A Data Analysis Study on the Evolution of the El Niño/ La Niña Cycle

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ABSTRACT

The curved surface of the maximum sea temperature anomaly (MSTA) was created from the JEDAC subsurface sea temperature anomaly data at the tropical Pacific between 1955 and 2000. It is quite similar to the depth distribution of the 20°C isotherm, which is usually the replacement of thermocline. From the distribution and moving trajectory of positive or negative sea temperature anomalies (STA) on the curved surface we analyzed all the El Niño and La Niña events since the later 1960s. Based on the analyses we found that, using the subsurface warm pool as the beginning point, the warm or cold signal propagates initially eastward and upward along the equatorial curved surface of MSTA to the eastern Pacific and stays there several months and then to turn north, usually moving westward near 10°N to western Pacific and finally propagates southward to return to warm pool to form an off–equator closed circuit. It takes about 2 to 4 years for the temperature anomaly to move around the cycle. If the STA of warm (cold) water is strong enough, there will be two successive El Niño (La Niña) events during the period of 2 to 4 years. Sometime, it becomes weak in motion due to the unsuitable oceanic or atmospheric condition. This kind process may not be considered as an El Niño (La Niña) event, but the moving trajectory of warm (cold) water can still be recognized. Because of the alternate between warm and cold water around the circuits, the positive (negative) anomaly signal in equatorial western Pacific coexists with negative (positive) anomaly signal near 10°N in eastern Pacific before the outbreak of El Niño (La Niña) event. The signals move in the opposite directions. So it appears as El Niño (La Niña) in equator at 2–4 years intervals. The paper also analyzed several exceptional cases and discussed the effect and importance of oceanic circulation in the evolution of El Niño / La Niña event.

Key words: El Niño (La Niña) events, curved surface of maximum sea temperature anomaly, Kelvin wave and Rossby wave, air–sea interaction

1. Introduction

The El Niño phenomenon is characterized as the interannual appearance of unusual oceanographic conditions–exceptionally high sea surface temperature (SST) in the eastern equatorial Pacific. Because it can cause the abnormal variability of the global climate by the way of air–sea interactions, a great deal of work has been done to try to make clear the physical process of its appearance and development in the past fifty years. Before the 1980s, it was believed that the original positive sea surface temperature anomalies (SSTA) originated from

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near the coast of Peru in South America and propagated to equator and then westward along the equator. And the composite model synthesized by Rasmusson and Carpenter (1982), according to SST evolvement, gave a description of such an analysis at the beginning of 1980s. However the El Niño of 1982–1983 which attained a very large amplitude (Gill and Rasmusson 1983) and the El Niño of 1986–1987 which attained a moderate amplitude (Mcphaden et al. 1990) were exceptional because their initial SSTA came into being in the central and western equatorial Pacific and then the positive SSTA propagated eastward along the equator. At that time, according to the evolution of SSTA, it was taken for granted that the development of El Niño may have two different processes, one from the east to west and the other from the west to east. One of the major accomplishments of the 10–year (1985–94) Tropical Ocean Global Atmosphere (TOGA) program is to improve the in–suit data and the historical data, and offer the data basis to study the physical process of development.

The El Niño of 1997–1998 was, by some measures, the strongest on record. Analysis made by Li and Mu (1999), McPhaden (1999) show that warm water of 1997 / 1998 El Niño event originates in the subsurface warm pool in the western Pacific, then spreads toward the east and upward along the equatorial thermocline. Further investigation made by Chao and Chao (2001), they indicated that the warm water of eleven El Niño events and also the cold water of eleven La Niña events are appearance in the subsurface warm pool, then propagate eastward along the equatorial curved surface of MSTA, when they reach the Nino 3 region the positive / negative temperature anomalies have already ascended to the surface and then appear as El Niño / La Niña events we usually consider.

The important question caused by the previous research is where the warm / cold water as the source of El Niño / La Niña event comes from and where it goes after they reach the Nino 3 region. For this question, Chao et al. (2002) recently studied the case of 1997 / 1998 El Niño and gave the moving path of warm / cold water mass. In this paper, the systematic analyses for all El Niño / La Niña events since late 1960s have been presented.

Monthly sea surface temperature and sea subsurface temperature data are used in this study. They are taken from Scripps Institute of Oceanography (JEDAC) on a 5° (lat.)× 2° (long.) grid. This study emphasizes the region of tropical and subtropical Pacific between 20°N and 20°S.

2. Seasonal variation of MSTA

The varied characteristic of sea temperature over thermocline is firstly to be analyzed. The position of 20°C isotherm is usually regarded as the thermocline depth. However, the SST over the equator and the southern part of the Eastern Pacific is less than 20°C and there still exists thermocline there. So another method needs to be developed. In this study, based on the previous research along equator, we point out that the variation of temperature near the thermocline is largest, then the historical data is used to construct the climatological curved surface of maximum sea temperature anomaly (MSTA) for approximately taking the place of the traditional thermocline curved surface in the whole tropical region. Figure 1 is the result based on the above two methods, and a very similar characteristic is shown in most regions of the tropical ocean, except for the smaller difference over the eastern Pacific. How does one construct the surface of MSTA? The first step is to find the depth over the region of MSTA during each month in each grid. Using the weighted averages method for the same month of each year, twelve climatic–averaged curved surface of MSTA are obtained.

The curved surface of MSTA of January, April, July and October is shown in Fig. 1a. Analysis shows little variation in different months. Among them, the depth is shallowest in April, becoming deeper as the month goes. It reaches the deepest level in December. The general depth distribution along the equator is that the thermocline reaches its deepest position beyond 120 m in the warm pool, and gradually becomes shallower to the east. It almost reaches the sea surface in the eastern Pacific. The deepest is not in the warm pool, but near 15°S. That phenomenon is perhaps related to the South Equatorial Current. Comparing Figs. 1a and 1b (20°C isotherm curved surface, i.e., thermocline curved surface), the trend is very similar.

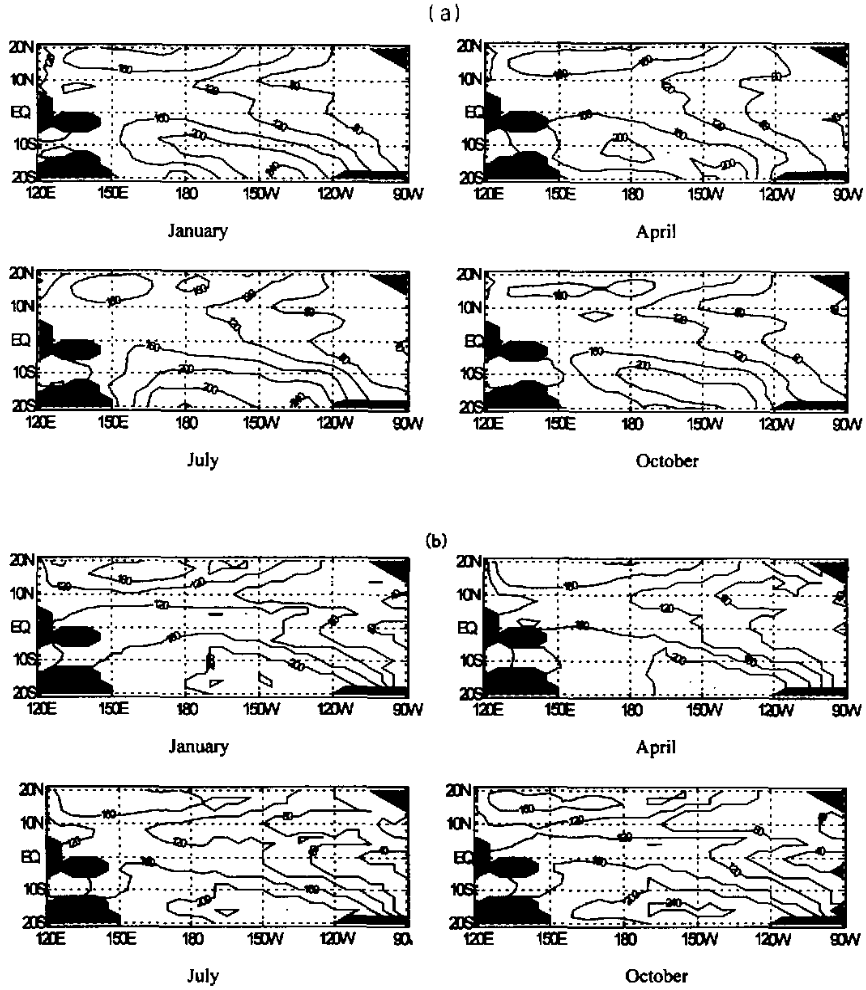

Fig. 1. (a) Climatically-averaged curved surface of maximum sea temperature anomaly (MSTA) (units: m). (b) Depth distribution of the 20°C isotherm (units: m).

3. The evolution characteristics of sea temperature anomaly in the MSTA curved surface

If defined by the index of SSTA in the Nino 3 region, there are totally seven El Niño events, which are in 1972 / 1973, 1976 / 1977, 1982 / 1983, 1986 / 1987, 1991 / 1992, 1994 / 1995, and 1997 / 1998. Moreover, one finds six La Niña events, in 1971, 1973 / 1974, 1978, 1983 / 1984, 1988 / 1989, and 1998. Observing the development of subsurface cold / warm water (Fig. 2), the appearing time of El Niño / La Niña may be not in the above years. The reason is that the values of sea temperature anomaly in the MSTA curved surface and the SSTA may be not totally the same, even over the equatorial eastern Pacific.

The abscissa in Fig. 2 is divided into five parts. For the left panels, the first part covers 140°E to 95°W along the equator, the second 2°N to 10°N along 95°W, the third 100°W to 145°E along 10°N, and the fourth 10°N to 2°N along 140°E. These four parts form a closed circuit in the Northern Hemisphere, being completed by the fifth part covering 140°E to 160°E along the equator.

For the right panels, the first part also covers 140°E to 95°W along the equator, the second 2°S to 10°S along 95°W, the third part 100°W to 170°E along 10°S, and the fourth along the grid of (165°E, 10°S), (160°E, 8°S), (155°E, 6°S), (150°E, 4°S), and (145°E, 2°S). The reason that we chose such a route in the fourth part is that there are many islands near the warm pool in the south of 140°E and no data there. The fifth part covers 140°E to 180° along the equator and hence forms a closed circuit in the Southern Hemisphere.

The ordinate in Fig. 2 shows time. The evolution of El Niño / La Niña, demonstrated in the figure, is explained in the following subsections.

3.1 *The development of typical warm water events*

Judged by the SSTA index in the Nino 3 zone, the event of 1968 / 1969 is not considered an El Niño event. However, if it is judged by the intensity and duration of sea subsurface temperature anomaly, it is indeed a warm water event. The warm signal in the warm pool of the western Pacific propagated eastward in 1968 and reached the equatorial eastern Pacific in 1969. It then left the equator and propagated westward along both 10°S and 10°N. It reached the warm pool in 1971 and propagated eastward to the equatorial eastern Pacific to become the El Niño event of 1972 / 1973. Another strong El Niño is the event of 1997 / 1998, which was analyzed by Chao and Chao (2001) and Chao et al. (2002). In Fig. 2 it is seen that the warm water in the warm pool subsurface comes from the warm water event of 1995. This signal of positive sea temperature anomaly of 1995 in the Nino 3 zone propagated westward along the closed circuit from 10°S and 10°N to the warm pool subsurface, and stayed and developed there to be a warm water mass. It then moved eastward along the equatorial thermocline to the equatorial eastern Pacific in 1997 to become the event of 1997 / 1998. Both cases show that the warm water in the warm pool subsurface usually comes from the positive sea temperature anomaly in the equatorial eastern Pacific and moves westward along the respective off–equator circuits.

3.2 *The development of weak El Niño events*

The event of 1976 / 1977 was a weak one. Following the origin of its warm water, it was found that the positive sea temperature anomaly of 1973 in the equatorial eastern Pacific moved to the warm pool from 10°N. The signal of the weaker positive sea temperature

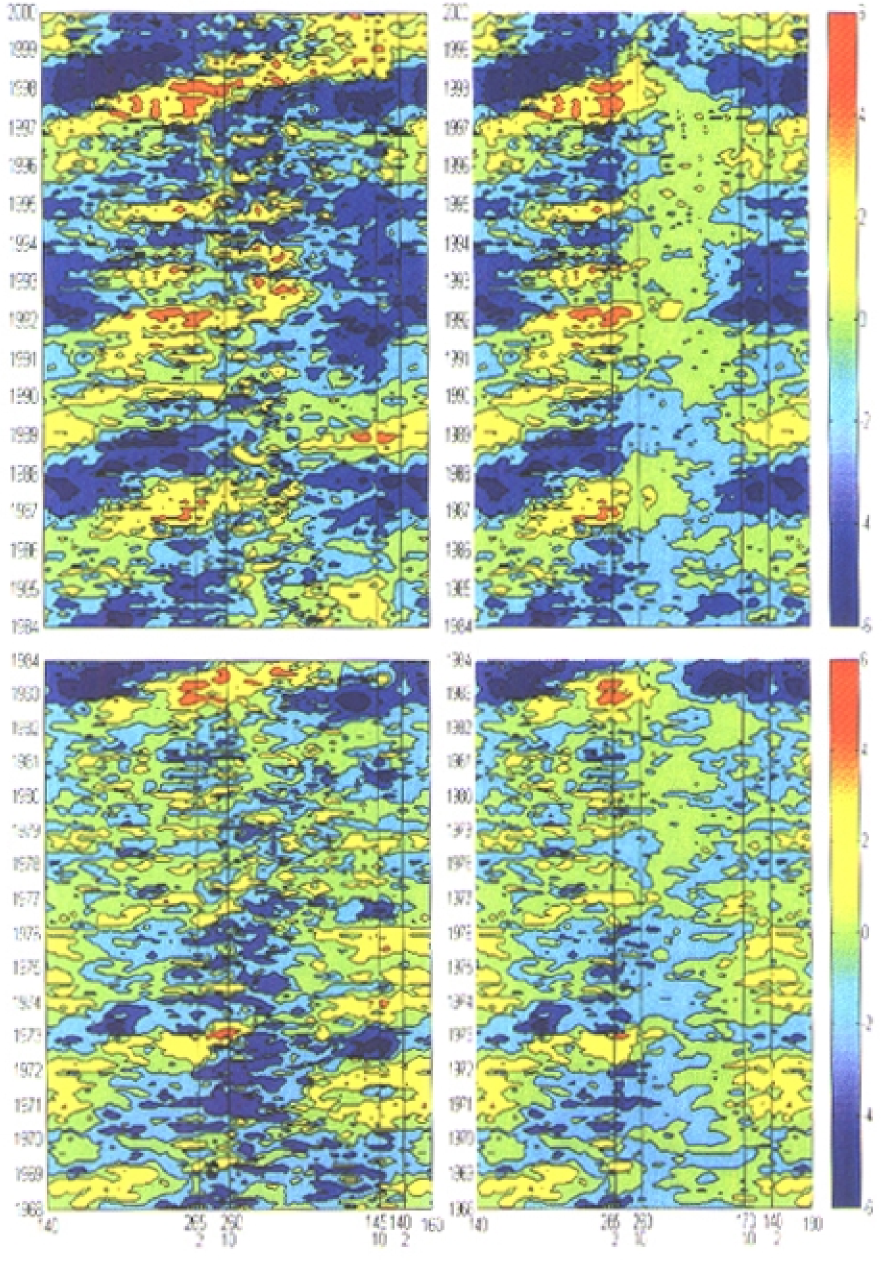

Fig. 2. The evolution process of the El Niño (La Niña) events.

anomaly moved to the Nino 3 zone along the equator and then westward along the north branch of the circuits. During the period, the temperature anomaly was negative. However, when it moved to the central Pacific in 1975, it changed to positive. After it reached the warm pool and propagated eastward along the equator, it became stronger. The process is finally developed into a weaker El Niño event. This case indicates that the intensity of sea temperature anomaly varies during its evolution, even totally changing sign on one occasion, while usually propagating westward along the circuit of 10°N. If the intensity of the temperature anomaly cannot be strengthened for some time, the warm water event will disappear.

3.3 *The development of La Niña events*

In 1969, the cold water stayed in the warm pool subsurface after the warm water of 1968 propagated eastward. Similarly, the cold water moved eastward along the equatorial thermocline and developed into a La Niña event in 1971. Then, the negative sea temperature anomaly near the surface of the equatorial eastern Pacific propagated westward to the warm pool subsurface around the northern (stronger signal) and southern (weaker signal) branch of the circuits respectively. A strong negative anomaly formed in the warm pool in 1973 and moved eastward to the eastern Pacific along the equatorial thermocline to form the strong La Niña event of 1973 / 1974. Another case is the development of cold water after the strong El Niño event of 1998 came to an end. Notice that when the sea temperature anomaly was positive in the equatorial eastern Pacific, the negative anomaly occurring in the warm pool subsurface started to move eastward along the equator to the equatorial eastern Pacific in late 1996. It then moved westward to the warm pool along the northern branch and moved eastward to the eastern Pacific along the equator to form the strong cold event of 1998.

3.4 *Alternative occurrence*

The positive and negative anomalies always appear at the same time at the equator and at 10°N or 10°S before the El Niño or La Niña event begins. Maybe, the positive anomaly moves westward to the north of the negative signal as the negative anomaly moves eastward along the equator. Or, the negative anomaly moves westward to the north of the positive anomaly as the positive anomaly moves eastward. In other words, before El Niño occurs, the negative signal moves near 10°N to the warm pool when the positive anomaly propagates eastward along the thermocline. The situation for La Niña is similar, but with the negative anomaly instead of the positive one. Therefore, the La Niña (El Niño) event is growing when El Niño (La Niña) develops. The El Niño and La Niña events form a cycle that alternates between a warm phase and a cold phase. Of course, the period between two warm (cold) events in succession may be different. For example, the interval between El Niño events of 1976 / 1977 and 1982 / 1983 is greater than six years but only two years between the La Niña events of 1971 and 1973 / 1974. The average interval, however, is 3 to 4 years in the last 30 years.

Of course, there are some unique characteristics for each El Niño or La Niña event beyond the above basic ones. The El Niño event of 1982 / 1983 is a rare case in which the warm water did not originate from the warm pool but from the central Pacific. In fact, a portion of the warm water came from the western Pacific, and the event's position was to the north of the equator and the intensity was weaker. So, the developing process has not been shown in the figure. This phenomenon also indicates external influences on El Niño events.

4. Summary and discussion

The above analysis shows that, corresponding to the warm event or cold event, the positive or negative anomaly propagates along the two closed circuits above the thermocline curved surface in the tropical off–equator ocean. The signal propagates eastward along the equator and westward along 10°N and 10°S respectively. Generally speaking, the warm event appears alternating with cold event. The average interval between two warm (cold) events in succession is about 3 to 4 years. The period is related to the propagating time along the circuits.

The following questions arise from the above analysis.

(1) Why does the signal propagate along the circuit above the thermocline curved surface? Can we consider that the variation in the temperature anomaly mainly reflects the depth variation of the thermocline in the process of internal ocean and atmospheric forcing?

(2) Why does the signal propagate westward along 10°N and 10°S respectively? Is this related to the distribution of equatorial current or to the pattern of atmospheric circulation in the tropical region?

(3) Does the Kelvin wave or another process reflect the eastward propagation of temperature anomaly along the equatorial thermocline?

(4) In many cases, it is difficult to explain with Rossby wave theory the westward propagation of the temperature anomaly along 10°N or 10°S, because the signal propagates westward too fast sometimes. For example, the speed of the westward propagation between 5°N and 15°N is faster than the warm signal speed of the eastward propagation along the equator in the event of 1997 / 1998. Even if the speed of the current is considered, the speed cannot reach that fast. So, it may be due to the sea temperature change responding to air–sea interaction. Thus, this needs further investigation.

In a sense, the results shown in this paper may change the traditional understanding on the evolution of the El Niño / La Niña event. So we should reconsider some past theory and develop new theoretical framework as well as conduct prediction simulations.

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厄尔尼诺和拉尼娜事件循环演变过程的资料分析研究

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摘　要

利用1955−2000年热带、副热带太平洋地区次表层温度距平资料，构造了温度距平极值深度分布曲面图，它很接近20°温度面的深度分布，因此有理由认为这一深度曲面很接近热带温跃层的深度面。在温度距平极值深度曲面上，分析了20世纪60年代后期以来所有El Niño／La Niña事件正／负海温距平信号的分布和传播"轨迹"，发现如果以暖池次表层作为起点，则一般来说，暖水或冷水先是沿赤道极值深度面向东、向上传播或运动，到达赤道东太平洋海盆边界附近后，在那里停留几个月，然后转北运动，在北纬10度左右再折向西运动到西太平洋转向南返回到暖池，即在赤道北侧形成闭合回路。温度距平运动一圈需时2−4年。如果暖(冷)水的温度距平都很强，就会在2−4年的时间上出现两次相邻的El Niño (La Niña)事件，但可能是由于大气或海洋环境条件不合适，温度距平的强度在运动过程中有时会减弱，就不能形成El Niño (La Niña)事件，但暖(冷)水运动的"轨迹"仍可辨认。由于暖、冷水绕环路的运动交替出现，El Niño (La Niña)爆发前，在赤道西太平洋出现正(负)距平信号的同时，在东太平洋北纬10度左右会有负(正)距平信号出现，并且当正(负)距平信号向东传播时，负(正)距平信号向西传播，在赤道上表现为2−4年间隔的El Niño(La Niña)交替出现。文中也分析了少数例外过程，指出大洋环流条件在El Niño和La Niña事件演变过程中的作用。

关键词：厄尔尼诺(拉尼娜)事件，温度距平最大值曲面，Kelvin波和Rossby波，海气相互作用