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Internal variability of the tropical Pacific ocean

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[1] A 40 year integration of an eddy resolving numerical model of the tropical Pacific ocean is analyzed to quantify the interannual variability caused by internal variability of ocean dynamics. It is found that along the Pacific cold tongue internal variability contributes a significant amount to the observed interannual variability. This suggests that in this location the predictability of SST is limited to the persistence time of SST anomalies which is approximately 100 days. Furthermore, a comparison with other sources of variability suggests that internal variability may play an important role in modifying or setting up El Niño. *INDEX TERMS:* 4522 Oceanography: Physical: El Niño; 1620 Global Change: Climate dynamics (3309); 3220 Mathematical Geophysics: Nonlinear dynamics; 4231 Oceanography: General: Equatorial oceanography. **Citation:** Jochum, M., and R. Murtugudde (2004), Internal variability of the tropical Pacific ocean, *Geophys. Res. Lett.*, *31*, L14309, doi:10.1029/2004GL020488.

1. Introduction

[2] The coupled ocean-atmosphere system varies on many timescales; however, it is the variability on multi-year and decadal timescales that currently receives the most attention. Understanding these long term variabilities will improve climate forecasts and the interpretation of historical climate records. Variability in the ocean-atmosphere system can be attributed to external forcing (e.g., ice ages), ocean-atmosphere coupling (e.g., El Niño), internal atmospheric variability (e.g., North Atlantic Oscillation) and, the focus of the present study, internal oceanic variability (e.g., Kuroshio path).

[3] Several authors demonstrated that the observed internal variability of the western boundary currents can be understood within the framework of dynamical systems theory [*Simmonet et al.*, 2003, and references therein]. These studies typically use high resolution shallow-water or quasi-geostrophic ocean models set in a rectangular basin with a mid-latitude double gyre. For certain ranges of Rossby and Ekman numbers the solutions exhibit chaotic or limit cycle behaviour which is usually tied to the strength of the inertial recirculation gyres near the western boundary. The not very comforting picture that emerges from these studies is that the nature of the ocean circulation could be sensitive to parameters that are not well known (e.g., friction or boundary conditions). The present authors are not aware of a study that shows the impact of this internal mid-latitude variability on large scale climate, but it can be speculated that it affects the water mass properties and the heat budget of the mid-latitude oceans.

[4] For the tropics it has been suggested that "the tropical ocean response on interannual timescales is reasonably well captured by linear or weakly nonlinear approximations to the ocean dynamics" [*Neelin et al.*, 1998]. However, the present authors recently concluded several studies that show that at least in the Atlantic nonlinear dynamics are a major part of the tropical circulation: the barotropically unstable North Equatorial Countercurrent generates rings which carry South Atlantic water and potential vorticity into the subtropical gyre [*Jochum and Malanotte-Rizzoli*, 2003] and the unstable Equatorial Undercurrent - South Equatorial Current system generates tropical instability waves (TIWs) [*Jochum et al.*, 2004a] that drive the Atlantic Tsuchiya jets [*Jochum and Malanotte-Rizzoli*, 2004]. In the Pacific as well as in the Atlantic, these TIWs have a period of approximately 20 to 40 days, a wavelength around 1000 km and, due to their nonlinear nature, are of varying strength every year, even under seasonal forcing [*Jochum et al.*, 2004a]. Because they are a major contributor to the equatorial mixed layer heat and momentum budget [*Hansen and Paul*, 1984], year to year changes in their strength will lead to changes in the annual mean SST. In fact, for the Atlantic, [*Jochum et al.*, 2004b] show that TIWs contribute a significant amount to the observed interannual variability of the cross-hemispheric SST gradient. The present study is a continuation of this work in the tropical Atlantic and quantifies the internal SST variability in the equatorial Pacific ocean.

[5] In the context of climate, research on mesoscale variability is important for many reasons, here we highlight two of them: interpretation of the observational record and as a source of stochastic noise to force the coupled ocean-atmosphere system. For the tropical Pacific, there is a large observational database and an extensive literature on the coupled ocean-atmosphere system - El Niño-Southern Oscillation (ENSO). The leading theories explain ENSO as self-sustained variability made irregular by low-order chaos [*Tziperman et al.*, 1994] or as disturbance of a basically stable state by stochastic noise [*Penland and Sardeshmukh*, 1995; *Kessler*, 2002]. For either concept it is important to understand the dynamics and structure of external forcing and stochastic noise on ENSO, because they can enhance or limit the predictability of El Niño. Here we show that internal oceanic variability, hitherto neglected as a relevant source of noise, is as

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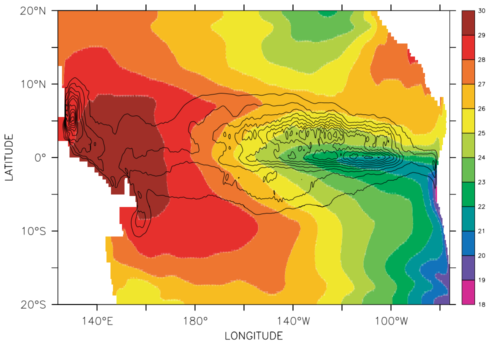

Figure 1. Eddy kinetic energy with periods less than 60 days (contour line: 100 cm^2/s^2, maximum: 1100 cm^2/s^2) superimposed on the annual mean SST.

important a source of variability as westerly windbursts or variations in the subtropical cells.

2. Model Description

[6] The ocean model employed for this study is the reduced gravity, primitive equation, sigma-coordinate model of *Gent and Cane* [1989]. It is coupled to an advective atmospheric mixed layer model which computes surface heat fluxes without any restoring boundary conditions or feedbacks to observations [*Seager et al.*, 1995; *Murtugudde et al.*, 1996]. A variable depth oceanic mixed layer represents the three main processes of oceanic turbulent mixing, namely, the entrainment/detrainment due to wind and buoyancy forcing, the gradient Richardson number mixing generated by the shear flow instability, and the convective mixing related to static instabilities in the water column [*Chen et al.*, 1994]. The model is initialized with *Levitus* [1994] temperature and salinity fields, driven by seasonal *Hellerman and Rosenstein* [1983] winds, thus the forcing is identical every year. It has a $\frac{1}{4}$ degree horizontal resolution and 12 layers in the vertical. At the meridional boundaries (at 20°N, S), temperature and salinity are restored to *Levitus* [1994]. The model is spun up for 20 years and the presented results are taken from the subsequent 40 years of simulation (Figure 1). From these 40 years we constructed the model climatology; the internal (equivalent to the model's interannual) SST anomalies discussed here are the deviations from it. It is important to note that with the atmospheric boundary layer model as the upper boundary condition, the model computes its own heat flux and can therefore develop its own SST. The SST is not artificially damped back to climatology, nor will a positive ocean-atmosphere feedback amplify small perturbations.

[7] Since this study focuses on the effect of internal oceanic variability, it is important that it properly resolves and reproduces the observed eddy field in the tropical Pacific, especially the TIWs as the main component. We found that $\frac{1}{4}$ degree horizontal resolution is sufficient to reproduce the observed TIWs (for a summary of the observations, see *Qiao and Weisberg* [1995]). While wavelength and period of simulated TIWs are relatively insensitive to viscosity [*Cox*, 1980], their strength is not. For the present study we found the strength of the TIWs to be consistent with the velocity observations of the TAO array. Figure 2 illustrates the strength of the TIWs at one particular location which can be compared to the observations of *Qiao and Weisberg* [1995]: The TIWs are weak in spring and reach their maximum strength of ±60 cm/s in the late summer. The model also reproduces the double peak in the spectrum at periods of approximately 20 and 34 days as observed by J. M. Lyman et al. (Structure of 17-day versus 34-day tropical instability waves in the equatorial Pacific, submitted to *Journal of Physical Oceanography*, 2004) (not shown). The magnitude of the SST variability caused by the TIWs is also in accordance with observations; here and in the observations by *Chelton et al.* [2000] the SST difference between wave crest and trough is approximately 5°C.

3. Internal Variability

[8] High internal variability in the Pacific is found at the center of TIW activity (Figure 1) where, as in the Atlantic, the chaotic year to year changes of their energy level leads to changes in the mixed layer heat budget and the SST. Although the leading cause for interannual SST variability in this area is the positive feedback between oceanic and atmospheric changes, the internal variability (Figure 3) accounts for approximately 40% of the observed [*Reynolds and Smith*, 1994] interannual variability. The effect of this internal variability on the zonal SST gradient looks rather small compared to the mean, but it should be noted that the internal variability can substantially affect its seasonal cycle

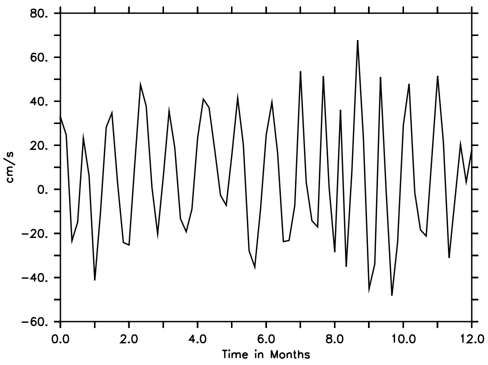

Figure 2. Meridional velocity in the mixed layer at the equator at 140°W.

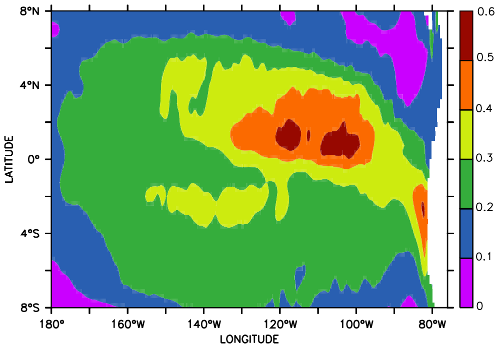

Figure 3. Standard deviation of interannual SST in the Pacific Ocean.

(Figure 4). During spring the SST gradient is weakest and favors the development of El Niño [*Zebiak and Cane*, 1987]. At this time, the east-west SST difference can be anywhere between 3 K and 3.6 K (Figure 4), simply because of internal variability.

[9] The observed SST anomalies in the tropical Pacific have scales of the order of 10000 km. This dwarfs the scales of the internal variability with an autocorrelation length of approximately 1000 km. However, it should be kept in mind that positive feedbacks in the ocean-atmosphere coupling, which can amplify and organize small SST perturbations, is purposely excluded from the present study. Therefore the present results should be compared not only to the observed SST variability which mostly reflects ENSO, but it should also be compared to external sources of variability that can affect the onset or the decadal variability of El Niño. The external and internal processes that affect El Niño are still under debate [*Neelin et al.*, 1998] and a detailed discussion is beyond the scope of this study. To put the present results into context, however, the effect of TIWs is compared to two processes that have been suggested to influence El Niño. There is currently only one purely oceanic source of SST variability that is discussed in the literature: variations in the subtropical cells which provide the source waters for the equatorial upwelling [*McCreary and Lu*, 1994; *Gu and Philander*, 1997]. *Nonaka et al.* [2002] quantify this effect to be not more than 0.2°C in a narrow band along the eastern equatorial Pacific which is as much as the effect of the internal variability in the same area (not shown). A second important process, the Madden-Julian oscillation [*Madden and Julian*, 1971], is estimated to generate a SST variance of up to 0.6 K, mainly centered around Indonesia and along the equator [*Waliser et al.*, 2003, 2004]. Thus, internal variability is a large a source of variability as any of the other yet quantified mechanisms. Each of these mechanisms acts in a different area, yet they all project to some extent on the optimal growing mode that leads to El Niño [see *Penland and Sardeshmukh*, 1995].

[10] The effect of the internal variability on the seasonal cycle in the eastern Pacific is rather profound (Figure 5). This highlights a problem in interpreting SST records: reliably defining a seasonal cycle in the eastern Pacific requires more than a decade of observations and changes in the seasonal cycle will be difficult to detect with the current database.

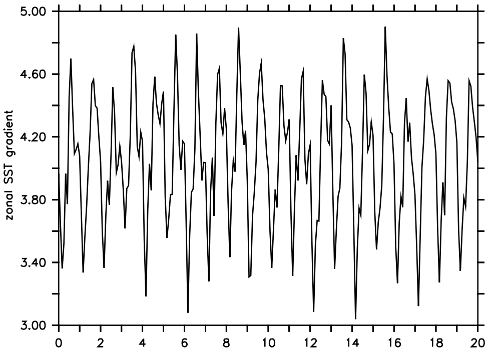

Figure 4. Difference between the western basin SST (averaged from 3°S–3°N and from 160°E–160°W) and the eastern basin SST (averaged from 3°S–3°N and from 160°W–90°W).

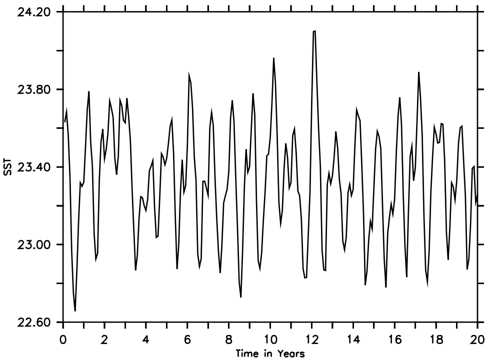

Figure 5. Time series of SST averaged from 2°S to 3°N and from 120°W to 110°W, 3 month running mean.

4. Summary and Discussion

[11] A high resolution primitive equation ocean model with climatological forcing has been used to study the internal variability of the tropical Pacific ocean. In most of this domain the internal variability appears to be negligible compared to the observed interannual variability. However, in the eastern equatorial Pacific internal variability explains a significant part of the observed SST variability. Internal variability has hitherto not been considered as a source of interannual SST variability but it is shown here that internal variability is comparable to the SST variability introduced by the subtropical cells or the Madden-Julian oscillations. Because the internal variability is restricted to the eastern equatorial Pacific, it projects directly on the zonal SST gradient and can change its seasonal cycle. This can have implications for the onset and development of El Niño, because El Niño is phaselocked to the seasonal cycle [*Zebiak and Cane*, 1987] which, at least in the east, is strongly modified by TIWs (Figure 5). The detailed physics behind ENSO is still under investigation, but whether it is a weakly chaotic system or a stochastically forced linear system, the results presented here suggest that TIWs may be an important component in ENSO's irregularity.

[12] The potential effect of internal variability on climate variability as lined out above is speculative and has to be supported by coupled model studies which will be the focus of the authors' research in the future. However, the large internal variability in the eastern Pacific has an direct implication for observations: The effect of mesoscale variability in the observational records cannot be removed by simply averaging over the eddy time scale. The eddies make a net contribution to the mixed layer heat budget; to the extent that the generating instability processes are chaotic this contribution will vary and the SST will be different from year to year even under climatological forcing. Moreover, this uncertainty will affect seasonal climate forecasts since it reduces the forecast time to the persistence time of SST anomalies which in the equatorial Pacific is approximately 100 days [*Kessler et al.*, 1996].

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