J. Korean Earth Sci. Soc., v. 36, no. 7, p. 611−616, December 2015
http://dx.doi.org/10.5467/JKESS.2015.36.7.611
ISSN 1225-6692 (printed edition)
ISSN 2287-4518 (electronic edition)

Development of Nonlinear Low-Order Climate Model and Simulated ENSO Characteristics

Jieun Wie and Byung-Kwon Moon*

Division of Science Education/Institute of Fusion Science, Chonbuk National University, Jeonju 54896, Korea

비선형 저차 기후모델 개발과 모의된 ENSO 특징

위지은 · 문병권*

전북대학교 과학교육학부/융합과학연구소, 54896, 전라북도 전주시 덕진구 백제대로 567

Abstract: El Nino and Southern Oscillation (ENSO) presents a broad band (2-8 year) variability and slowly changing amplitude and period, which are respectively referred to as ENSO irregularity and ENSO modulation. In this study, we developed a nonlinear low-order climate model by combining the Lorenz-63 model of nonlinear atmospheric variability and a simple ENSO model with recharge oscillator characteristics. The model successfully reproduced the ENSO-like variations in the sea surface temperature of eastern Pacific, such as the peak period, wide periodicity, and decadal modulations. The results show that the chaotic atmospheric forcing can lead to ENSO irregularity and ENSO modulation. It is also suggested the high probability of La Nina development could be associated with strong convection of the western warm pool. Although it is simple, this model is expected to be used in research on long-term climate change because it well captures the nonlinear air-sea interactions in the equatorial Pacific.

Keywords: ENSO, low-order climate model, ENSO irregularity, ENSO modulation

요 약: 엘니뇨와 남방진동(엔소)은 변동 주기가 2-8년으로 넓게 걸쳐있으며 그 진폭과 주기 또한 천천히 변하는데 이런 특징을 각각 엔소 불규칙성과 엔소 변조라 한다. 이 연구는 비선형 대기 변동성을 나타나는 Lorenz-63 모형과 간단한 충전 진동자 모형을 결합함으로써 비선형 저차 기후모델을 개발하였다. 이 모델은 동태평양의 해수면 온도 변동의 중심 주기, 넓은 주기성, 강도의 수십 년 변동 등과 같은 관측에서 보이는 엔소 특징을 잘 재현하였다. 이것은 대기 카오스 강제력이 엔소의 불규칙성과 변조를 이끌 수 있음을 보여준다. 덧붙여 모델은 서태평양 온난역의 대류활동이 강해지면 라니냐 발생 가능성이 높아지는 것을 제시하였다. 이 모델은 간단하면서도 적도 태평양의 대기-해양 비선형 상호작용을 잘 모사하고 있기에 향후 장기 기후변화 연구에 활동될 것으로 기대된다.

주요어: 엔소, 저차 기후모델, 엔소 불규칙성, 엔소 변조

Introduction

El Nino and Southern Oscillation (ENSO) -a phenomenon in which the sea surface temperature (SST) of the tropical Pacific Ocean changes interannually-affects not only the global climate but also the society and economy (Alexander et al., 2002; McPhaden et al., 2006; Cha, 2007; Jang and Ha, 2008; Spencer and Braswell, 2014). One of the interesting characteristics of ENSO is its irregular 2-8 year cycle and amplitude variations of over 10-20 years (Neelin et al., 1998; Timmermann et al., 2003). This irregularity makes the prediction of ENSO difficult (Ji et al., 1996), and its mechanism has not yet reached an agreement.

*Corresponding author: moonbk@jbnu.ac.kr
Tel: +82-63-270-2824
Fax: +82-63-270-2802

Atmospheric stochastic forcing, mean tropical Pacific climate changes, and nonlinearity of ENSO have been suggested as the cause of ENSO irregularity (Munnich et al., 1991; Kleeman and Power, 1994; Tziperman et al., 1995; Blanke et al., 1997; Kirtman and Schopf, 1998; Fedorov and Philander, 2000). In each of these factors, ENSO is viewed as a damped oscillator or a self-sustained air-sea coupled oscillator (Yeh et al., 2014).

Recent efforts have attempted to elucidate the relationship between nonlinearity and ENSO irregularity by using a low-order ENSO model. Timmermann et al. (2003) suggested that ENSO irregularity was generated by the nonlinear advection of the temperature equation. However, their study focused on the nonlinearity inherent in tropical Pacific Ocean. Since air-sea coupling has an important role in ENSO, the effect of nonlinear atmospheric motions on ENSO should be investigated. Jin et al. (2007) analyzed the effect of atmospheric forcing on ENSO irregularity focused on stochastic noise. However, they did not investigate the effect of deterministic nonlinearity inherent in the atmospheric motions. The purpose of this study is to develop a new low-order climate model that reproduces ENSO nonlinearity and ENSO modulation characteristics, and illustrate changes in ENSO according to the convection of the tropical western Pacific.

Nonlinear Low-order Climate Model

We combined the Lorenz-63 model (Lorenz, 1963; hereafter L63 model), which describes the chaotic characteristics of atmospheric convection, and the ENSO recharge oscillator model (Jin et al., 2007; hereafter J07 model) to develop a new low-order climate model. An equation system was developed as follows (1):

$$\frac{dX}{dt} = -\sigma X + \sigma Y - \beta T$$

$$\frac{dY}{dt} = -XZ + rX - Y$$

$$\frac{dZ}{dt} = XY - bZ \tag{1}$$

$$\frac{dT}{dt} = -\lambda T + \omega h - \alpha X$$

$$\frac{dh}{dt} = -\omega T$$

Here, X, Y, and Z are L63 model's state variables representing the intensity of convective motion, temperature, and the temperature gradient in the western Pacific, respectively. When X and Y have the same sign, there are the rising motion of relatively warm air and sinking of cold air. Positive values of Z are associated with the large gradient near the boundaries (see Lorenz, 1963 for details). The oceanic variables T and h represent the eastern Pacific SST anomaly and zonally averaged equatorial heat-content anomaly in the J07 model, respectively. The L63 and J07 models are coupled through positive real numbers α and β, which represent air-sea coupling strengths. In the first equation of (1), if T increases (El Nino development), X decreases (decrease in western Pacific convection). The negative correlation between T and X was employed in the model, considering the increase (decrease) in the western Pacific convection associated with La Nina (El Nino) (Yoshida et al., 2007). As a result, the atmospheric effect according to the ENSO phase was established. Similarly, the fourth equation shows that if X increases (increase in western Pacific convection), T decreases (La Nina development). Therefore, the term of $-\alpha X$ in the fourth equation represents the SST changes in the eastern Pacific forced by irregular wind through the oceanic Kelvin wave (McPhaden, 1999). Instead of the stochastic forcing of the J07 model, we used the nonlinear deterministic forcing (i.e., $-\alpha X$) to reflect the chaotic properties of the atmospheric flow.

The dimensionless coefficients σ and r are the Prandtl and Rayleigh numbers, respectively, and b is the aspect ratio of the model domain (Lorenz, 1963). Coefficients λ and ω, which are related to the surface-layer SST and subsurface ocean wave dynamics, denote the damping rate and thermocline feedback, respectively (Jin, 1997; Jin et al., 2007). For these

Table 1. Value of the low-order model coefficients

Variable	Symbol	Value
Prandtl number	σ	10
Rayleigh number	r	24.74
Aspect ratio	b	8/3
Damping rate	λ	1/6 month^{-1}
Thermocline feedback	ω	2π/48 month^{-1}
Coupling strength	α	0.1
Coupling strength	β	1.0

coefficients, the values in Lorenz (1963) and Jin et al. (2007) were used. As the air-sea coupling strength, α=0.1 and β=1.0 were used, which are empirically determined. These values are listed in Table 1. The model was numerically integrated using the ode45 function, which is a differential equation solver in Matlab, and the initial value (X, Y, Z, T, h)=(0, 1, 0, 0, 2) represents the nearly state of no convection in the western Pacific, maximum heat in the tropical Pacific, and neutral SST anomaly in the eastern Pacific. The model was spun up for 100 years and then integrated for 300 years.

Results

Figure 1 shows the simulated times series and orbits of the atmospheric parameters X, Y, and Z in the state space, for the first 60 months of the 300-year simulation to clearly identify the variations and orbit characteristics with time. The amplitude of X gradually increases first which indicates the growing instability of the convection, but abruptly drops at a certain threshold occurred at 17th and 37th month for example, and then increases again (Fig. 1a); the signs of Y and Z change irregularly with systematic amplified oscillation. Figure 1b shows the orbits of these three variables, depicting the characteristics of the well-known strange attractor or Lorenz attractor (Lorenz, 1963).

Our model attempted to simulate the response of the ocean to such chaotic atmospheric forcing. Figure 2 shows the time series of T (eastern Pacific SST anomaly) and h (equatorial heat content) for the entire period of integration. Interestingly, the T time series

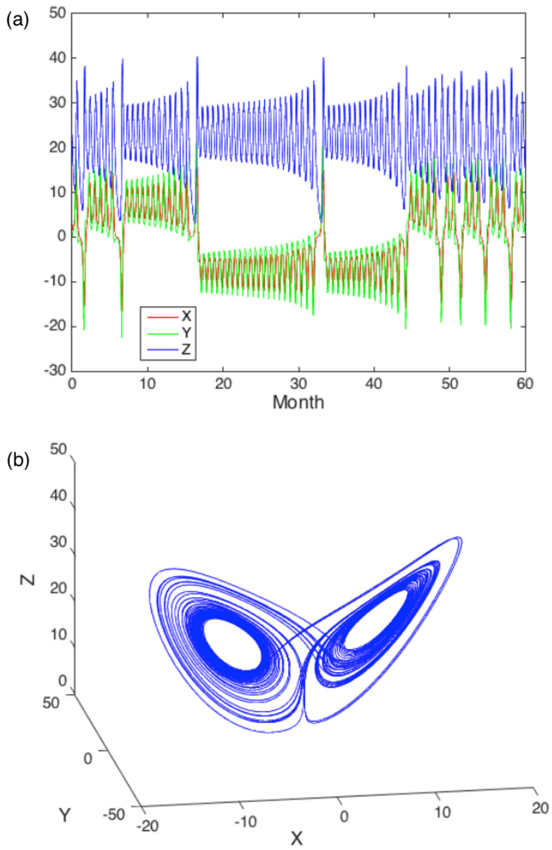

Fig. 1. (a) Time series of the simulated X, Y, and Z for the first 60-month period, and (b) their orbit in the state space.

changed irregularly with time, successfully simulating the interannual variability of the actual tropical eastern Pacific. This characteristic was also clearly evident in the h time series. Upon careful examination for the reduced time range, h seems to T by about 1/4 of the wavelength (not shown). Such a relationship between h and T is a well-known characteristic of the recharge-discharge oscillator paradigm of ENSO (Jin, 1997; Moon, 2007), which indicates the recharge and discharge of equatorial heat content causes the phase shift of SST in the equatorial Pacific. Similar to the observation, the power spectrum analysis of the simulated T clearly showed a broad band period (2-8 year) of ENSO variability centered on 40-month period (Fig. 3).

Both the amplitude and period of the observed ENSO vary on decadal time scales in observation,

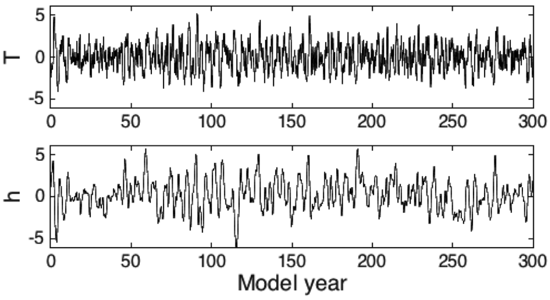

Fig. 2. Time series of the simulated T (eastern Pacific SST anomaly), and h (equatorial Pacific heat content) during 300 years. All variables have non-dimensional units.

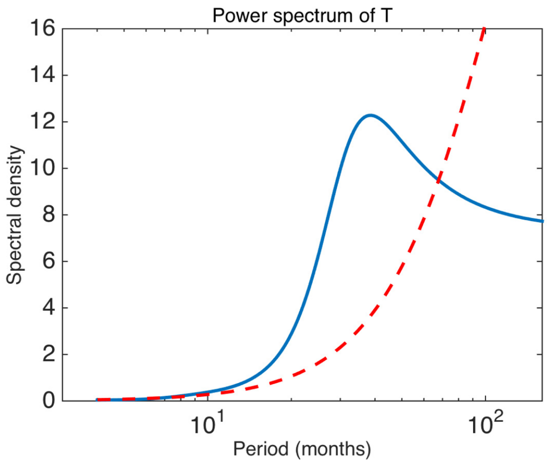

Fig. 3. Power spectrum for the simulated T from maximum entropy power spectrum analysis. Dashed line represents the 95% confidence level.

which is so called as ENSO modulation (Gu and Philander, 1995; Wang and Wang, 1996; Wittenberg et al., 2014). To investigate the ENSO modulation in the simulation, we further perform a wavelet analysis on T time series. Figure 4 shows the normalized wavelet power spectrum using the Morlet wavelet (Torrence and Compo, 1998). The T time series exhibits large interannual variability (Fig. 4a) and much of the power concentrated at 2-8 year band, which is consistent with the power spectrum in Fig. 3. In addition, the wavelet analysis shows that the amplitude of the interannual variability has changed over the decades (Fig. 4b). For example, the model simulated a low ENSO intensity compared to other time periods of 15-45, 190-225, and 280-300. This feature is consistent

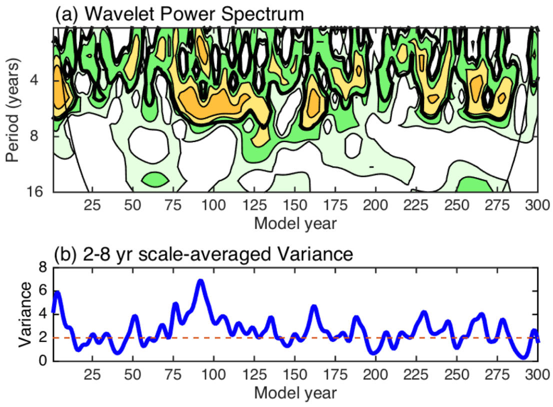

Fig. 4. (a) Wavelet power spectrum of the simulated T time series using the Morlet wavelet. The thick contour denotes the regions of greater than 95% confidence level. (b) The time series for the scale-averaged variance in 2-8 years. Dashed line indicates the variance of 2 as a baseline for ENSO modulation.

with the observation when the strength of ENSO is suppressed during 1920-1960 (see Fig. 8 of Torrence and Compo, 1998). Furthermore, the model showed changes in the ENSO frequency from short (~4 year) to long cycles (~6 year) during 250-280, which is similar to what actually happened during 1960-1980 (see Fig. 1 of Torrence and Compo, 1998). The power spectrum and wavelet analysis show that our low-order model, consisting of the L63 and J07, can well reproduce the observed ENSO variability and ENSO modulation. Thus we argue that nonlinear atmospheric forcing may be the cause of ENSO variability and ENSO modulation.

Yoshida et al. (2007) suggested that the western Pacific convection is closely related to ENSO. To examine this relationship with our model, the state variable X (representing the western Pacific convection) and T (representing ENSO variability) were shown in Fig. 5. Interestingly, when $X<0$ (i.e., weak convection), T tends to appear more often as a positive value, which means that El Nino occurs more frequently than La Nina. On the other hand, when $X>0$ (i.e., strong convection), La Nina seems to develop more frequently. Note here that the ENSO phase is not completely determined by the sign of X, indicating the nonlinearity of the ENSO dynamic system.

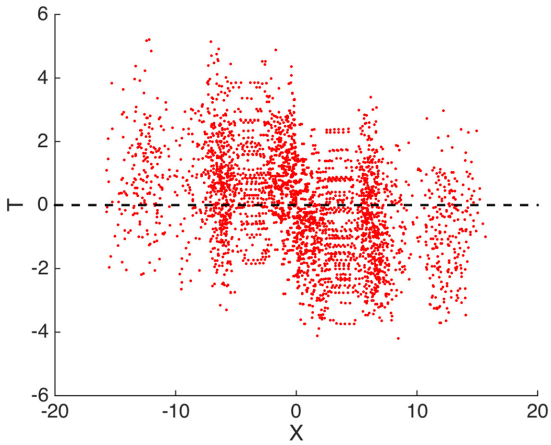

Fig. 5. The distribution of X and T depicting El Nino-flavored or La Nina-flavored months associated with the sign of X.

Summary and Discussion

A nonlinear low-order climate model was developed by combining the L63 model, which describes the nonlinearity of the atmosphere, and the J07 model, which has the ENSO dynamics of the tropical Pacific. To develop the model equation system, the state variable X in L63 was assumed to represent the convection in the western Pacific, and the negative correlation between the observed convection intensity and ENSO phase was used. In addition, the response of the ocean to the nonlinear atmospheric forcing was implemented by removing the stochastic forcing term in J07 and replacing it with the chaotic atmospheric forcing term.

The long-term numerical integration results (300 yrs) showed that the model produced results similar to the observed ENSO nonlinear properties, irregularity and modulation. The simulated eastern Pacific SST anomaly well reproduced the 2-8 year broad band periodicities centered at about 40 months and the ENSO modulation, in which the amplitude and peak period of interannual variability changed slowly over decades. These results indicate that ENSO changes should be associated with the nonlinear deterministic forcing, even without stochastic randomness of atmosphere. This model also showed that ENSO cold (warm) phase could occur more frequently, i.e., La Nina-flavored (El Nino-flavored), as the western Pacific convection becomes stronger (weaker).

Although this model is simple, consisting of five differential equations, it has the advantage of enabling the study of both atmospheric nonlinearity and ENSO irregularity. Moreover, its simplicity allows integration over thousands of years, making it a useful tool for studying changes in long-term atmosphere-ocean interactions. In the future, it may be applied to investigations of the atmospheric nonlinearity and ENSO changes according to air-sea coupling strength, or the analysis of meteorological variability associated with changes in the climate mean state and seasonal forcing.

Acknowledgments

The authors would like to thank Dr. E.-J. Lee (Korea Meteorological Administration) and an anonymous reviewer for their helpful comments. This research was supported by the Korea Ministry of Environment (MOE) as “Climate Change Correspondence Program.”

References

Alexander, M.A., Blade, I., Newman, M., Lanzante, J.R., Lau, N.C., and Scott, J.D., 2002, The atmospheric bridge: The influence of ENSO teleconnections on air-sea interaction over the global oceans. Journal of Climate, 15, 2205-2231.

Blanke, B., Neelin, J.D., and Gutzler, D., 1997, Estimating the effect of stochastic wind stress forcing on ENSO irregularity. Journal of Climate, 10, 1473-1486.

Cha, E.J., 2007, El Nino-Southern Oscillation, Indian Ocean Dipole Mode, a relationship between the two phenomena, and their impact on the climate over the Korean Peninsular. Journal of Korean Earth Science Society, 28, 35-44.

Fedorov, A.V. and Philander, S.G., 2000, Is El Nino changing? Science, 288, 1997-2002.

Gu, D.F. and Philander, S.G.H., 1995, Secular changes of annual and interannual variability in the tropics during the past century. Journal of Climate, 8, 864-876.

Jang, S.R. and Ha, K.J., 2008, On the relationship between typhoon intensity and formation region: Effect of developing and decaying ENSO. Journal of Korean Earth Science Society, 29, 29-44.

Ji, M., Leetmaa, A., and Kousky, V.E., 1996, Coupled model predictions of ENSO during the 1980s and the 1990s at the national centers for environmental prediction. Journal of Climate, 9, 3105-3120.

Jin, F.F., 1997, An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. Journal of the Atmospheric Sciences, 54, 811-829.

Jin, F.F., Lin, L., Timmermann, A., and Zhao, J., 2007, Ensemble-mean dynamics of the ENSO recharge oscillator under state-dependent stochastic forcing. Geophysical Research Letters, 34, L03807, doi:10.1029/2006GL027372.

Kirtman, B.P. and Schopf, P.S., 1998, Decadal variability in ENSO predictability and prediction. Journal of Climate, 11, 2804-2822.

Kleeman, R. and Power, S.B., 1994, Limits to predictability in a coupled ocean-atmosphere model due to atmospheric noise. Tellus A, 46, 529-540.

Lorenz, E.N., 1963, Deterministic nonperiodic flow. Journal of the Atmospheric Sciences, 20, 130-141.

McPhaden, M.J., 1999, Genesis and evolution of the 1997-98 El Nino. Science, 283, 950-954.

McPhaden, M.J., Zebiak, S.E., and Glantz, M.H., 2006, ENSO as an integrating concept in earth science. Science, 314, 1740-1745.

Moon, B.K., 2007, Characteristics of the simulated ENSO in a CGCM. Journal of Korean Earth Science Society, 28, 343-356. (in Korean)

Munnich, M., Cane, M.A., and Zebiak, S.E., 1991, A study of self-excited oscillations of the tropical ocean atmosphere system. Part II: Nonlinear cases. Journal of the Atmospheric Sciences, 48, 1238-1248.

Neelin, J.D., Battisti, D.S., Hirst, A.C., Jin, F.F., Wakata, Y., Yamagata, T., and Zebiak, S.E., 1998, ENSO theory. Journal of Geophysical Research-Oceans, 103, 14261-14290.

Spencer, R.W. and Braswell, W.D., 2014, The role of ENSO in global ocean temperature changes during 1955-2011 simulated with a 1D climate model. Asia-Pacific Journal of Atmospheric Sciences, 50, 229-237.

Timmermann, A., Jin, F.F., and Abshagen, J., 2003, A nonlinear theory for El Nino bursting. Journal of the Atmospheric Sciences, 60, 152-165.

Torrence, C. and Compo, G.P., 1998, A practical guide to wavelet analysis. Bulletin of the American Meteorological Society, 79, 61-78.

Tziperman, E., Cane, M.A., and Zebiak, S.E., 1995, Irregularity and locking to the seasonal cycle in an ENSO prediction model as explained by the quasi-periodicity route to chaos. Journal of the Atmospheric Sciences, 52, 293-306.

Wang, B. and Wang, Y., 1996, Temporal structure of the Southern Oscillation as revealed by waveform and wavelet analysis. Journal of Climate, 9, 1586-1598.

Wittenberg, A.T., Rosati, A., Delworth, T.L., Vecchi, G.A., and Zeng, F.R., 2014, ENSO modulation: Is it decadally predictable? Journal of Climate, 27, 2667-2681.

Yeh, S.W., Kug, J.S., and An, S.I., 2014, Recent progress on two types of El Nino: Observations, dynamics, and future changes. Asia-Pacific Journal of Atmospheric Sciences, 50, 69-81.

Yoshida, S., Morimoto, T., Ushio, T., and Kawasaki, Z., 2007, ENSO and convective activities in Southeast Asia and western Pacific. Geophysical Research Letters, 34, L21806, doi:10.1029/2007GL030758.

Manuscript received: November 5, 2015
Revised manuscript received: November 21, 2015
Manuscript accepted: December 9, 2015