Vol.8 No.2 **JOURNAL OF TROPICAL METEOROLOGY** December 2002

Article ID: 1006-8775(2002) 02-0168-12

DIAGNOSTIC PREDICTIONS OF SST IN THE EQUATORIAL EASTERN PACIFIC OCEAN BASED ON FUZZY INFERRING AND WAVELET DECOMPOSITION

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ABSTRACT: Methods and approaches are discussed that identify and filter off affecting factors (noise) above primary signals,based on the Adaptive-Nework-Based Fuzzy Inference System. Influences of the zonal winds in equatorial eastern and middle/western Pacific on the SSTA in the equatorial region and their contribution to the latter are diagnosed and verified with observations of a number of significant El Niño and La Niña episodes. New viewpoints are propsed. The methods of wavelet decomposition and reconstruction are used to build a predictive model based on independent domains of frequency,which shows some advantages in composite prediction and prediction validity.The methods presented above are of non-linearity, error-allowing and auto-adaptive/learning, in addition to rapid and easy access,illustrative and quantitative presentation,and analyzed results that agree generally with facts. They are useful in diagnosing and predicting the El Niño and La Niña problems that are just roughly described in dynamics.

Key words: fuzzy inferring; ANFIS model; El Niño/La Niña

CLC number: P433 **Document code:** A

1 INTRODUCTION

The El Niño/La Niña is a complicated non-linear system, which is jointly subject to various factors through non-linear processes. Its mechanism of activity is still poorly understood. Questions like what the important factors are in governing the El Niño/La Niña, by what processes and how much individual factors contribute to individual episodes, remain to be studied. Showing basic features of wave motion, screening systematic fast waves and highlighting main characteristics of weather and climate, approaches like low-band pass filter, Fourier transform and statistic smoothing do have their drawbacks. During the filtering, they are only coping with the frequency structure of the signal itself, being incapable of definitely resolving how and where the filtered noise is generated. It is general in filtering so that it is impossible to perform efficient extracts of major affecting factors that are useful in diagnosis of weather and climate abnormalities. It is true that it is possible, through computation of the fractional dimension, Liapunov index or Renyi entropy of the observations, to get information about the changes in weather and climate in attempts to understand the complexity of the system and approximate validity of predictable periods, but we are still way off from diagnosing and testing factors that are playing important roles in the system. The fuzzy inferring system is an efficient technique that deserves trial in our effort to extract and induce observation-contained mapping relationships and non-linear correlation between individual factors, for sublimation of a quantitative control system and a diagnostic predictive model. The ANFIS fuzzy model is used in

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Received date: 2001-06-24; **revised date:** 2002-07-19

Foundation item: Backbone Teachers Foundation of Higher Education Colleges from the Ministry of Education (3149)

Biography: ZHANG Ren (1963 –), male, native from E'mei City Sichuan Province, professor, Ph.D., mainly undertaking the study of weather and climate over the tropical oceans.

the work to study the contribution and influence of the zonal winds in the eastern and western Pacific Ocean with regard to the important episodes of El Niño/La Niña since the 1970's.

It is equally complex to predict the El Niño/La Niña event. Relevant work[1-3] was conducted without much success using artificial neural network to modify and improve the predictive model, due to the complexity of the El Niño/La Niña event. The greatest challenge in prediction is the dilemma for perfect description of both general trends of SST and specific details. The prediction will not be complete if focus is laid on the fitting of significant lines of trends at the expense of detailed probes, because of fears that some fine-scale, fast processes may then be neglected that happen to reflect major variations in the system. What is our choice if we want to retain as much information about the predicted objects as necessary without making the prediction process to an extent that is overwhelmingly complicated? It is studied here in the work with the aid of wavelet decomposition and reconstruction.

2 FUZZY SYSTEM AND ANFIS MODEL

The fuzzy theory was founded by Lotfi Zadeh of the Berkeley University, California. He published his "fuzzy sets" in 1965, which first introduced the concept of fuzziness. For every substance in a set, a complete algebraic system of fuzzy sets is described in detail and expanded to a theory of convex separation for model identification[4]. The core of the fuzzy system is for a language-interpreted mathematical model to be set up in complicated systems or processes, through which expert experience or practical perception that are described in natural languages are transformed to quantitative computer algorithms and control systems that are expressed by fuzzy regulations and sets. Through drilling and auto-adaptation, the ANFIS can accomplish the work of error reduction and efficiency increase for approximation that would otherwise require empirical adjustment of the subordinate function in conventional fuzzy systems. Based on composite learning, it resolves linear parameters from non-linear ones by way of the least square and backward gradient decreasing methods. A fuzzy inference system is then established that uses a series of "IF…THEN" rules and appropriate subordinate functions are gradually adjusted to satisfy the input/output relationships needed in fuzzy inference[5]. For basic theories of the fuzzy systems and basic structures of the ANFIS, see relevant references[6-7].

In the atmospheric science, it is sometimes difficult to have accurate recognition of major affecting factors that truly restrain the system dynamically. If the magnitude of linear correlation is used to determine how the mutual relationships and influence are, it is likely to miss some non-linear systems or factors; if there are significant correlation coefficients, it should be with care that they may be superficial reflection as they are the factors having indirect dynamic links with the system. As the ANFIS is non-linear, allows errors and adapts automatically, the current work applies it to the diagnostic/discriminating analysis of affecting factors of the El Niño/La Niña events and predicts them and the SST in the equatorial eastern Pacific, in combination with wavelet decomposition and reconstruction.

3 THE TESTING AND ANALYSIS OF AFFECTING FACTORS FOR THE EL NIÑO/LA NIÑA EVENT

As shown in studies, the release of oceanic potential energy as a consequence of weakened trade wind anomalies in the Pacific Ocean is one of the important causes for the onset of El Niño[8]. Apart from the anomalies of the trade wind in the equatorial eastern Pacific, the region of equatorial central and western Pacific is also a key to the development and cycle of the ENSO. Similarly, the trade wind anomalies in that region are as important[9]. From the ANFIS model, we will discuss the basic corresponding and mapping relationships between the trade winds in the equatorial eastern and central/western Pacific and the El Niño/La Niña events.

3.1 *Selection of data*

The data used include 396 months of time series of global monthly mean SST and zonal wind fields in 1958~1990 (33 years) from NCEP/NCAR and COADS. The object of interest is the SST anomalies (denoted as SST_e) over the equatorial eastern Pacific (averaged over waters at 180°~90°W; 10°S~0°) and the affecting factor is the 850-hPa 3~5 month leading zonal wind anomalies (denoted as U_w and U_e, which are both divided by 4 for coordination of graphic plotting) averaged over the waters at 120°E~180°, 0°~10°N (the equatorial central/western Pacific) and 180°~90°W, 10°S~0° (the equatorial eastern Pacific).

3.2 *The mapping characteristics of SST_e in the ANFIS*

In the ANFIS, a Takagi-Sugeno type fuzzy inference system that has 2^N rules is used to adapt to the drilled data, in which N is the number of dimension of data being input ($N<7$ is usually taken). After the drilling, the fuzzy system returns in the form of a FIS matrix. The work employs an ANFIS consisting of 3 input and 1 output network. The Matlab programming language is used in the drilling and establishment of the model, inference and artificializing are materialized in the environment of Fuzzy Toolbox[10]. Input/output data, paired with 3~5 month leading U_w and U_e and lagging SST_e, are drilled for 261 months that span from 1958 to 1979. After 200 drilling iterations, a preset order of magnitude for error is acquired (10^{-1}) and a fuzzy inference system and mapping relationships are set up for zonal winds in the equatorial eastern and western Pacific. Fig.1 and Fig.2 are the input/output mapping relationships between U_w, U_e and SST_e. Basic mappings are summarized from the figures as follows.

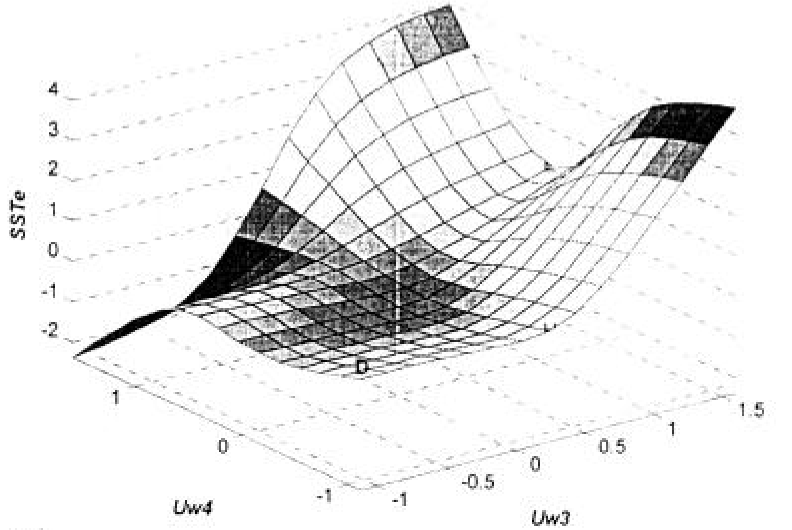

图 1

Fig.1 The equatorial central/western Pacific zonal winds U_e leading by 3 months (U_{e3}) and 4 months (U_{e4}) in fuzzy mapping relationships with SST_e.

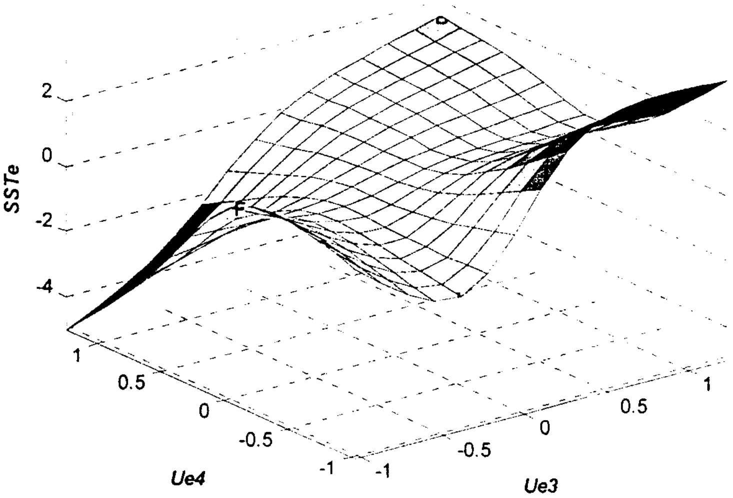

图2

Fig.2 The equatorial eastern Pacific zonal winds U_e leading by 3 months (U_{e3}) and 4 months (U_{e4}) in fuzzy mapping relationships with SST_e.

(1) If there is strong easterly trade wind in the equatorial central/western Pacific four months earlier ($U_{w4}<0$) and it changes to a strong equatorial westerly three months earlier ($U_{w3}>0$), then there will be positive anomalies of SST_e (Fig.1, Point A).

(2) If there are westerly anomalies (U_{w3} and U_{w4} are both positive) in the equatorial central / western Pacific leading by 3 ~ 4 months, positive anomalies can also be resulted in SST_e (Fig.1, Point B)

(3) If there is strong westerly in the equatorial central/western Pacific four months earlier ($U_{w4}>0$) and it changes to a strong equatorial easterly three months earlier ($U_{w3}<0$), then there will be strong negative anomalies of SST_e (Fig.1, Point C).

(4) If normal easterly trade wind is maintained (U_{w3} and U_{w4} are both negative) in the equatorial central / western Pacific leading by 3 ~ 4 months, weaker negative anomalies can be resulted in SST_e (Fig.1, Point D).

(5) Provided that U_w is strong westerly ($U_{w3}>1$) three months ago, U_w is between 0 and 1 ($0<U_{w4}<1$) four months earlier and has a minimum point of SST_e (Fig.1, Point E). It shows that positive anomalies of SST_e (El Niño) can be present only when there is strong westerly ($U_{w4}>1$) or easterly ($U_{w4}<0$) four months earlier. Point F in Fig.1 is the point of maximum SST_e and similar discussions can be held: in the case of strong easterly ($U_{w3}<-1$) three months earlier, large negative anomalies of SST_e (La Niña) can be present only when there is strong westerly ($U_{w4}>1$) or easterly ($U_{w4}<0$) four months earlier. No significant changes will take place in the positive or negative SST_e of either westerly or easterly three months earlier if the westerly is weak four months earlier (Fig.1, in the direction of E-F).

(6) Provided that U_w is strong westerly ($U_{w4}>1$) four months ago and consequently U_w takes the values (U_{w3}) that change gradually from negative to positive three months earlier, then SST_e roughly turns sharply upward at Point 0 of U_{w3} (Fig.1, Point G). In other words, if the strong westerly in the preceding period (four months earlier) maintains till a consequent period (three

months earlier), then the transitional phase of the westerly will correspondingly have a sharp growth of SST_e and Point G can be viewed as a point of abrupt change in the course of El Niño evolution. If there is strong easterly ($U_{w-4}<-1$) four months earlier and U_w changes from negative to positive three months earlier, there is also a point of abrupt El Niño change, though with a less steep slope (Fig.1, Point H).

For the fuzzy inference system, similar patterns of mapping is found between preceding U_e and lagging SST_e in the equatorial eastern Pacific (Fig.2). Points A ~ H resemble those in Fig.1 in significance, but with smaller amplitude of variation and less distinct physical images than the former. As shown in the comparison between Fig.1 and Fig.2, we know that the positive anomalous amplitude caused by U_w anomalies is larger than that of U_e while the negative anomalous amplitude caused by U_e is more significant than that of U_w. It is then clear that significant El Niño phenomena may result in higher contribution from U_w while significant La Nina event may be more closely related with U_e.

The mappings of inference as summarized in the above (1) ~ (6) give a general picture of the basic facts and main characteristics of the trade wind variation in the Pacific Ocean and its corresponding relationships with the El Niño/La Niña event. They are in general agreement with the viewpoints of existing trade wind relaxation theory concerning the generation mechanism of ENSO. The significant non-linear mappings as revealed in (5) ~ (6) are to be verified by facts for explanation of dynamic mechanisms. Entirely based on U_w and U_e and the time series of observations, the fuzzy inference system gives objective outcome.

3.3 *Noise exploitation and discussions of inference results*

Data from two periods in 1970~1979 and 1980 ~ 1990 are used in yielding pairs of input / output dataset of 3- to 5- month leading U_w and U_e and SST_e for the set-up of ANFIS model that relates the equatorial eastern and western Pacific zonal winds and lagging SST in the equatorial eastern Pacific. The artificial mappings in the model are used to approximate the disturbance contribution of the zonal winds in the eastern and western Pacific to the SST evolution in the equatorial eastern Pacific (Figs.3 & 4), with SST_e having the following phase characteristics:

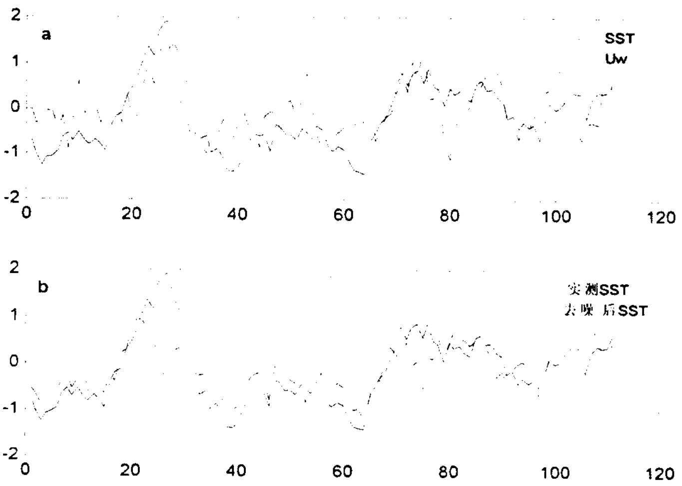

图 3

Fig.3 3-month leading U_w and lagging SST_e (a); observed SST_e and SST_e with the 3~5 month U_w disturbance filtered (b) [1970~1979]. Legend for the lower panel: upper line: observed SST; lower line: noise-filtered SST.

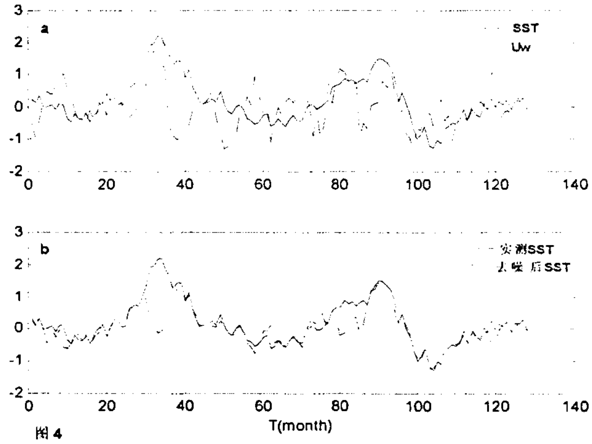

Fig.4 3-month leading U_w and lagging SST_e (a); observed SST_e and SST_e with the 3~5 month U_w disturbance filtered (b) [1980~1990]. Legend for the lower panel: same as Fig.3.

3.3.1 PHASE CHARACTERISTICS ONE

As shown in Fig.3b, with the removal of the U_w effect (the dotted line), the El Niño phenomenon for 1972 has been much reduced (see the period 20 ~ 30 in the figure). A negative anomalous span of SST_e is even present during the El Niño in 1976 (see the period 70 ~ 80). In contrast, no significant influences are evident in the La Niña events in 1970 (corresponding to periods 1 ~ 5), 1973 (periods 35 ~ 42) and 1975 (periods 60 ~ 65), only that a small amplitude of intensity has been decreased. It is conferred that the 3- to 5- month leading zonal winds in the equatorial western Pacific are having very important influence on the El Niño events in 1972 and 1976. Studying the mechanism from the distribution of U_w in Fig.3a (the dotted line) and the lagging SST_e (the solid line), we find that the 3-month leading U_w has peaks of generally the same phases as the consequent SST_e over the episodes of 1972 and 1976 El Niño events (corresponding to periods 20 ~ 30 and periods 70 ~ 80, respectively). In other words, the westerly anomalies U_w during the processes may be an important cause and triggering mechanism for the El Nino event in 1972 and 1976.

3.3.2 PHASE CHARACTERISTICS TWO

In Fig.4b, with the removal of U_w effect, the strong El Niño phenomenon for 1982/1983 (periods 25 ~ 40) has been generally eliminated while that for 1986/1987 (periods 78 ~ 92) remains largely unaffected, only that its intensity has been decreased to some extent in the first half but to least effect in the second half of the period. The La Nina event is virtually unaffected for 1988 (approximately over the periods 98 ~ 108). By another presentation, the preceding zonal winds in the equatorial western Pacific have much influence on and contribution to the El Niño in 1982/1983 while having little with regard to the El Niño event in 1986/1987 and the following La Nina event. The distribution curves of U_w against the lagging SST_e are useful in our study of the characteristics and mechanism behind the influence. It is known from Fig.4a that the 3-month leading U_w experiences a growing period that is in phase with SST_e — there is a significant intensification of westerly anomalies in the equatorial western Pacific three months prior to the El Niño event and the anomalous display of U_w may be one of the important causes for the 1982/1983 El Niño. In comparison, the 3- to 5- month leading U_w experiences a growing period that is out of phase with SST_e — there is a significant intensification of easterly trade in the equatorial western Pacific three months prior to the El Niño event, which is unfavorable for the appearance of El Nino. It is concluded that for the 1986/1987 El Niño event the zonal wind in the equatorial western Pacific is not a major factor to affect and trigger.

Fig.5 & 6 are the fuzzy approximation and artificial study of the effect of the equatorial eastern Pacific zonal wind U_e on the equatorial eastern Pacific SST_e.

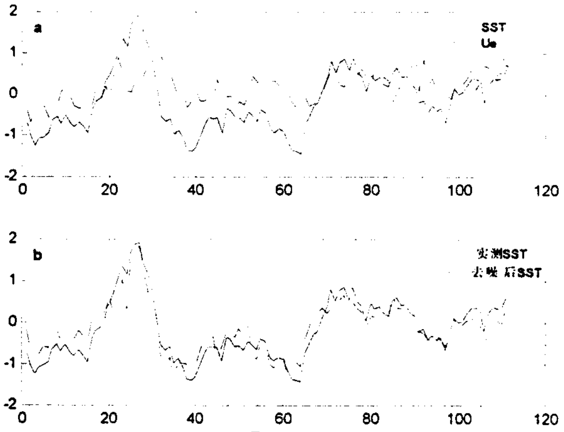

图5

Fig.5 3-month leading U_e and lagging SST_e (a); observed SST_e and SST_e with the 3- to 5- month U_e disturbance filtered (b) [1970~1979]. Legend for the lower panel: same as Fig.3.

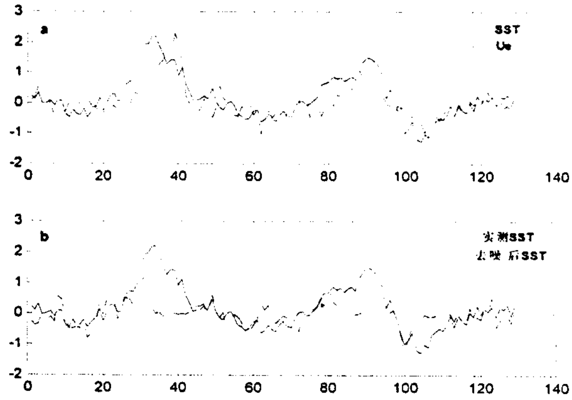

图6

Fig.6 3-month leading U_e and lagging SST_e (a); observed SST_e and SST_e with the 3- to 5- month U_e disturbance filtered (b) [1980~1990]. Legend for the lower panel: same as Fig.3.

3.3.3 PHASE CHARACTERISTICS THREE

With the removal of U_e effect, as shown in Fig.5b, the strong 1972 El Niño process (approximately the periods 20 ~ 30) is largely what it has been and the 1976 El Niño process (approximately the periods 70 ~ 80) has not changed much either in structure. No significant changes are seen in the La Nina event for 1970, 1973 and 1975. In other words, the 3~5 month leading zonal wind in the equatorial eastern Pacific are having little influence on or contribution to the El Niño/La Niña event. It is known from the distribution curves of U_e and lagging SST_e as shown in Fig.5a that during the El Niño in 1972 the 3-month leading U_e is not only unfavorable for the westerly disturbance of El Niño, but witnesses the appearance of an out-of-phase westerly decrease. It is then concluded that the 1972 El Niño event is not generated by the triggering of preceding U_e in the equatorial eastern Pacific. For U_e in other periods of time, no outstanding amplitude of disturbance is found in either the westerly or easterly, thus posing no obvious influence on the El Niño/La Niña.

3.3.4 PHASE CHARACTERISTICS FOUR

It is clear from Fig.6b that with the removal of U_e effect, the El Niño process has been effectively eliminated for 1982/1983 (periods 25 ~ 40) and 1986/1987 (periods 78 ~ 92) and the La Niña phenomenon has also been much weakened for 1988 (periods 98 ~ 108). In other words, the 3- to 5- month leading equatorial eastern Pacific zonal wind has great influence on and contribution to the 1982/1983 and 1986/1987 El Niño and 1988 La Niña. To find out the influence process and mechanism, Fig.6a is examined. During the 1982/1983 El Niño event (periods 25 ~ 40), the SST_e experiences a growing period of positive anomalies being in phase with simultaneous or even lagging U_e. To put it alternatively, a significant intensification of westerly anomalies appears in the equatorial eastern Pacific during and after the El Niño event. As they are in phase with or even lagging behind the warming of SST_e, the westerly anomalies of U_e cannot be the triggering mechanism but rather the strengthening and maintaining factor for the 1982/1983 El Niño. For the 1986/1987 El Niño event (periods 78 ~ 92) and 1988 La Niña (periods 98 ~ 108), U_e also has a westerly disturbance growth that leads by 3 ~ 5 months and an easterly disturbance growth that leads by 2 ~ 3 months. Preceding anomalies of the westerly (easterly) in the equatorial eastern Pacific are also a major factor triggering the 1986/1987 El Niño and 1988 La Niña events. The effect of U_w and U_e on the SST_e over the two periods are summarized as follows:

(1) As the equatorial eastern Pacific zonal winds have little influence on the 1970 and 1976 El Niño events, U_e cannot be a factor important for them. In contrast, the zonal wind in the equatorial central and western Pacific have important influence on the 1970 and 1976 El Niño events, leading to speculation that the 3-month leading westerly anomalies may be an essential mechanism triggering the events.

(2) In the 1982/1983 El Niño event, the westerly anomalies intensify first in the equatorial central and western Pacific, resulting in anomalous warming of SST_e about three months later. With the onset of El Niño, an intensification of westerly anomalies occurs in the equatorial eastern Pacific, strengthening and maintaining the El Niño. In other words, the preceding changes in the west Pacific zonal wind triggers the 1982/1983 El Niño event while the following growth of westerly disturbance in the equatorial eastern Pacific plays a consolidating role for that event. It is the appearance in succession of westerly anomalies of the zonal winds in the central / western and eastern Pacific, of the equatorial region, and their joint interactions, that are generating the 1982/1983 El Niño event which is the strongest in the 20th century.

(3) Similar to the 1982/1983 event, the 1986/1987 El Niño is also marked by a westerly intensification of U_w (approximately in the period 80) followed by a westerly disturbance strengthening of U_e (approximately in the period 86) to maintain the episode. As the westerly disturbance of U_w and U_e are less strong and last for a shorter period as compared to the 1982/1983 process, they are less remarkable. Relatively speaking, the zonal wind should be the factor playing a major role in the maintaining and strengthening of the 1986/1987 El Niño event while the preceding easterly anomalies of the trade wind of U_e in the equatorial eastern Pacific are the major play in the 1988 La Nina phenomenon.

(4) The fuzzy inference results and mechanism analysis are compatible with part of the observational facts and relevant study. The 1982/1983 El Niño event[8] is one such example. The warming first appears in the central Pacific region and the warm sector then spreads eastward. It can be explained by the mechanism analysis that the westerly anomalies appear successively in the equatorial central/western and eastern Pacific to initiate and intensify the warming. In a way similar to the classification of SST for the El Niño event[11-12], other factors can also be grouped. The El Niño event, which is mainly caused by the contribution of the equatorial eastern Pacific zonal wind, is called Group One (like the 1986/1987 process); if caused mainly by the

contribution of the equatorial central/western Pacific zonal wind, it is called Group Two (like the 1972 and 1976 processes); if caused mainly by the contribution of both the equatorial eastern and central/western Pacific zonal wind, it is called Group Three (like the 1982/1983 process). In comparison, the contribution by the equatorial central/western Pacific zonal wind is a major factor that is slightly higher in probability than the equatorial eastern Pacific zonal wind.

(5) The objective fuzzy noise filtering and inferring results as shown in the lower panels of Fig.3 ~ Fig.6 generally agree with the mechanism analysis and reality based on the figure above. It indicates that the fuzzy inference is a method to be relied on in dealing with the El Niño/La Niña issue. Our research results are further proves of the multiplicity of the evolution patterns and dynamic processes and the uncertainty of the triggering mechanism.

(6) Part of the conclusions presented here have been documented earlier but the current work attempts to verify the objectivity and reliability of the fuzzy system. As shown in the result, the method can efficiently learn and extract from datasets relevant regular patterns and input/output mappings and describe them quantitatively. They can then be illustratively used in numerical analysis and quantitative prediction. This is what the current paper is different from others and aims at.

4 DECOMPOSITION OF FREQUENCY DOMAINS OF THE SST IN THE EQUATORIAL EASTERN PACIFIC

The analysis shows that the equatorial eastern Pacific SST is of continuous power spectrum and temporal frequency spectrum, or, of dynamic randomization. It looks, therefore, quite complicated to have accurate prediction of the El Niño/La Niña. Attempts[1-3] have been made to apply artificial neural network model to predictive study of the SST in the equatorial eastern Pacific. The results are poorer than previously expected due to the complexity of the SST system. The dilemma is to give perfect description of both trends and details. Techniques like wavelet decomposition and reconstruction are powerful enough to separate complicated signals in terms of frequency or periodicity so that a complicated system can be changed to relatively simple, quasi-periodic signals. The difficulty is thus efficiently reduced for the prediction. It is based on this conception that the following discussions are held.

During his construction of orthogonal wavelet base, S. Mallat proposes a concept of Multi-Resolution Analysis, which illustratively outlines the multi-resolution features of wavelets from the concept of space and gives a construction method of orthogonal wavelets and their rapid algorithm. It is also known as the Mallat algorithm[13]. A 3-layer decomposed structure is used to interpret the multi-resolution. Its wavelet decomposition tree is shown in Fig.7. The ultimate aim of wavelet decomposition is to build a base of orthogonal wavelet that highly approximates the original signal from frequency. These bases, varying in the resolution of frequency, are equivalent to a band-pass filter with variable width[14]. Fig.7 shows that the multi-resolution analysis in the wavelet transform gives fine decomposition of signal's low-frequency space to increase the resolution of its low-frequency section. The reconstruction is related to the decomposition by S=d1+d2+d3+a3. For more decomposition, the a3 in the low-frequency part is decomposed to low-frequency a4 and high-frequency d4, etc.

The data used in the study are the monthly mean anomalous series of SST in the equatorial eastern Pacific from January 1950 to October 1995 (46 years in all), which are provided by NCEP/NCAR and COADS. The Daubechies's wavelet function db5, which has a 5-order matrix of losses, is used to conduct a fifth-layer decomposition and reconstruction of the SST anomalies. As they are monthly mean data, the highest sampling frequency is 1 (times/month) for the temporal series of data. For the wavelet decomposition, a second-power division is applied. Band-pass or low-pass filters are for the decomposition of wavelets in various layers, which take up sections of frequency as follows:

Low-frequency section	Periods	High-frequency section	Periods
a1: 0 ~ 0.5	2 months plus	d1: 0.5 ~ 1.0	1 ~ 2 months
a2: 0 ~ 0.25	4 months plus	d2: 0.25 ~ 0.5	2 ~ 4 months
a3: 0 ~ 0.125	8 months plus	d3: 0.125 ~ 0.25	4 ~ 8 months
a4: 0 ~ 0.0625	16 months plus	d4: 0.0625 ~ 0.125	8 ~ 16 months
a5: 0 ~ 0.03125	32 months plus	d5: 0.03125 ~ 0.0625	16 ~ 32 months

The original signal S= d1+d2+d3+d4+d5+a5

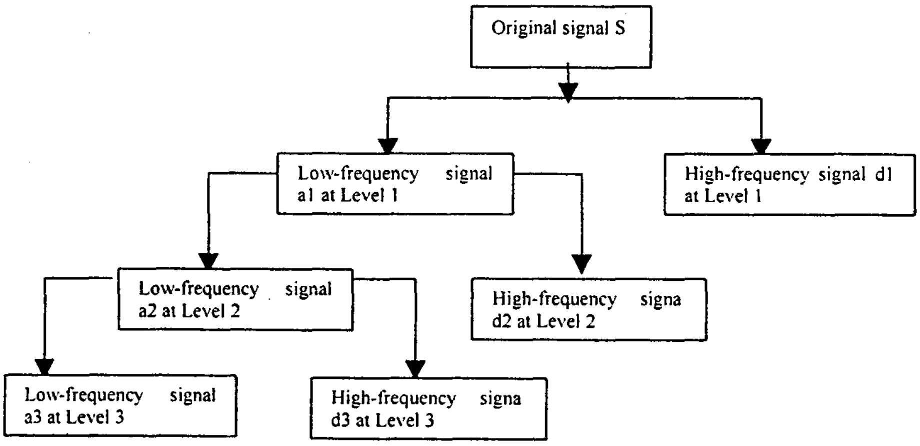

Fig.7 Schematic plotting of decomposed multi-layer wavelets

First, the db5 wavelet is used to decompose the SST anomalies to extract the coefficients of high and low frequency at Layers 1 ~ 5. Then, the coefficients are reconstructed for individual layers to obtain signal series over all sections of frequency (domains of period). Realistic changes in SST can be accurately obtained with the sum of reconstructed signals between the high frequency at Layers 1 ~ 5 and the low frequency at Layer 5. Specifically, d, the sum of the decomposed and reconstructed signals d3, d4, d5 and a5, is in good fitting with the actual SST signal s by a coefficient of 0.9765 (verified to be significant with confidence level $\alpha=0.05$). It shows that the SST changes in the equatorial eastern Pacific can be described by the superposition of four decomposed and reconstructed signals of d3 (4 ~ 8 months), d4 (8 ~ 16 months), d5 (16 ~ 32 months) and a5 (over 32 months). Then, the prediction of SST is converted to one of the four band-pass and low-pass components. As d3, d4, d5 and a5 are much more regular and simpler than the original signals, they are then predicted with much less difficulty.

5 COMPOSITE PREDICTION OF SST FOR THE EQUATORIAL EASTERN PACIFIC BASED ON FREQUENCY DECOMPOSITION

From the above results of decomposition and reconstruction, an auto-adaptive fuzzy inference system ANFIS is used to set up models of extrapolating prediction of the four signals of d3 (4 ~ 8 months), d4 (8 ~ 16 months), d5 (16 ~ 32 months) and a5 (over 32 months). To say it differently, the SST anomalies in the equatorial eastern Pacific that lead by 3, 4 and 5 months are used to predict the evolution of SST with a validity of 3 months.

Set P and T the output series of input predictors and output prediction in the ANFIS model, i.e.

$$P=[x(t-5),x(t-4),x(t-3)],\quad T=[x(t)]$$

Corresponding to each time level, a pair of drilling data is expressed by:

$$x(t-5), x(t-4), x(t-3), x(t)$$

To verify the independent prediction based on the ANFIS model, the 550-month-long SST anomalies are divided into two parts, the first part (380 months from January 1950 to August 1981) is used to set up the prediction model and the second part (170 months from September 1981 to October 1995) is used to verify the prediction independently.

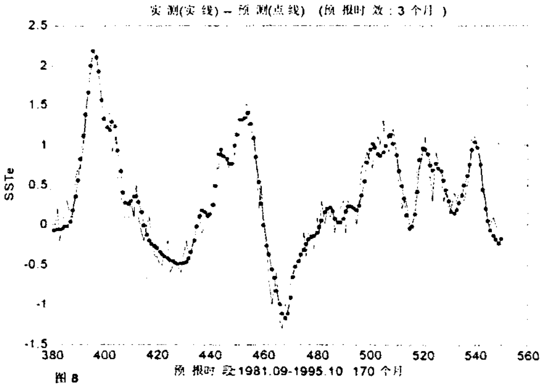

Fig.8 Observed signals (solid line) and independent predictions by the ANFIS model (dashed line) with 3-month validity. The prediction covers 170 months from September 1981 to October 1995.

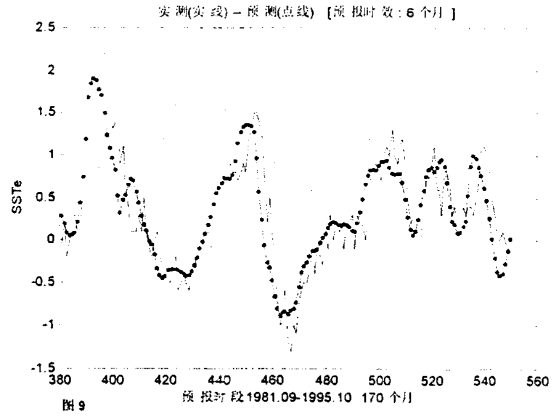

Fig.9 Observed signals (solid line) and independent predictions by the ANFIS model (dashed line) with 6-month validity. The prediction covers 170 months from September 1981 to October 1995.

A high fitting accuracy has been seen between the computed ANFIS model results and d (by a coefficient of 0.9805) and s (by a coefficient of 0.9586). Independent predictions are also capable of giving accurate basic characteristics of real signals of d and s, by coefficients of 0.9859 and 0.9653, respectively (verified to be significant with $\alpha=0.05$). The results of the composite prediction by the ANFIS model are realistically approaching observed signals in both overall tendency and local details (Fig.8).

When the prediction validity is extended to 6 months, i.e. the SST anomalies leading by 6, 7 and 8 months are used to forecast its changes in six months to come, the same method of wavelet decomposition and reconstruction can also be used to compose a prediction technique with the results correlated with d and s by 0.8650 and 0.8459, respectively (which are verified to be significant with $\alpha=0.05$). Somewhat decreasing in the effect of prediction, they still have similar usefulness for reference (Fig.9).

6 CONCLUDING REMARKS

Being different from the filtering technique based on the structure of frequency, detection and analysis based on the fuzzy system employs the fuzzy inference method to approach and detect primary affecting factors and recognize how much they contribute to the system. It is then possible for it to improve the detection and analysis of various factors in terms of their contribution and influence with regard to the variation or anomalies of the atmospheric and oceanic systems. More often than not, non-linear correlation is usually found between the interference noise and its source in the oceanic and atmospheric systems. The noise is generally detected and analyzed using general statistic methods and filtering techniques based on linear theories, though with some degree of restrains. Being highly non-linear, error-allowing, auto-adapting and learning in association, the fuzzy system has wide scope of application due to its capability of diagnosing and predicting indefinite complicated issues of air-sea interactions. The composite prediction method using decomposed and reconstructed wavelets is efficient in reducing the difficulty of objects being predicted and greatly improves the accuracy and validity of prediction of the SST in the equatorial eastern Pacific and El Niño and La Niña. It is shown that the wavelet decomposition and reconstruction is advantageous in analyzing and predicting complicated issues like El Niño and La Niña.

Acknowledgements: Mr. CAO Chao-xiong, who works at the Guangzhou Institute of Tropical and Oceanic Meteorology, China Meteorological Administration, has translated the paper into English.

REFERENCES:

[1] ZHANG Ren. Non-linear BP neural network mapping and prediction of SST in the equatorial eastern Pacific [J]. *Marine Science Bulletin*, 2000, **19**(4): 1-7.

[2] ZHANG Ren. Retrieval and prediction of the SST in the equatorial eastern Pacific and El Niño/ La Niña [J]. *Journal of Meteorological Institute of China PLA University of Science & Technology*, 2000, **1** (5): 7-12.

[3] ZHANG Ren. Neural network BP model approximation and prediction of complicated weather systems [J]. *Acta Meteorologica Sinica*, 2000, **14**(4): 105-115.

[4] ZADEH, L A. Fuzzy Sets [J]. *Information and Control*, 1965, **8**: 338-353.

[5] ROGER Jang J.S, SUN C T, Mizutani E. Neuro-Fuzzy and soft computing: A computational approach to learning and machine intelligence [M]. Prentice-Hall, Inc., 1997. 156-162.

[6] KOSKO B, Fuzzy Engineering [M]. Translated by HUANG Chong-fu. Xi'an: Xi'an Communications University Press, 1999. 31-41.

[7] TAKAGI T, SUGEON M, Fuzzy identification and its application to modeling and control [J]. *IEEE SMC*, 1985, **15**(1): 116-132.

[8] WYRTKI K, El Nino-the dynamic response on the equatorial Pacific Ocean to atmospheric forcing [J]. *Physics Ocean*, 1975, **5**: 572-584.

[9] LI Chong-yin. Introduction to Climatological Dynamics [M]. Beijing: Meteorological Press. 1995. 234-240.

[10] WEN Xin, ZHOU Lu, LI Dong-jiang, et al. Study of the Toolbox for Matlab Fuzzy Logic and Application [M]. Beijing: Science Press, 2001. 153-157.

[11] RASMUSSON E M, WALLACE J M. Meteorological aspects of El Nino/Southern Oscillation [J]. *Science*, 1983, **222**: 1195-1202.

[12] FU C, FLETCHER J, DIAZ H. Characteristics of the response of sea surface temperature in the central Pacific associated with warm episodes of Southern Oscillation [J]. *Monthly Weather Review*, 1986, **114**: 1716-1738.

[13] MALLAT S. A theory for multiresolution signal decomposition: the wavelet representation [J]. *IEEE Trans. Pattern Anal. and Machine Intell*, 1989,**11**(7): 674-693.

[14] HU Chang-hua et al. System analysis and design based on Matlab — wavelet analysis [M]. Xi'an: Xi'an Electronic Science & Technology, 1999. 217-221.