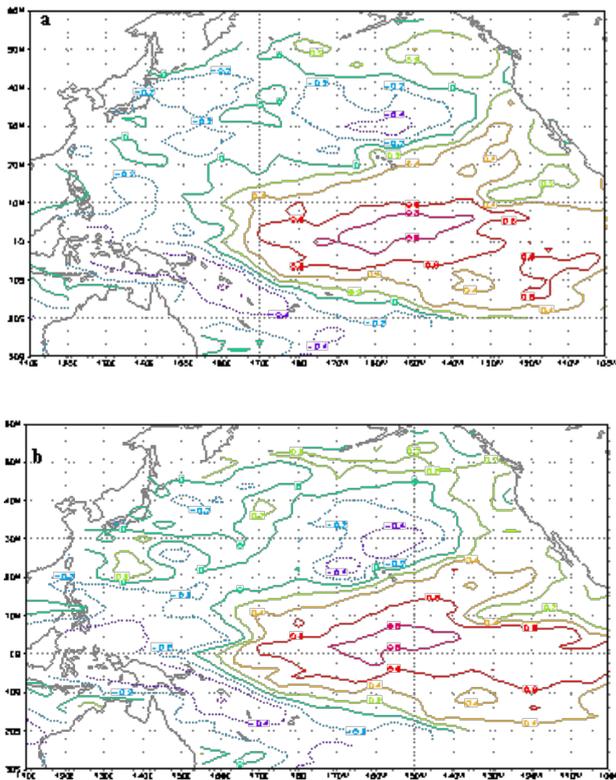


Figure 2. Similar to Figure 1, but for the second eigenvector

It is still notable that there is an interannual anomaly sensitive area of symmetry distributing in a horizontal direction of sub-surface in this set of charts. Especially the sea temperature change has an opposite phase between the east equatorial Pacific and west Pacific, connected with Walker circulation, warming water area located near Indonesia and the west Pacific equatorial, and the sea temperature is lower in east equatorial Pacific. We can find a similar result with the first eigenvector in the vertical structure, and there is barotropic character in sub-surface.

Figure 3 is the third eigenvector of sea temperature's spatial structure. The feature is that there is a wave transforming in the direction of south-north and the main changing area is north of the Pacific. The main sensitive area of the sea surface is centralized in the northern equatorial area (Figure 3), and the sensitive area of temperature's inter-annual anomaly appears + - - - + symmetry distributed along from the north to south. The distribution of sea temperature at the 40m layer (Figure 3.b) has a similar situation with above the sea surface. We can also find the symmetric distribution of the sensitivity area; however, the annual anomaly of west wind drift becomes a little stronger. At the 120m layer (Figure 3.c), there is still a wave transforming in the direction of north to south, but the spatial scale is relatively small and the sensitive area of temperature's interannual anomaly is quite random, every large value's area of sea temperature's interannual anomaly clearly reduces compared with the former two layers, but we can also find the same distributing pattern of sensitive area with the first two layers in the ocean surface of the Northern Hemisphere. Simultaneously, the spatial area of wave transforming expands to the south, that is to say the scale of wave transformation becomes small, but the transforming range becomes large at 120m.

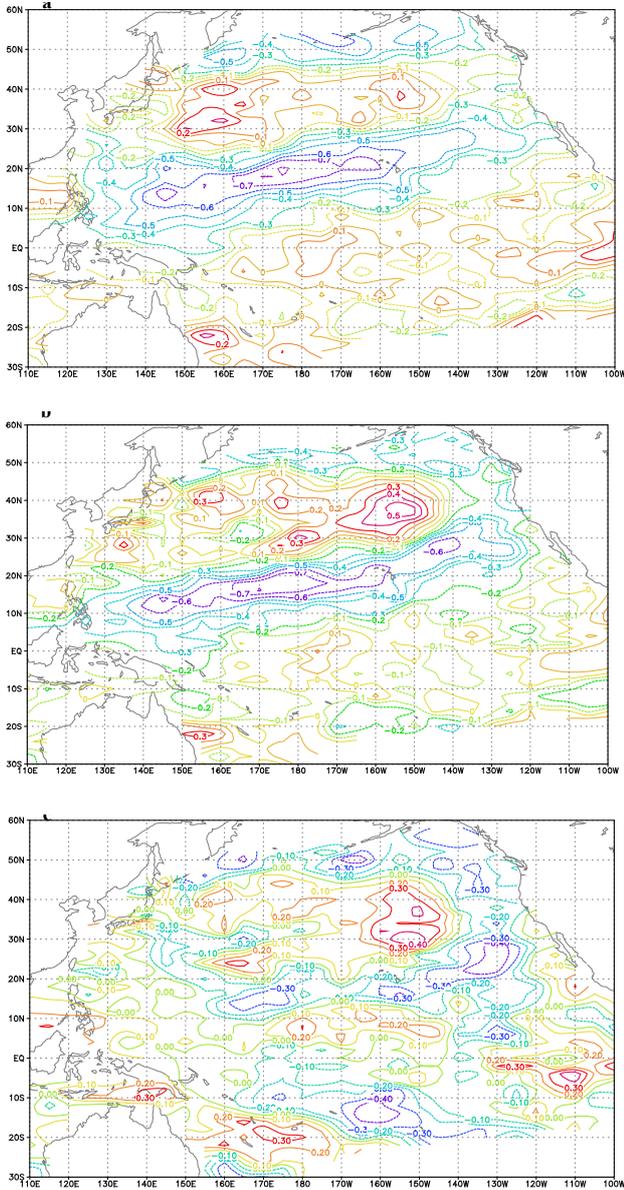


Figure 3. Similar to Figure 1, but for the third eigenvector

Along section of south - north, the sea temperature's change in the area of the tropical and subtropical Pacific has a connection of an opposite phase with a sea temperature change in the area of middle or high latitude of Pacific. This pattern of 'Seesaw' along the section of south to north inosculates with the NPO and also indicates the close relation between sea temperature's field and the field of air pressure.

The sensitive area of the western equatorial Pacific is represented more clearly in the three layers in the fourth eigenvector of the sea temperature's spatial distribution (Figure 4). Because of the influence of the warm equatorial ocean stream, the warm water accumulates in the area of the west equatorial Pacific and forms the ocean area that has the highest average whole Pacific sea tempera-

ture, which is called the 'warm pool' area. The sensitive area of sea temperature's interannual anomaly represented by the fourth eigenvector corresponds well to the position of "warm pool". We can discover from Figure 4 that the position of the warm pool in the shallow ocean area and the influenced area does not change too much, while the anomaly area is separated into two parts at the deeper layer of 120m, the southern equatorial part expands to the east and that reflects the existence of different ocean stream exchange; that is to say, the discord caused by the characteristic and property of sub-surface and surface's ocean stream, brings the change of the sea temperature's distribution in up and down.

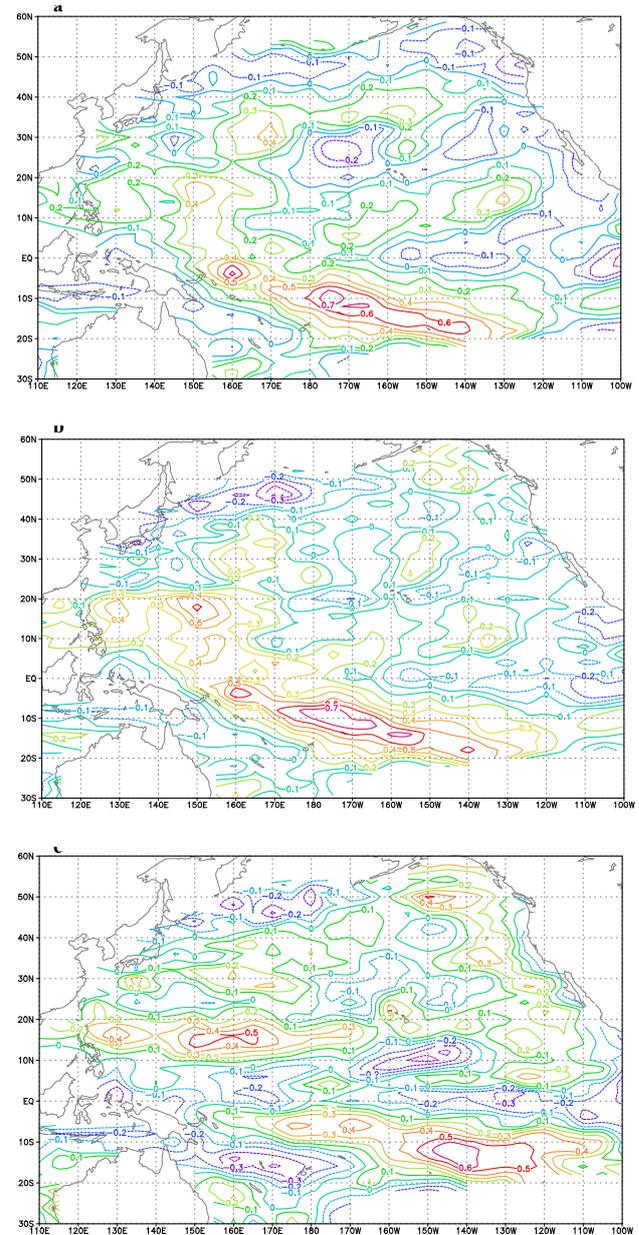


Figure 4. Similar to Figure 1, but for the fourth eigenvector

Based on the above analysis, the spatial distribution of the sea temperature's structure in Pacific is not only closely related to the action of ocean stream, but also to the atmospheric circulation. The position and distribution of the sensitive area of the sea temperature in surface and sub-surface correspond well with that of ENSO, NPO and Walker circulation, which shows the interaction between the ocean and the atmosphere.

The first four eigenvectors reveal almost the total structure of the barotropy of the subsurface sea temperature field. This barotropy will be replaced by the baroclinity when the depth increases and reached to some level.

4. Temporal Evolution of Summer Sea Temperature in Pacific

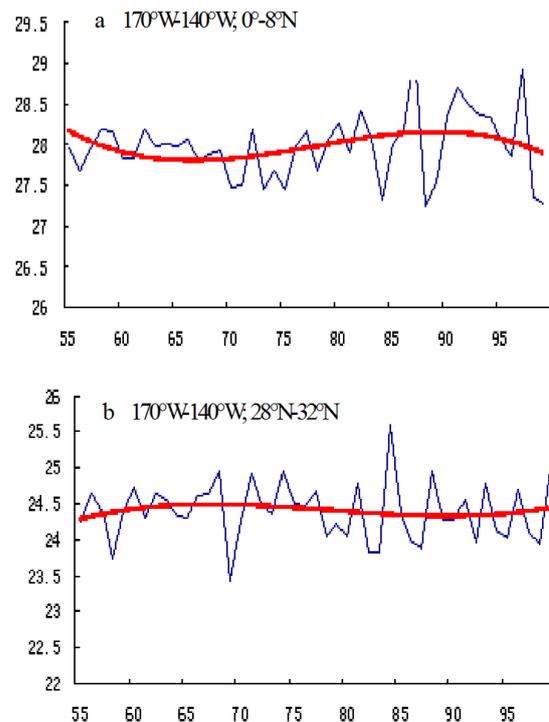
Studies have shown that the interannual anomaly of sea temperature has increased evidently since 20th century, especially in middle to east Pacific, and the annual variability is still at the high stage since 1980s from the changing trend [4,22-25]. In order to analyze the temporal evolution of the summer sea temperature, the most sensitive area of the annual sea temperature anomaly in different layers is chosen in this study, the regional average is used to indicate the average sea temperature of this area. Figures 5-7 is the curve of average sea temperature change and the 2 orders fitting in different layer of the sensitive area. Meanwhile for a better compare and analysis, a sensitive area on every layer is made the most same at Ocean region, and represents the east equatorial Pacific, middle Pacific and west Pacific.

From Figures 5-7, it can be seen that the sea temperature in Pacific shows the opposite phase's change in the part of south and north. The SST in east equatorial Pacific shows a decreasing trend from the 1950s to the middle of the 1960s; it turns back in the 1970s and gets to the highest value in the end of the 1980s; there also appears to be a down trend in the 1990s. Figure 5.a shows that the surface temperature in western equatorial Pacific has had an increasing trend since the 1980s and annual anomaly bigger significantly. This feature is also appears in another corresponding ocean area, where some research has shown that the frequency of El Nino happens become frequently and its strength stays in the bigger moment from the 1980s to 1990s. [4] So we infer that the change of sea temperature closely connects with the frequency of El Nino; sea temperature change has the opposite trend between middle of northern Pacific and east Pacific equatorial (Figure 5.b), there is a trend of high-low-high. In the area of southwest Pacific, the changing trend of sea temperature presents a persistently increasing trend and the interannual variability is smaller (Figure 5.c).

Comparing Figure 5 with Figure 6, it is found that the changing trend of sea temperature is opposite in the western equatorial and in southeast of the Pacific, being similar with the surface sea temperature, and the amplitude of sea water's temperature of interannual change becomes significantly large since the 1980s, while the changing trend of temperature in west or south of ocean is opposite to that in the area of east Pacific.

Comparing Figure 5 with Figure 6, an opposite trend occurred between the west Pacific's SST and southeast. Similar to SST, Ocean temperature annual anomaly amplitude was larger after 1980. An opposite change trend occurred between the southern area and west Pacific.

The annual sea temperature change in the tropical ocean area (Figure 7a) of the western equatorial Pacific at the depth of 120 m since the 1980s becomes significantly high and its changing trend is similar with that over the surface and at 40m, which reflects the increasing sea temperature's interannual variability in the deeper layer since the 1980s, there is a increasing trend. It is the most sensitive and most remarkable area of Ocean temperature anomaly in the area of northern Pacific. For the middle Pacific (Figure 7.b), the change of sea temperature similar to the sine function form, and the sea temperature is at its peak in the 1960s and the middle of 1990s. In the tropical ocean area of the southeast Pacific (Figure 7c), the changing trend of sea temperature is opposite to that of the surface, furthermore the interannual variability begins to increasing from the 1970s.



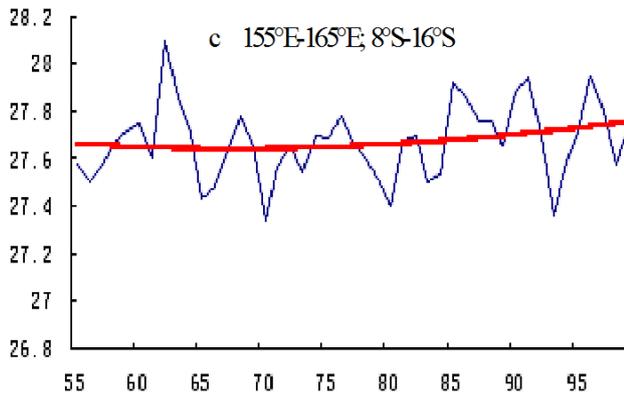


Figure 5. Annual variations of the sea surface temperature in the sensitive area such as (a) 170°W-140°W; 0°N-8°N, (b) 170°W-140°W; 28°N-32°N, and (c) 155°E-165°E; 8°S-16°S

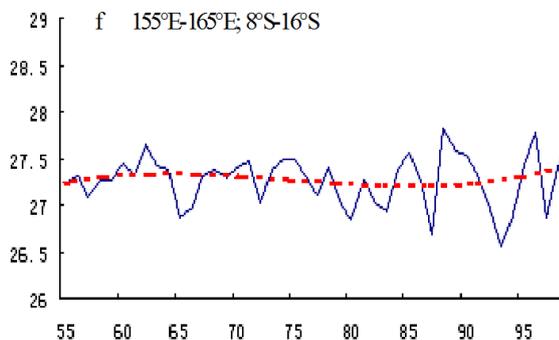
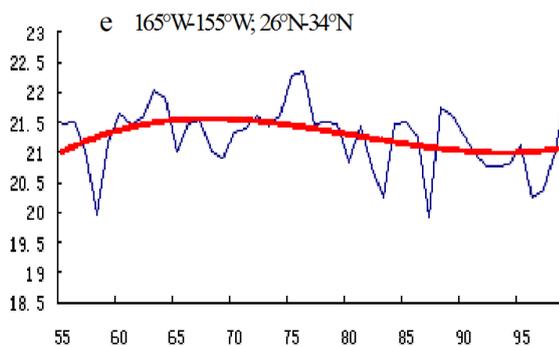
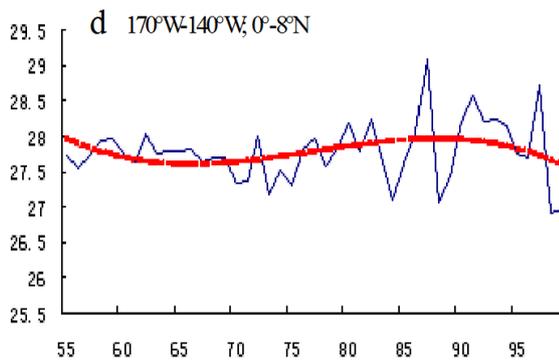


Figure 6. Similar to Figure 5, but for sea temperature at 40 m

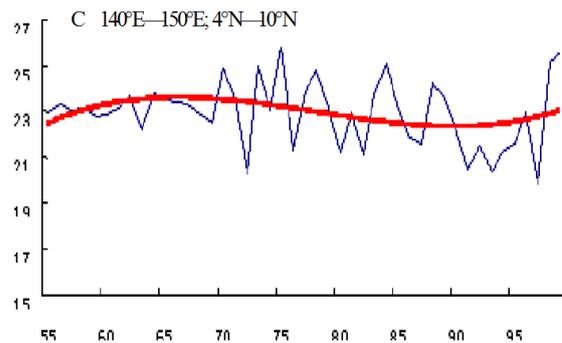
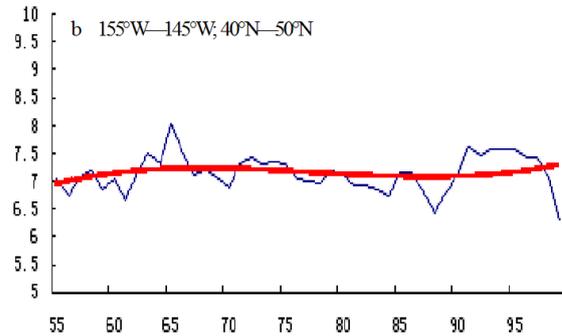
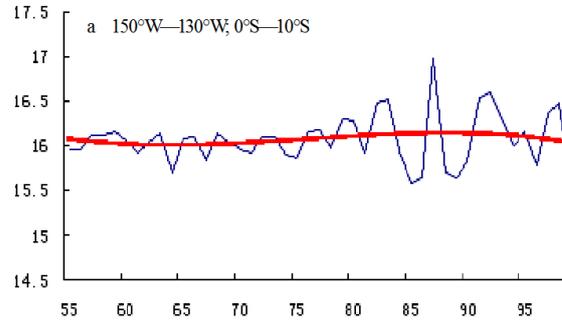


Figure 7. Similar to Figure 5, but for sea temperature at 120 m in the regions of (a) 150°W-130°W; 0°-10°S; (b) 155°W-145°W; 40°N-50°N; (c) 140°E-150°E; 4°N-10°N

5. Conclusion and Discussion

In this study, the averaged monthly sea temperature's departure field over the past 45 years in three layers in the ocean area of northern Pacific is analyzed using the spatial-temple synthesis method. The conclusions are summarized as follows:

(1) The most sensitive area of the annual sea temperature change is in the middle to east equatorial Pacific, where the change can reach down to 120 m below sea level, but the spatial range becomes marginal from sea surdace down to the deeper sea; while the annual sea temperature change is relatively small in west Pacific and the range is also smaller. The annual sea temperature change of the above sea surface in the west Pacific area (warm pool) clearly becomes larger than at 120 m and has the op-

posite phase with the east Pacific; the observation shows that the initial departures of the sea temperature producing El Nino or La Nina mainly appear in the thermocline at about 150 m of 'warm pool', when developing to specific threshold, it transforms to the area of east tropical Pacific along with the climatic thermocline and ascends to the surface. The abnormality forced by atmosphere in western boundary of Pacific can cause abnormal temperature in the subsurface and mainly transforms to the east ocean along with the east passing Kelvin wave, finally it leads to the abnormality of the whole Ocean. Therefore, the changing relation of the opposite phase of the abnormally sensitive area of interannual change between west and east equatorial Pacific is the remarkable trait in the northern Pacific.

(2) The sea temperature change in middle to east equatorial Pacific is related to the opposite phase in west equatorial Pacific, which is the basic and main characteristic not only in the sea surface, but also in the whole sub-surface.

(3) The sensitive area of the sea temperature in Pacific changes in different layers can better reflect the general trend of sea temperature in different sea layers. The Sea surface, which is affected by the east and west wind and is adjusted by the change of atmospheric circulations, presents evident uniformly. Meanwhile, the inter-annual abnormal signal of sea temperature in sub-surface can provide better signal to the circulation of ENSO.

(4) The inter-annual change of sea temperature shows an increasing interannual rate from the 1980s to the middle 1990s in the ocean's surface and at 40 m below sea surface level, the increasing trend inosculates with the high frequency of El Nino. Thermocline presents the opposite change with the surface at a depth of 120 m. The break of interannual signal in the Pacific not only exists in the atmosphere and ocean's surface, but also exists in the whole subsurface.

Acknowledgments

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