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Evidence of deceleration of atmospheric vertical overturning circulation over the tropical Pacific

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[1] Analyses of ship-based measurements of sea level pressure reveal a systematic weakening of the horizontal pressure gradient across the Pacific in the last fifty years. This reduction is also present in the NCAR/NCEP and ECMWF reanalysis sea level pressure products. The magnitude is estimated to be between 2% to 13%. This weakening is consistent with simulations from general circulation models when sea-surface temperatures are uniformly raised. It is also consistent with reductions of the large-scale subsidence over the eastern Pacific in the models. Since the reduction of vertical overturning circulation in the models can be explained through fundamental thermodynamic constraints on the atmospheric circulation, we postulate that the weakening of the sea-level pressure gradient is an intrinsic characteristic of the tropical atmosphere in a warmer climate, and the observed trend in the sea-level pressure provides an indirect evidence of the reduction of atmospheric vertical overturning circulation in the tropical Pacific. It is also pointed out that the weakening of the vertical overturning circulation does not mean the weakening of the hydrological cycle. **Citation:** Zhang, M., and H. Song (2006), Evidence of deceleration of atmospheric vertical overturning circulation over the tropical Pacific, *Geophys. Res. Lett.*, *33*, L12701, doi:10.1029/2006GL025942.

1. Introduction

[2] Atmospheric variability in the tropics plays a significant role in regulating weather and climate on global and regional scales. Basin-scale vertical circulations are a key component of the tropical atmospheric system. Previous modeling studies have shown weakening of the atmospheric Walker circulation in a warmer climate [*Betts and Ridgeway*, 1989; *Knutson and Manabe*, 1995]. This weakening has not been supported by observational data. Models also show weakening of Hadley circulations [*Mitas and Clement*, 2006]. Several recent studies using reanalysis products however have shown signs of strengthening of the Hadley circulation in recent decades [*Tanaka et al.*, 2004; *Quan et al.*, 2004; *Mitas and Clement*, 2005].

[3] In the reanalysis products, atmospheric vertical velocity was derived from the mass continuity equation through the divergence and convergence of horizontal winds [*Kalnay et al.*, 1996; *Gibson et al.*, 1999]. The horizontal winds in the tropics are strongly coupled with convective processes [e.g., *Zhang*, 1997]. As a result, biases in the trends of the input radiosonde temperature, as have been recently suspected [*Sherwood et al.*, 2005; *Santer et al.*, 2005], can seriously affect the reliability of the vertical velocity trend in the reanalysis products [*Mitas and Clement*, 2006]. Furthermore, radiosondes over the tropical Pacific were sparse and there were discontinuities of the input data due to the incorporation of satellite measurements in 1979. These factors make the detection of the trends of vertical circulation in the reanalysis product a difficult task [*Bengtsson et al.*, 2004; *Kinter et al.*, 2002, 2004].

[4] Large-scale vertical circulation in the tropics is an integral part of the atmospheric system that consists of centers of low and high pressures. Any trend in the vertical circulation should therefore accompany trends in other components of the system. This study reports the trend of the system by using the sea-level pressure (SLP) data that was constructed from more abundant ship-based measurements.

2. Data and Models

[5] The extended reconstructed sea level pressure (ERSLP) analysis of the NOAA National Climate Data Center are used [*Smith and Reynolds*, 2004a]. The data incorporated the most recent Comprehensive Ocean-Atmosphere Data Set (COADS) data and additional coastal and island stations. Improved statistical methods were employed in the construction similarly to those used for the widely used Smith and Reynolds SST data [*Smith and Reynolds*, 2004b]. The monthly 2° by 2° SLP data span 1854 to 1997. We use data after 1950 since the ship-based COADS data have better coverage during this period [*Woodruff et al.*, 1987].

[6] Monthly SLP from the National Center of Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and from the European Center for Medium Range Weather Forecasting (ECMWF) ER-40 reanalyses are also used [*Kalnay et al.*, 1996; *Gibson et al.*, 1999]. The NCEP/NCAR reanalysis is from 1948 to 2004, and the ECMWF ER-40 reanalysis is from 1958 to 2001.

[7] The two general circulation models (GCMs) we use are the National Center for Atmospheric Research (NCAR) Community Atmospheric Model (CAM) [*Collins et al.*, 2006], and the Geophysical Fluid Dynamics Laboratory (GFDL) Atmospheric Model (AM) 2.12b [*GFDL Global Atmospheric Model Development Team*, 2004]. The CAM is a preliminary version of CAM 3.0 (CAM2.02_rio33). The

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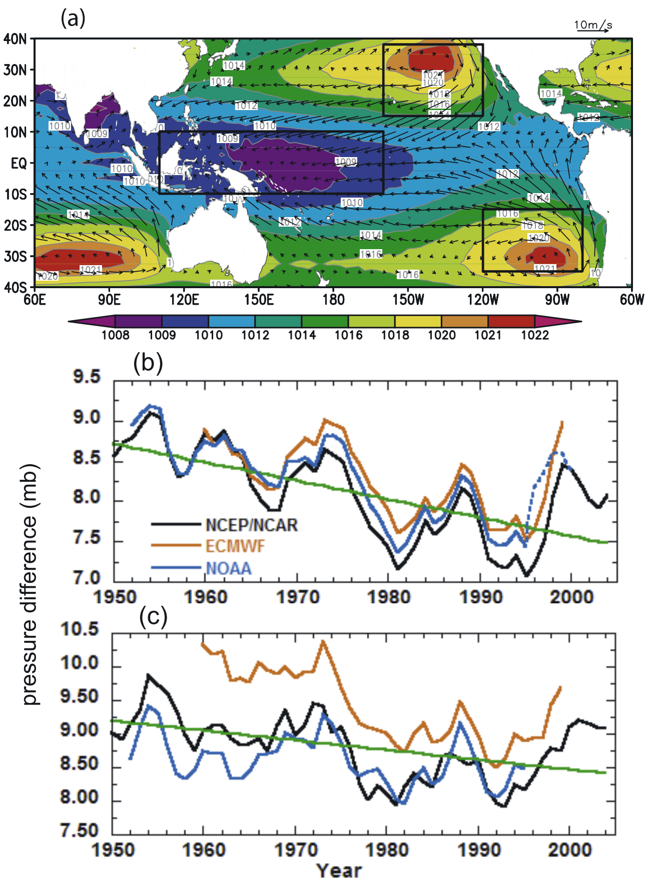

Figure 1. (a) Climatology of sea-level pressure (SLP) from the NCEP/NCAR reanalysis (color and contour). Arrows represent wind climatology at the 1000 hpa level. (b) Time series of the SSP differences between the two boxes in the Northeastern Pacific and Tropical Western Pacific in Figure 1a by using the three data sets from the NOAA ship-based observations, NCEP/NCAR reanalysis, and ECMWF reanalysis. Plotted are five-year running averages. The straight line is a linear regression from using the NCEP/NCAR reanalysis. Units are in hpa. (c) The SSP differences between the two boxes in the Southeastern Pacific and the Tropical Western Pacific, similar to Figure 1b.

physical parameterizations of these two GCMs are listed in Table 1 of *Wyant et al.* [2006].

3. Results

[8] In the tropical Pacific, the most conspicuous features of the SLP distribution are the subtropical highs north and south of the Equator and the low pressure center in the Tropical Western Pacific (TWP) (Figure 1a). Together with the Coriolis force due to the rotation of the Earth, the pressure gradient forces directing from the highs to the low drive the northeast and southeast surface trade winds on the two sides of the Equator. Surface air converges in the Western Pacific to form the rising branch of atmospheric circulation, and diverges from the two centers of the subtropical highs to form its subsidence branch. As a first step, we deliberately avoid using the separate Hadley and Walker circulations in this paper but infer the general vertical overturning circulation from the SLP distributions.

[9] The difference of area-averaged sea-level pressure between the subtropical high in the northeast Pacific (160°W–110°W, 15°N–35°N) and the tropical western Pacific (110°E–140°E, 10°S–10°N) from 1950 to 1997, analyzed from using the NOAA ERLSP data, is shown as a time series in Figure 1b by the blue solid line. There are large interannual and interdecadal variations, including the climate shift around 1976 [e.g., *Trenberth and Hurrell*, 1994; *Deser et al.*, 2004; *Kinter et al.*, 2004]. There is, however, a clear trend of the decrease of sea-level pressure gradient in the five decades.

[10] The corresponding pressure differences in the NCEP/NCAR and the ECMWF reanalyses are also shown in Figure 1b. There are good agreements among the two reanalysis products and the NOAA data, all of them indicated decreasing gradient of surface pressure. Since the two reanalysis products both indicated the upward swing of pressure difference after the NOAA data ended, the NOAA data were extended to 2004 by regression against the NCEP/NCAR data for the overlapping period of 1950 to 1997. The regression coefficient between the two data sets is 0.98. The extended period is shown as the blue dashed line in Figure 1b. With this modification, the gradient of sea-level pressure in the NOAA data decreased by 11 ± 7% in fifty years, while it is 12 ± 11%, and 5 ± 7% respectively in the two reanalysis products from NCEP/NCAR and ECMWF. The error bars represent the ninety-five confidence ranges. The statistical significance tests are carried out using Student's -t distributions of the trends with the number of degrees of freedom calculated based on autocorrelation of the time series.

[11] Figure 1c shows the variations of the pressure gradient directing from TWP to the southeast subtropical Pacific (120°W-70°W, 35°S-15°S). The decreases of the pressure gradient are 2 ± 8%, 8 ± 7% and 13 ± 10% respectively in the NOAA SLP data, the NCEP/NCAR and the ECMWF reanalyses. While there are large differences in the values of these trends among the data sets, and the trend in the NOAA data does not pass the ninety-five percent confidence test, none of the data sets suggests an opposite sign. We note that the COADS SLP data in the Southeast Pacific is relatively sparse compared to other regions [*Woodruff et al.*, 1987].

[12] Since there is a seasonable variation of the pressure pattern in Figure 1a, we carried separate analyses for the boreal winter and summer by using spatial averaging domains appropriate for each season. The trend results are very similar. We also examined the possible changes in the locations of the subtropical highs, and found no systematic variation in the locations that can explain the pressure gradient trends.

[13] It has been known that there is a decadal variation of the ENSO in the last fifty years [e.g., *An and Wang*, 2000; *Trenberth*, 1990]. One can ask whether the SLP trend is part of the ENSO trend. Because the pressure difference between Darwin and Tahiti is often used to define ENSO, it is clearly related with the pressure difference reported here. We argue, however, that the result presented above is very different since it concerns with the pressure differences directing

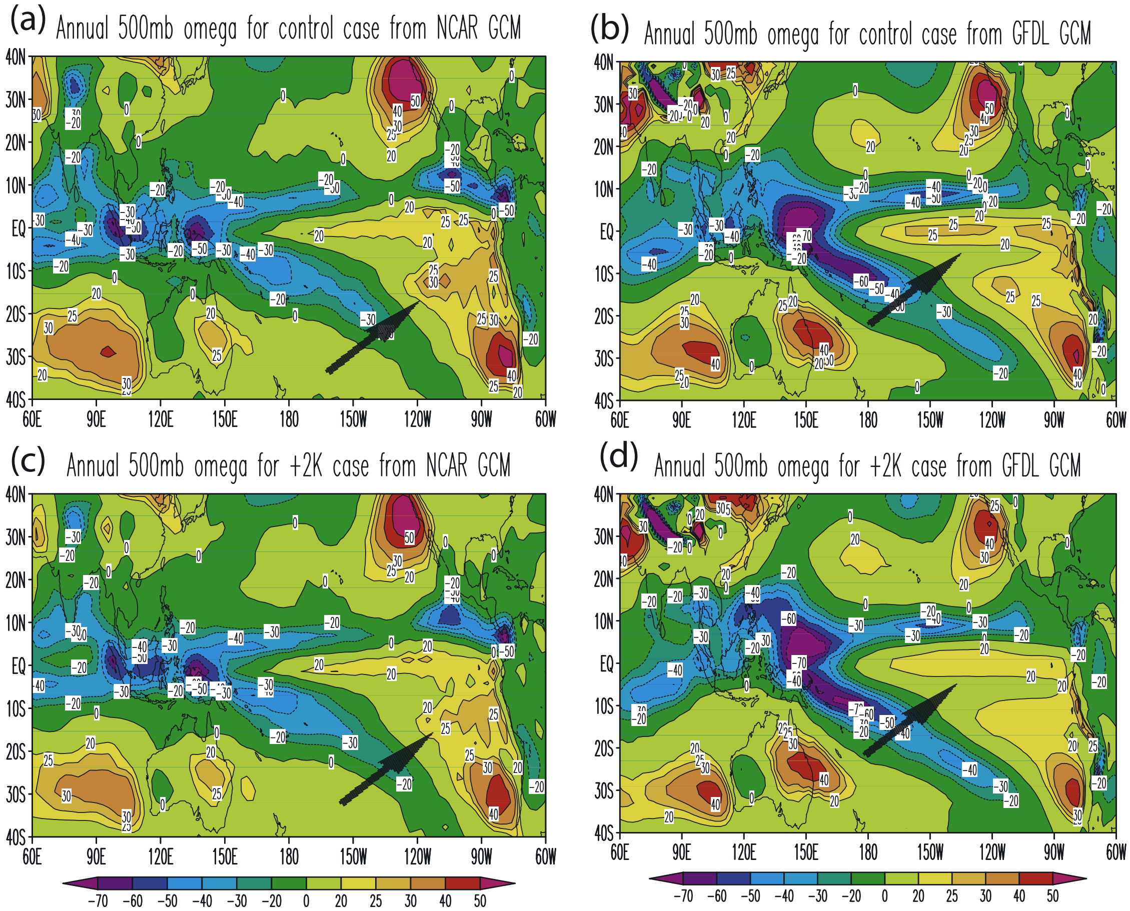

Figure 2. (a and b) Climatology of pressure vertical velocity (mb day-1) simulated in the NCAR GCM and GFDL GCM (unit: hpa) when observed monthly sea surface temperatures (SST) are prescribed in the models. Positive values mean subsidence and negative values mean upward motion. (c and d) Climatology of pressure vertical velocity (mb day^{-1}) when SSTs are uniformed increased by 2°C in the two models. The black arrows highlight the changes in the subsidence rate.

from the subtropical highs to the TWP low. The impact of individual El Nino events on these trends is found to be insignificant after we regress the time series in Figures 1b and 1c against the Nino 3 index to remove the El Nino signature.

[14] During the period from 1950 to 2004, SST averaged from 30°N to 30°S and 60°E to 60°W has risen by about 0.5°C according to *Reynolds and Smith* [2004b]. We postulate that the decrease of the surface pressure gradient is an intrinsic characteristic of a warmer climate. We use the NCAR CAM3 and the GFDL AM2 to examine this more closely. Control simulations were carried out by using prescribed seasonally varying monthly SSTs. The SSTs are then uniformly perturbed by +2K [*Cess et al.*, 1996]. There is therefore no ENSO forcing in the models. The experiments were conducted as part of the Climate Process Team on low latitude climate feedbacks [*Bretherton et al.*, 2004]. In the GFDL GCM, the SLP gradients corresponding to those in Figures 1b and 1c are reduced by 7.8% and 5.1% in the northern and southern hemispheres respectively. In the CAM3, they are reduced by 1.0% and 3.0%. The quantitative values differ among the models, but the sign of the pressure gradient variation across the Pacific is consistent in all simulations and with observational data sets. We note that the reductions in the models are much smaller than in the observational analyses when normalized to a unit global temperature increase. Part of this could be related with the spatial distribution of the observed SST increase that is larger in the eastern tropical Pacific than in the western tropical Pacific [*Wittenberg*, 2004].

[15] Associated with the reduction of surface pressure gradient, the models exhibited weakening of the overall intensity of the vertical circulation in a warmer climate, as shown in the subsidence rate at 500 mb level in the Eastern Pacific (Figure 2). When averaged from 30°N to 30°S and normalized to 1°C SST increase, the monthly subsidence rate decreased by about 3% percent in the models when averaged over the subsidence regions. This weakening has been also reported by *Knutson and Manabe* [1995] and by *Bony et al.* [2005]. The latter showed the narrowing of the frequency distribution of the vertical velocity in the tropics in three European GCMs. What we emphasize here is that the weakening of the vertical circulation is consistent with the reduction of surface pressure gradient across the tropical Pacific.

[16] Since the reduction of vertical circulation in a warmer climate can be physically explained through the requirement of enthalpy conservation of the tropical troposphere [*Held and Soden*, 2006], the decrease of surface pressure gradient is therefore an intrinsic characteristic of a warmer tropical atmosphere. When the tropical SST warms up, vertical stability of the dry atmosphere is increased. In the subsidence region, the increased stability accompanies weak subsidence to maintain the thermodynamic balance in the subsidence regions. An alternative explanation is to consider the heat budget of the tropical atmosphere as a whole, where the dominant balance is between latent heating and radiative cooling. As surface temperature increases, the radiative cooling of the atmosphere does not change as much as the vertical gradient of moisture. Thus, the vertical circulation must decrease so that the latent heating does not over-compensate the radiative cooling. This leads to less wind divergences and convergences in the upper troposphere, and smaller surface pressure gradient. The reported reduction of surface pressure gradient can be therefore considered as an indirect evidence of the weakening of the atmospheric vertical circulation in the tropical Pacific.

[17] As noted in the introduction, the vertical velocity trends in the reanalysis products are inconsistent with modeling results, and may not be suitable to study the long-term trends of the vertical circulation in the tropics. This is also reflected in the trends of atmospheric temperature lapse rate between models and radiosondes [*Santer et al.*, 2005]. Why then is the trend in SLP gradient in the reanalysis products consistent with ship-based SLP measurements but the vertical overturning circulation is not? A straightforward explanation is that surface pressure is directly observed that has no obvious sources of the trend biases. There are however known trend biases in radiosonde temperatures in addition to the discontinuity in the use of satellite data. The reanalysis products are not dynamically and thermodynamically consistent [*Trenberth*, 1997], and thus the dynamic relationship between sea level pressure and vertical velocity is not guaranteed.

4. Discussion

[18] The evidence of reduction of surface pressure gradient supports the model predictions of weakening vertical circulation in a warmer climate. This reduction in pressure gradient may have important implications for the interpretation of future climate changes. As the surface pressure gradient weakens, the trade winds should also weaken. If this proves to be true, the SST contrast between warm pool and cold tongue across the Pacific should also decrease since the equatorial cold tongue is driven by upwelling of cold water in the Eastern Pacific due to surface trade winds. The observed spatial pattern of SST change of the tropical Pacific in the last fifty years indeed shows this feature [*Wittenberg*, 2004]. Previous modeling results from coupled GCMs are also somewhat consistent with this deduction [e.g., *Knutson and Manabe*, 1995; *Meehl et al.*, 2000]. Along this line of deduction, SST anomaly in a global warming scenario would be somewhat similar to an El Nino signature in which the anomaly should be larger in the Eastern Pacific than in the Western Pacific. Further observational and modeling studies are needed to confirm these speculations.

[19] Finally, we point out that the weakening of the atmospheric vertical circulation does not necessarily lead to the weakening of the atmospheric hydrological cycle. One can think of the latter as a convolution of the dynamical circulation with water vapor content. Since moisture in the air increases with temperature, the hydrological cycle, defined as precipitation, should in fact intensify as long as the overall radiative cooling of the atmosphere increases in a global warming scenario. This may reconcile some seemingly conflicting results [*Chen et al.*, 2002; *Kinter et al.*, 2004]. As discussed earlier, however, trends in the dynamical circulation have their own significance in the climate system.

[20] Further study is needed to establish the relationship between SLP gradient and vertical circulation more robustly and to infer trends in the vertical circulation directly from data. Additionally, possible trend of zonally averaged circulation in the tropics, which has not been addressed in this paper, remains an open question.

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