SEA SURFACE SALINITY VARIABILITY OF THE 1999 CLIMATE SHIFT IN THE TROPICAL PACIFIC

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ABSTRACT

An analysis of 1980-2007 sea surface salinity (SSS) data collected from Geophysical Fluid Dynamics Laboratory coupled with climate model enables us to comprehend the decadal signals of climate change in the tropical Pacific. The magnitude of decadal variability connected with the Pacific Decadal Oscillation (PDO) is higher than that of interannual cycle for salinity changes. Although a -0.024 ± 0.011 psu/decade reveals a freshening trend during the data span, the SSS shows dramatic decadal shift approximately -0.840 ± 0.013 psu/decade during 1980-1999 in the positive phase of the PDO and 0.361 ± 0.036 psu/decade during 2000-2007 in the negative phase of the PDO. The result indicates that the 1999 climate shift has strong influence on SSS changes. Possible implication of these SSS changes for ocean-atmosphere interaction and with the PDO events are discussed.

I. INTRODUCTION

Salinity, temperature, and pressure are the three crucial variables in the equation of state for seawater. Salinity has been considered as a fundamental variable in the ocean for global climate system. Observing salinity variability in the ocean is important for studying climate change and for realizing the interaction of momentum, heat, fresh water, and CO_2 fluxes between the ocean and the atmosphere [8, 21, 22].

With some of the highest precipitation rate found over the global ocean, the regions are characterized by relative low sea surface salinity (<35 psu) which is called the western equatorial Pacific "fresh pool" [5, 15]. Being the earth's heat engine and a major source of moisture for the atmosphere, the warm pool and fresh pool in the western tropical Pacific Ocean has been identified as a key region for ocean-atmosphere interaction [5, 8, 12]. Cravatte *et al*. [5] analyzed

sea surface salinity (SSS) trends for the tropical Pacific during 1955-2003 and found that waters were freshened by 0.34 psu during the 50 years. Delcroix *et al*. [8] and Cravatte *et al*. [5] discussed the SSS-PDO (Pacific Decadal Oscillation) pattern and pointed out that the PDO variability is a key factor to SSS decadal variability [10, 19]. They paid attention to SSS temporal variation and freshening trends. Due to the existence of decadal variability, the trend generated by linear regress over a shorter time period may be affected by lower frequency variations [20]. In the study, we focus on the saltier trends and freshening trends associated with the 1999 climate shift in the tropical Pacific quantitatively. A decrease in SSS may lead to shallow the mixed layer depth and then to enhance the ocean-atmosphere coupling. It may take influence on temperature and oceanic circulation in the tropical Pacific. Moreover, observing long-term SSS change is of great importance to infer possible changes in the hydrological cycle that has been indicated to reinforce under global warming [1, 5, 22].

Because of the sparse in-situ salinity profiles, the mechanisms influencing on the SSS variability remain poorly known. In this study, we introduce model salinity data to overcome the disadvantage of the sparse in-situ salinity data. A state-of-the-art coupled general circulation model has been developed at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (NOAA/GFDL) and GFDL coupled climate model (CM) simulated the current tropical climate quite realistically [3, 13, 14, 23]. Delcroix *et al*. [7] analyzed the ability of 23 coupled models used to observe the salinity variability in the seasonal and interannual modes. Their results suggested that the GFDL-CM model included in one of the five models is the 'best' suited for simulating the salinity changes. Hence we adopt the SSS simulation results from the GFDL CM 2.1 to study the decadal variability in the tropical Pacific with principal focus on the influence of the Pacific Decadal Oscillation.

II. DATA

To enrich the quantity of the salinity data, we apply the model data for the tropical Pacific (120°E-70°W; 30°N-30°S) from 1980 to 2007. The model was designed to simulate oceanic and atmospheric climate and variability from the diurnal

time scale through multicentury time scale, given an opportunity to investigate climate change. The ocean model uses a finite difference approach to solve the primitive equations. Its data is available in monthly-averaged form, and the horizontal resolution is $1° \times 1°$ and the meridional resolution reduces to $1/3°$ equatorward of $15°$ with 50 vertical layers [4, 23].

In contrast to previous models that used the rigid-lid approximation to solve for the surface pressure, the CM models use an explicit free surface. This allows for real fluxes of fresh water, in contrast to the "virtual salt fluxes" used by most ocean models. The simulations are initialized from the World Ocean Atlas 2001 data [6, 9] for temperature and salinity. The control runs are using 1860s radioactive conditions with a net ocean heating of 0.3 W/m². The ocean model is forced with heat and water fluxes from an integration of the atmosphere model, along with observed wind stress [2, 13, 14]. Details of the model formulation were documented in Anderson *et al*. [2], Delworth *et al*. [13], and Gnanadesikan *et al*. [14].

We also take climatological in-situ SSS for comparison with model results. The in-situ SSS data was extracted from World Ocean Database 2011 (WOD11) provided by the National Oceanographic Data Center of NOAA [6, 9, 17]. The WOD11 is a historical database, containing measurements of SSS since 1874 which originate from several data bases and measurement techniques. These records include: (a) CTD, XBT, hydrocasts data collected during research cruises, (b) surface samples collected from Voluntary Observing Ship (VOS) programs, (c) thermosalinograps (TSGs) installed on board the VOS, (d) TSGs installed on TAO/TRITON moorings and on vessels surviving this moorings, and (e) CTD data from Argo floats. We consider as SSS all salinity measurements between 0 and 10 m depth [6, 9, 17].

We process the data to generate monthly and $1°$ latitude by $1°$ longitude grid data sets. The standard deviation check is used to remove the outliers. This means that the data points being more than three standard deviations apart from the mean are removed. These data points are considered as being affected by transient effects of waves, strong winds, or other dynamic processes. To enrich hydrographic salinity profiles, the objective analysis procedure is used to process WOD11 Salinity fields for each $1°$ latitude-longitude square at each standard depth level [3].

III. RESULTS AND DISCUSSION

The 1980-2007 annual mean SSS map inferred from GFDL-CM model (Fig. 1(a)) and WOD11 (Fig. 1(b)) shows low salinity area mainly in the Intertropical Convergence Zone (ITCZ), the south Pacific Convergence Zone (SPCZ), and northeastern tropical Pacific, but high salinity area locate near French Polynesia. This mean distribution of model SSS pattern is similar to in-situ SSS pattern observed from previous studies [5, 8, 9, 15] and tends to mirror the mean pattern of E-P (evaporation minus precipitation) [5, 15, 21]. Although the main features of the SSS field are well reproduced, the
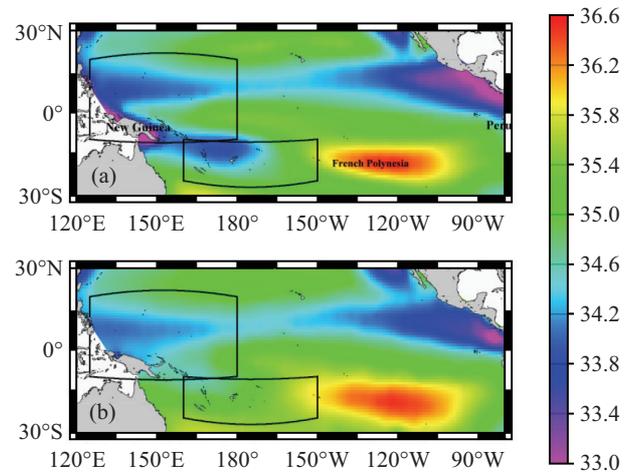
Fig. 1. (a) Model mean SSS and (b) observed mean SSS of the tropical Pacific from 1980 to 2007. The two regions with closed black lines represent interesting regions of the WPWP (125°E-180°E; 20°N-10°S) and SPCZ (160°E-70°W; 10°S-25°S). The marginal sea regions are stripped.

model is a little fresh in the western areas of Southern America and in the eastern areas of Luzon and New Guinea.

In order to understand the trend and variability of SSS in the tropical Pacific, we plotted SSS variations and fresh pool size from 1980 to 2007 as shown in Fig. 2 and Fig. 3. Because in the tropical Pacific, the low-salinity and warm waters of the warm pool are separated from the saltier waters of the central Pacific by a distinctive salinity front characterized by ITCZ and SPCZ [5, 11]. Thus, we presents the SSS time series in the tropical Pacific (125°E-70°W; 20°N-25°S), the western Pacific warm pool (WPWP), and the SPCZ, respectively in Fig. 2. Although notable decreasing trends are shown in these three areas, slowly freshening trend and SST increasing trend in the tropical Pacific are evident. The SSS freshening trends calculated by linear regression at the significant 95% confidence level are -0.024 ± 0.011, -0.096 ± 0.023, and -0.048 ± 0.041 psu/decade in the tropical Pacific, the WPWP, and the SPCZ, respectively. These values are similar to the results estimated from Delcroix *et al*. [8] for 0.1 to 0.3 psu per 30 years in the tropical Pacific. As a marked note, the trend in the WPWP, the strongest compared to other regions, may be due to the extension of fresh pool in the ITCZ and SPCZ.

The PDO has been described by some as a long-lived El Niño-like pattern which can affect the Pacific climate system on decadal to interdecadal time scales. Cravatte *et al*. [5] and Delcroix *et al*. [8] discussed the SSS-PDO pattern and pointed out that the PDO variability is a key factor to SSS decadal variability with the display of lower SSS in the western-central equatorial Pacific during the positive phase of the PDO [10, 11, 19]. Due to the existence of strong decadal variability, the trend generated by linear regress over a shorter time period may be affected by the PDO variability. So we emphasize the importance of SSS variability between the
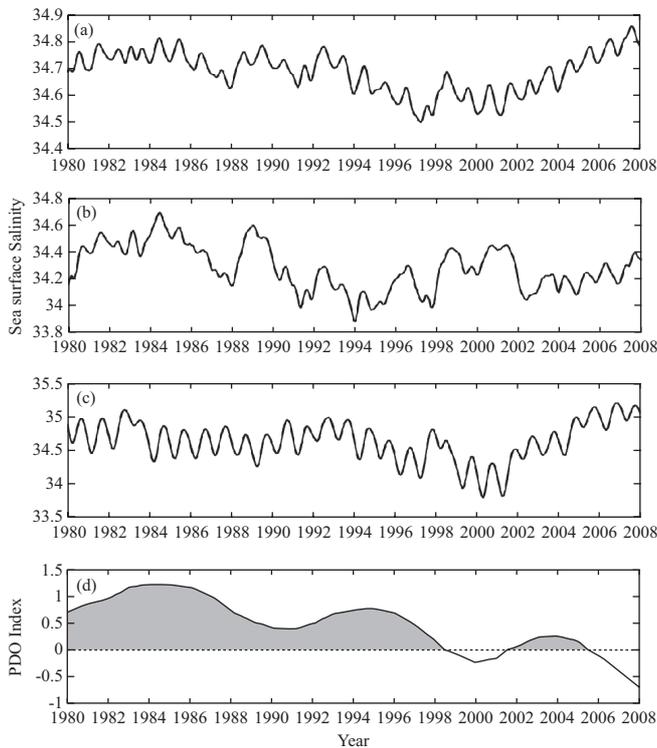
Fig. 2. Time series of monthly SSS from 1980 to 2007 in (a) the tropical
Pacific, (b) the WPWP area, (c) the SPCZ area, and (d) the PDO
index with a 25-monthly running-mean low pass filter applied.

positive and negative phase of the PDO. Between alternative
the positive and negative phase of the PDO (Fig. 2(d)), we
divided the study period into two periods, one period is from
1980-1999 during the positive phase of the PDO; the other is
from 2000 to 2007 during the negative phase of the PDO. The
mean SSS in the tropical Pacific, the WPWP, and the SPCZ
decreased by -0.840 ± 0.013, -0.192 ± 0.038, and -0.192 ±
0.055 psu/decade respectively from 1980 to 1999. On the
contrary, the mean SSS in the tropical Pacific, the WPWP, and
the SPCZ increased respectively by 0.361 ± 0.036, approach
zero, and 1.548 ± 0.168 psu/decade from 2000 to 2007. In
summary the saltier trends during the negative phase of the
PDO is one order higher than the fresh trends during the
positive phase of the PDO, especially in the SPCZ. To further
focus on the description of salinity trends, Fig. 3 shows time
series of the extensions of the fresh pool covered by SSS
values lower than 34.5, 34.0, and 34.0 psu in the tropical Pa-
cific, the WPWP, and the SPCZ, respectively. Because Maes
et al. [18] pointed out that the zonal front at the east edge of
fresh pool characterized by a strong SSS gradient located at
the position of the 34.6 and 34.8 isohalines, we define 34.5 and
34.0 isohalines as our thresholds for different regions.

It is noted that the fresh pool area signal contains significant
decadal variability. In particular, the time series shows an
increasing trend from 1980 to 2000 and then a decreasing
trend after 2000. The period between 1980 and 1999 is asso-
ciated with the positive phase of the PDO, and larger fresh
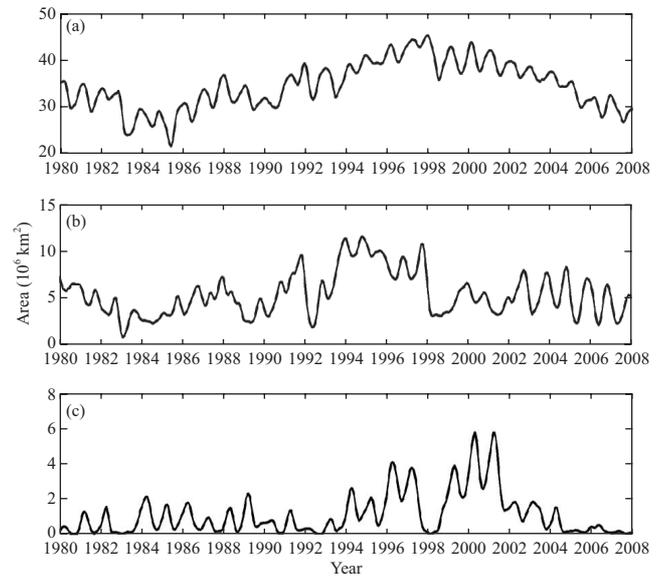
Fig. 3. Time series of area extensions of SSS fresh pools in (a) the tropical
Pacific, (b) the WPWP, and (c) the SPCZ.

pool can be found in this period. As can be seen, linear trends
computed from 1980 to 2007, 1980 to 1999, and 1999 to 2007
illustrate changes of about (2.48 ± 0.69), (7.07 ± 0.84), and
$(-17.12 \pm 1.52) \times 10^6$ km^2/decade, respectively in the tropical
Pacific for water fresher than 34.5 psu. Furthermore, the areas
of ocean surface covered by SSS values lower than 34 psu in
the WPWP has the trends of about (0.38 ± 0.35), (7.1 ± 0.56),
and $(-1.03 \pm 1.13) \times 10^6$ km^2/decade from 1980 to 2007, 1980
to 1999, and 1999 to 2007. The mean SSS of the water fresher
than 34 psu change by (0.32 ± 0.18), (0.82 ± 0.21), and $(-5.76 \pm
0.92) \times 10^6$ km^2/decade from 1980 to 2007, 1980 to 1999, and
1999 to 2007 in the SPCZ. Among the results calculated
between the positive and negative phase of the PDO, it indi-
cates the opposite variability and has one order larger values
than the trends during the 28 years.

Interannual SSS trend inferred from model SSS dataset
over the period of 1980 to 2007, 1980 to 1999 during the
positive phase of the PDO, and 2000 to 2007 during the
negative phase of the PDO are shown in Fig. 4. We first note
that the SSS trends during the three decades (Fig. 4(a)), is
observed up to 0.30 psu/decade in the maximum freshening
area near eastern areas of New Guinea. The saltier trends,
which can reach up to 0.30 psu/decade are located in the SPCZ
and western areas of Peru, but become weaker or even zero in
northwestern tropical Pacific and southeastern tropical Pacific.

An obvious freshening took place across most of the west-
ern and the central tropical Pacific from 1980 to 1999 (Fig.
4(b)). The positive phase of the PDO accompanying the de-
creasing salinity trends are computed almost in whole tropical
Pacific, the freshening trend can reach up to 0.45 psu/decade
in the northeast of Australia. Fig. 4(c) shows the shorter SSS
trends from 2000 to 2007. The significant increasing salinity
trend can be found in the study area, especially in the SPCZ.
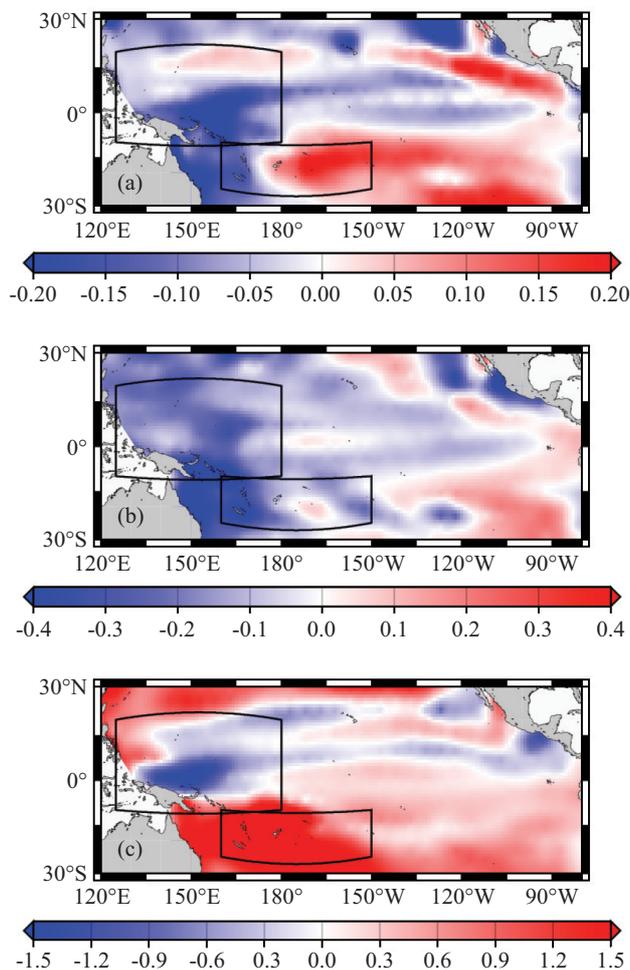
Fig. 4. SSS change rates inferred from (a) 1980 to 2007, (b) 1980 to 1999, and (c) 2000 to 2007. Units are psu/decade.

Fig. 5. Linear trends of SSS from 1980 to 2007 (thick line), 1980 to 1999 (thin line), and 2000 to 2007 (dash line) zonally averaged along the latitude from 30°N to 30°S.

Compared Fig. 4(c) with Fig. 4(b), it shows almost an out of phase pattern. The most notable decreasing and increasing salinity trends can be found in the equatorial cold tongue and SPCZ but the sizes are totally different. The freshening trends can reach up to 1.20 psu/decade. This freshening is more noticeable in the low-salinity regions under the SPCZ, where it exceeds 1.20 psu/decade and exceeds 5 standard deviations of the decadal signal (Fig. 2(c)). Because of the dramatic trends derived from the shorter time series, the values of the salinity trend are one order higher than the long-term trends estimated by the results from Cravatte et al. [5] and Delcroix et al. [8]. However it is clearly suggested that the alternative positive and negative PDO take strong influence on the salinity changes.

Fig. 5 suggests a more comprehensive view of the decadal trends estimated from different time scales. There is an overall tendency for negative trends during 1980 to 2007 and 1980 to 1999 with the values from -0.17 to 0.02 psu/decade. The freshening pattern can be clearly found in the tropical Pacific during 1980-2007. Nevertheless, if we consider the negative phase of the PDO (2000-2007) only (dash line), the trend

becomes positive. The dash line has positive values one order larger than negative values of the thick line and thin line. The data span is thus significantly a key factor affecting the quantification of trends, especially when alternative positive and negative phase of the PDO occur in the time series such as in 1999.

Finally, it also appears in Fig. 2 to Fig. 5 that fresh waters extended in all direction during the data span. Not only the average position of the salinity front but also eastern edge of the fresh pool in the western Pacific extended eastward to play an important role on decadal variability. During the negative phase of the PDO, the SSS become saltier in almost the whole tropical Pacific.

In this study, we used linear regression to detect the SSS variability between the positive and negative phase of the PDO, and determine the variability trend. Some investigations argued that the linear regression method is not always suitable to climate, because the data of time series could be nonlinear, non-periodic and non-stationary. In order to overcome the difficulties of searching for a small amplitude signal embedded in noisy data, Huang et al. 1998 [16] employed the Empirical Mode Decomposition method, which is suitable to deal with more complex data. It can provide another kind of aspects to realize the variability and trend of the time series.

IV. SUMMARY

Decadal variability and long-term trends of SSS in the tropical Pacific was investigated with GFDL CM simulations. The present analysis reports different behaviors of the SSS decadal variability depending on three well-sampled regions over the 1980-1999, 2000-2007, and 1980-2007 time span, respectively. Both SSS freshening and fresh pool extension can be found in the tropical Pacific, WPWP, and SPCZ from

1980 to 2007. However the SSS variability shows dramatic changes during the past few decades. Stronger decrease trends were found in the tropical Pacific, the WPWP, and the SPCZ during 1980-1999 but increase trends during 1999-2007 were observed.

Some of the mechanisms controlling the decadal variability of SSS are considered as PDO changes. The PDO generates distinct SSS anomalies strongly on salt flux advection, fresh-water exchanges, evaporation and precipitation either in a positive or negative phase of the PDO. Geographical SSS patterns show clearly freshening trends during 1980-1999 in the positive phase of the PDO and obviously freshening trends during 2000-2007 in the negative phase of the PDO, in contrast to the long-term freshening trends of 1980-2007. The fresh pool in the tropical Pacific for water fresher than 34.5 psu has SSS changes approximately (7.07 ± 0.84), and $(-17.12 \pm 1.52) \times 10^6$ km^2/decade respectively between the positive phase and negative phase of the PDO. The salinity changes show dramatic variability between alternative the positive and negative phase of the PDO. What are possible feedbacks of salinity variability on the climate system? To give a convinced answer to this problem, we need further observation, analysis and modeling.

REFERENCES

1. Allen, M. R. and Ingram, W. J., "Constraints on future changes in climate and the hydrologic cycle," *Nature*, Vol. 419, pp. 224-232 (2002).

2. Anderson, J. L. and Coauthors, "The new GFDL global atmosphere and land model AM2/LM2: Evaluation with prescribed SST simulations," *Journal of Climate*, Vol. 17, pp. 4641-4673 (2004).

3. Antonov, J. I., Levitus, S., and Boyer, T. P., "Steric sea level variations during 1957-1994: Importance of salinity," *Journal of Geophysical Research*, Vol. 107, doi: 10.1029/ 2001JC000964 (2002).

4. Chang, Y.-S., Rosati, A., Zhang, S., and Harrison, M. J., "Improvement of salinity representation in an ensemble coupled data assimilation system using pseudo salinity profiles," *Journal of Geophysical Research*, Vol. 38, L13609, doi: 10.1029/2011GL 048064 (2011).

5. Cravatte, S., Delcroix, T., Zhang, D., McPhaden, M., and Leloup, J., "Observed freshening and warming of the western Pacific warm pool," *Climate Dynamics*, Vol. 33, pp. 565-589, doi: 10.1017/s00382-009-0526-7 (2009).

6. Delcroix, T., "Observed surface oceanic and atmospheric variability in the Tropical Pacific at seasonal and ENSO time scales: a tentative overview," *Journal of Geophysical Research*, Vol. 103, pp. 18611-18633 (1998).

7. Delcroix, T., Alory, G., Cravatte, S., Corrège, T., and McPhaden, M., "A *gridded* sea surface salinity data set for the tropical Pacific with sample applications (1950-2208)," *Deep Sea Research Part I*, Vol. 58, pp. 38-48 (2011).

8. Delcroix, T., Cravatte, S., and McPhaden, M. J., "Decadal variations and trends in tropical Pacific sea surface salinity since 1970," *Journal of Geophysical Research*, Vol. 112, C03012, doi: 10.1029/2006JC003801 (2007).

9. Delcroix, T., Hénin, C., Masia, F., and Varillon, D., "Three decades of in situ SSS measurements in the tropical Pacific Ocean," CD ROM available from the Centre IRD (Institut de Recherche pour le Développement) de Nouméa, New Caledonia (2000).

10. Delcroix, T. and McPhaden, M. J., "Interannual sea surface salinity and temperature changes in the western Pacific warm pool during 1992-2000," *Journal of Geophysical Research*, Vol. 107, No. 8002, doi: 10.1029/2001JC000862 (2002).

11. Delcroix, T., McPhaden, M. J., Dessier, A., and Gouriou, Y., "Time and space scales for sea surface salinity in the tropical oceans," *Deep Sea Research Part I*, Vol. 52, pp. 787-813 (2005).

12. Delcroix, T. and Picaut, J., "Zonal displacement of the western equatorial Pacific fresh pool," *Journal of Geophysical Research*, Vol. 103, pp. 1087-1098 (1998).

13. Delworth, T. L. and Coauthors, "GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics," *Journal of Climate*, Vol. 19, pp. 643-674 (2006).

14. Gnanadesikan, A. and Coauthors, "GFDL's CM2 global coupled climate models, Part II: The baseline ocean simulation," *Journal of Climate*, Vol. 19, pp. 675-697 (2006).

15. Hénin, C., du Penhoat, Y., and Ioualalen, M., "Observations of sea surface salinity in the western Pacific fresh pool Large-scale changes in 1992-1995," *Journal of Geophysical Research,* Vol. 103, pp. 7523-7536 (1998).

16. Huang, N. E., Shen, Z., Long, S. R., Wu, M. C., Shih, E. H., Zheng, Q., Tung, C. C., and Liu, H. H., "The empirical mode decomposition method and the Hilbert spectrum for non-stationary time series analysis," *Proceedings of the Royal Society of London*, Vol. 454, pp. 903-995 (1998).

17. Levitus, S., Boyer, T. P., Conkright, M. E., O'Brien, T., Antonov, J., Stathoplos, C. L., Johnson, D., and Gelfeld, R., *NOAA Atlas NESDIS 18, World Ocean Database 1998, Volume 1: Introduction*, U.S. Government Printing Office, Washington, DC (1998).

18. Maes, C., Picaut, J., Kuroda, Y., and Ando, K., "Characteristics of the convergence zone at the eastern edge of the Pacific warm pool," *Geophysical Research Letters*, Vol. 31, doi: 10.1029/2004GL019867 (2004).

19. Mantua N. J. and Hare, S. R., "The Pacific decadal oscillation," *Journal of Physical Oceanography*, Vol. 58, pp. 35-44 (2002).

20. McPhaden, M. J. and Zhang, D., "Pacific Ocean circulation rebounds," *Geophysical Research Letters*, Vol. 31, doi: 10.1029/2004GL020727 (2004).

21. Mignot, J. and Frankignoul, C., "On the interannual variability of surface salinity in the Atlantic," *Climate Dynamics*, Vol. 20, pp. 555-565 (2003).

22. Williams, P. D., Guilyardi, E., Sutton, R., Gregory, J., and Madec, G., "A new feedback on climate change from the hydrological cycle," *Geophysical Research Letters*, Vol. 34, L08706, doi: 10.1029/2007GL029275 (2007).

23. Zhang, S., Harrison, M. J., Rosati, A., and Wittenberg, A. T., "System design and evaluation of coupled ensemble data assimilation for global oceanic climate studies," *Monthly Weather Review*, Vol. 135, pp. 3541-3564 (2007).