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Pacific's Response to Surface Heating in 130 Years of SST: La Niña-Like or El Niño-Like?

by

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Abstract

Using a modified method of Multiple Linear Regression on instrumented sea-surface temperature (SST) in two longest historical datasets (ERSST and HadISST), we find that the response to increased greenhouse forcing is a warm SST in mid to eastern Pacific in the equatorial region in the annual or seasonal mean. The warming is robustly statistically significant at 95% confidence level. Consistent with this, the smaller radiative heating from solar forcing produces a weak warming also in this region, and the spatial pattern of the response is neither La Niña-like nor El Niño-like. We note that previous reports of a cold-tongue (La Niña-like) response to increased greenhouse or to solar-cycle heating were likely caused by contaminations due to the dominant mode of natural response in the equatorial Pacific. The present result has implications on whether the Walker circulation is weakened or strengthened in a warmer climate, and on coupled atmosphere-ocean climate model validation.

1. Introduction

El Niño-Southern Oscillation (ENSO) is a dominant mode of natural oscillation of the equatorial coupled atmosphere-ocean system in the Pacific. The question of whether the equatorial Pacific responds to radiative heating in a La Niña-like (cold-ENSO) pattern or an El Niño-like (warm-ENSO) pattern is under debate in the context of global warming (see Vecchi *et al.* [2008]). It has been argued that because of the tight coupling of the atmospheric Walker circulation with the thermocline depth in the eastern equatorial Pacific Ocean, the response to a larger radiative heating may not necessarily be a warmer sea-surface temperature (SST). There are currently two competing theories, differing in the degree with which the atmosphere is coupled to the ocean. Clement *et al.* [1996] presumed that the eastern Pacific SST is controlled by ocean cold water upwelling and therefore a basin-wide heating increases only the SST in the western Pacific. The resulting east-west temperature gradient strengthens the atmospheric Walker circulation, whose easterly flow near the surface induces stronger ocean upwelling in the eastern Pacific, thus a cold-ENSO-like response. On the other hand, Held and Soden [2006] and Vecchi and Soden [2007] suggested that tropical circulations, especially zonal overturning circulations (such as the Walker Circulation) would weaken in a warmer climate. The weakened surface easterlies lead to an El Niño (warm-ENSO)-like SST, of a warm tongue in the eastern Pacific. Held and Soden [2006] pointed out that this is a robust response of the current crop of coupled atmosphere-ocean general circulation models: As the SST warms, convection actually decreases, because the lower tropospheric water vapor increases faster than the global mean precipitation. Xie *et al.*

[2010] suggested that the warming pattern should be less El Niño-like because of the strengthened southeasterlies south of the equator, due to hemispheric asymmetry in land-sea area (Liu *et al.* [2005]). Observational evidence is ambiguous. Vecchi *et al.* [2008] showed that the trend in 1880-2005 has a cold-ENSO-like pattern in one dataset (HadISST) but a warm-ENSO-like pattern with asymmetry in another (ERSST). Karnauskas *et al.* [2009] found the zonal SST gradient strengthened in boreal fall but weakened in spring. We hope to reconcile these disparate results in the present study.

A related phenomenon is that of the 11-year solar cycle. Does the tropical Pacific respond with a La Niña-like or an El Niño-like pattern during solar max, when the solar radiation is about 0.1% stronger than during solar min? Since the time scales for tropical convection and for ENSO responses are much shorter than both 11 years and the multi-decadal scale of greenhouse gas increases, these mechanisms in the equatorial Pacific should be equally applicable to the two phenomena. Recently there is a series of papers, by Meehl and Arblaster [2009]; Meehl *et al.* [2009]; Van Loon and Meehl [2008]; Van Loon *et al.* [2007] , showing that the equatorial Pacific responds in a prominent symmetric *cold*-ENSO-like pattern during the northern winter season of the peak solar year, as compared to climatology. The mechanism proposed by the authors is a variant of the "ocean thermostat" mechanism of Clement *et al.* [1996] , with an additional detail of positive cloud feedback: A basin-wide radiative heating will preferentially heat the eastern Pacific, which is more cloud-free because of the colder SST. The authors suggested that the increased evaporation does not locally form clouds but is instead transported by the surface easterlies to the western Pacific, and that the Walker circulation is strengthened instead of weakened, keeping the eastern Pacific cloud-free.

Meehl *et al.* [2009] proposed this as an amplifying mechanism for the response to solar forcing. The referenced work of Gleisner and Thejll [2003] appear to support a strengthened Walker circulation. However, Coughlin and Tung [2006] have showed that the Gleisner and Thejll results was problematic.

The van Loon/Meehl's "solar response" pattern is *not* a response to solar forcing, because the level of total solar irradiance (TSI) for the 11 sunspot peaks used, relative to the 1968-1996 "climatology" that was subtracted from it, is almost zero (the JF mean difference is -0.021 Wm^{-2}, compared to a typical value of 1 Wm^{-2} variation from solar max to solar min). Our second argument is that their response, if it were solar related, would have been opposite in peak sunspot minimum years compared to the peak maximum years. Yet they did not find a warm-ENSO-like pattern in the former while a cold-ENSO-like pattern was found in the latter. Of the eleven sunspot peak years studied by Van Loon and Meehl [2008]; Van Loon *et al.* [2007] , eight (1860, '70, '83, '93, 1917,'37,'57,'68,'79,'89,2000) are cold-ENSO years, and three (1905,'28,'47) belong to warm-ENSO (with the classification defined by the cold tongue index (CTI) in January-February mean). Van Loon and Meehl [2008] mentioned 1989 as the only cold event, but 1893, not mentioned, was even colder. Van Loon and Meehl [2008] later added three more solar peak years to the time series, all of them belonging to cold-ENSO. It is therefore not surprising that their "solar peak" patterns take the beautiful form of a La Nina pattern. In the solar min peak years, distribution of warm- and cold-ENSO years is even, and hence no coherent pattern was found (see also Roy and Haigh [2010]).

A common technique for disentangling responses to multiple phenomena is the method of multiple linear regression. A modified version is employed next.

2. Multiple Linear Regression

We use the instrumented record of surface temperature from 1880 to 2008, in the form of Extended Reconstructed Sea-Surface Temperature (ERSST) (*NOAA_ERSST_V3* data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, at http://www.cdc.noaa.gov/*)*, as described in Smith and Reynolds [2003]; Smith and Reynolds [2004]; Smith *et al.* [2008] . Hadley Center's Global Ocean Surface Temperature is part of the HadISST dataset of sea ice and SST(Rayner *et al.* [2003]) and available from 1870 to present from http://hadobs.metoffice.com/hadisst/.

In the multiple regression study, it is assumed that the SST variation in space x (an vector) and time t can be modeled by:

$$SST(x,t) = p_S(x)\cdot TSI(t) + p_E(x)\cdot CTI(t) + p_G(x)\cdot G(t) + p_V(x)\cdot V(t) + \varepsilon(x,t), \qquad (1)$$

where G is the anthropogenic greenhouse emissions (Hansen *et al.* [2007] , text file available at http://data.giss.nasa.gov/modelforce/), and V the volcano aerosol index (Sato *et al.* [1993]). ε is the remainder and may or may not be Gaussian noise. The *TSI* is from Lean *et al.* [2005] and Wang *et al.* [2005] extended to 2008 and kindly provided to us by J. Lean. *CTI* is the averaged SST over 6N-6S, 180-90W minus the global mean SST (offered by the University of Washington http://jisao.washington.edu/data/cti/).

To take into account the possibility that *CTI* itself could be forced by *TSI, G* and *V*, (1) is supplemented by:

$$CTI(t) = \beta_S TSI(t) + \beta_G G(t) + \beta_V V(t) + R(t), \qquad (2)$$

The residual R obtained from (2) represents the unforced ENSO index. The nested model (1)+(2) is equivalent to model (1) alone with the regressor *CTI* replaced by R. No lag is used here in the response relative to the forcing index although Lean and Rind [2008] incorporated various lags in their multiple regression. The spatial patterns are little changed when we repeated the calculation with their lags.

Figure 1 (Figure 2) shows the various responses, p's, for the ERSST (HadISST) data. The left panel shows the result of model (1) using *CTI* as the ENSO index, while the right panel uses the unforced ENSO index R. A two-tailed Student's t-test (yellow contour) answers the question of whether the signal is different from zero, while the one-tailed t-test (black contour) tests whether the signal is positive or negative. Some of the previous applications of student t-tests may have overestimated the statistical significance by assuming ε to be white noise, but it is positively auto-correlated in reality (see Figure 6). Here the t-test is applied only over the locations that pass the Durbin-Watson test. In other regions, additional processing to take into account of autocorrelation is required (see Appendix).

Anthropogenic response is warming in almost the entire Pacific and the signal is statistically significant above 95% confidence level. There is very little projection of G unto *CTI* and so there is not much difference between the left and right panels. The anthropogenic warming is consistent with the sea-level pressure result of Vecchi *et al.* [2006] that showed a weakening of the Walker circulation. The results for the two datasets are consistent. There is however a very thin strip over the equator in HadISST where the small anthropogenic response is not statistically significant. Such a narrow strip of different behavior likely indicates a data quality problem. Our statistical test also shows a larger area of insignificance in the mid Pacific in HadISST than in the ERSST case. Seasonal behavior for the anthropogenic response is shown in Figures 3 for the two datasets using model (1)+(2), and it is consistent with the annual mean result. The contrasting behavior between fall and spring season mentioned by Karnauskas *et al.* [2009] is not seen in our analysis. There is again a thin strip of possibly bad data (not statistically significant) in the HadISST along the equator, which is more confined to mid and eastern Pacific during boreal autumn and this may have contributed to the strengthened zonal temperature gradient in Karnauskas *et al.* [2009] .

Solar response is weakly warm in the equatorial Pacific, as was found by Roy and Haigh [2010] using a multiple regression model similar to our Model (1) and by Zhou and Tung [2010] using a different method. This warming is not statistically significant, in annual mean or in seasonal mean, when we use Model (1)+(2). It is neither El Niño-like nor La Niña- like. It looks nothing like the large (~-1 C) cold tongue found by Van Loon *et al.* [2007] . This does not mean that there is no solar response; it just means that the amplitude of the response in the equatorial Pacific is too weak. Zhou and Tung [2010] established that the global SST pattern is related to solar forcing.

Volcano response: Volcano aerosol forcing projects partly onto the *CTI*. While the response obtained using *CTI* as the regressor is weakly negative in the Pacific, it becomes warm-ENSO-like when *R* is used as the regressor. The result is statistically significant, and appears consistent with the earlier suggestion of Handler [1984] . However there is uncertainty in the choice of the volcano index and the time behavior of the response a few years after the eruption may not follow the aerosol optical depth.

We repeated the calculation without using *V* as one of the regressors, and our previous responses to anthropogenic, solar and ENSO indices are little changed; so these responses are unaffected by the choice of volcano index.

3. Conclusion

We have demonstrated that in the tropical Pacific the anthropogenic or solar forcing produces mostly a warmer sea-surface temperature, but the spatial pattern is not in the form of an ENSO-like warm tongue or cold tongue. There is consistency in such responses in two different sea-surface temperature datasets of long duration. The warming response in the tropical Pacific to greenhouse forcing is consistent with recent IPCC model results (Vecchi *et al.* [2008]; Xie *et al.* [2010]). The magnitude of solar warming is found in this region to be about 0.1 ± 0.3 C. The much larger response (of 1 C cooling in a beautiful cold tongue in equatorial Pacific) found by Van Loon and Meehl [2008] is likely due to ENSO and not to the amplifying effect of positive cloud feedback.

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Appendix Student's *t*-tests and prewhitening

The multiple linear regression model takes the form $Y(t)=\sum_{j=1}^{k}x_j(t)\beta_j+\varepsilon(t)$, where the *regressors* $x_j(t)$'s are predetermined and the error $\varepsilon(t)$ is unobserved. Given n observations $\{Y_i, x_{i1},\cdots x_{ik}\}_{i=1}^{n}$, the ordinary least squares (OLS) fitting gives the estimators, $\hat{\beta}_j$, of the unknown regression coefficients β_j, in vector form as: $\hat{\beta}=MY$, where $M=(X^TX)^{-1}X^T$ and X is an $n\times k$ matrix of observations of all the regressors. If the error is i.i.d. normal: $N(0,\sigma^2)$, then the Gaussian distribution of $\hat{\beta}_j \sim N(\beta_j, \sum_{i=1}^{n}M_{ji}^2\sigma^2)$ follows. Furthermore, it can be shown that $RSS/\sigma^2 \sim \chi^2_{n-k}$, where

$RSS = \sum_{i=1}^{n} \left(Y_i - \sum_{j=1}^{k} x_{ij} \hat{\beta}_j \right)^2$ is the *residual sum of squares*, and $S^2 = RSS/(n-k)$ is independent of any $\hat{\beta}_j$. Therefore $(\hat{\beta}_j - \beta_j) \Big/ \sqrt{S^2 \sum_{i=1}^{n} M_{ji}^2} \sim t_{n-k}$ for $j = 1, \cdots, k$. This expression can be used to form a Student's *t*-test of the null hypothesis $\mathbf{H_0}$: $\beta_j = 0$ versus the alternative hypothesis $\mathbf{H_1}$: $\beta_j \neq 0$ (two-sided) or $\mathbf{H_1}$: $\beta_j > 0$ (one-sided; $\mathbf{H_1}$: $\beta_j < 0$ is tested in a similar way). We reject $\mathbf{H_0}$ at significance level α in favor of $\mathbf{H_1}$: $\beta_j \neq 0$ if $\left| (\hat{\beta}_j - 0) \Big/ \sqrt{S^2 \sum_{i=1}^{n} M_{ji}^2} \right| > t_{n-k, \alpha/2}$; in favor of: $\beta_j > 0$ if $(\hat{\beta}_j - 0) \Big/ \sqrt{S^2 \sum_{i=1}^{n} M_{ji}^2} > t_{n-k,\alpha}$.

In climate data the errors are usually autocorrelated so the above analysis does not apply directly. The Durbin-Watson test (Durbin and Watson [1971]; Savin and White [1977]) can be used to detect the presence of autocorrelation in the residuals from a regression analysis. In case of autocorrelated error terms (suppose they are AR(1): $\varepsilon(t+1) = \rho\varepsilon(t) + \omega(t+1)$), a two-stage regression can be employed to correct the model as follows: **(1)** Fit linear model to original data by OLS. **(2)** Estimate the autocorrelation ρ with the sample value $\hat{\rho} = \sum_{t=2}^{n} (\hat{\varepsilon}_t \hat{\varepsilon}_{t-1}) \Big/ \sum_{t=1}^{n} \hat{\varepsilon}_t^2$ where $\hat{\varepsilon}_t$ is the residual from the first step analysis. **(3)** Prewhiten the data using $\hat{\rho}$ and then refit the model. The prewhitening process is done by introducing new data $\widetilde{Y}_{i+1} = Y_{i+1} - \hat{\rho} Y_i$ and regressors $\widetilde{x}_{i+1,j} = x_{i+1,j} - \hat{\rho} x_{ij}$ for $i = 1, \cdots, n-1$ and $j = 1, \cdots, k$. Now the model becomes

$\widetilde{Y}(t+1) = \sum_{j=1}^{k} \widetilde{x}_j(t+1)\beta_j + \widetilde{\varepsilon}(t+1)$ with the new noise $\widetilde{\varepsilon}(t+1) = \omega(t+1) + (\rho - \hat{\rho})\varepsilon(t)$.

The Durbin-Watson test can be applied to the new noise. If it does not satisfy the test, the prewhitening process is repeated. This has not been necessary in our case (see Figure 6).

Finally the statistical significance of regression coefficients obtained from a model with white noise can be tested as above using the Student's *t*-test.

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Figure Legends

Figure 1. Spatial pattern in annual mean SST response obtained using multiple linear regression method (1) in the left panel and model (1)+(2) in the right panel using ERSST data. From the top to bottom panels, responses to: ENSO, net anthropogenic forcing, solar and volcano aerosols. Yellow (black) contour enclose regions of 95% confidence level in a two-tailed (one-tailed) test after prewhitening. The unit for the solar response is in degrees C per 1 Wm^{-2} of variation in the solar constant (TSI), which in recent decades (since direct satellite measurement) varies by about 1 Wm^{-2} between solar max and solar min. The anthropogenic response is in units of degrees C per Wm^{-2} of net radiative forcing (RF, at the top of troposphere). The RF change since 1880 is about 1.8 Wm^{-2}. The ENSO response is in degrees C per degrees C of the CTI index. The aerosol response is in degrees C per optical depth variation of the aerosol index.

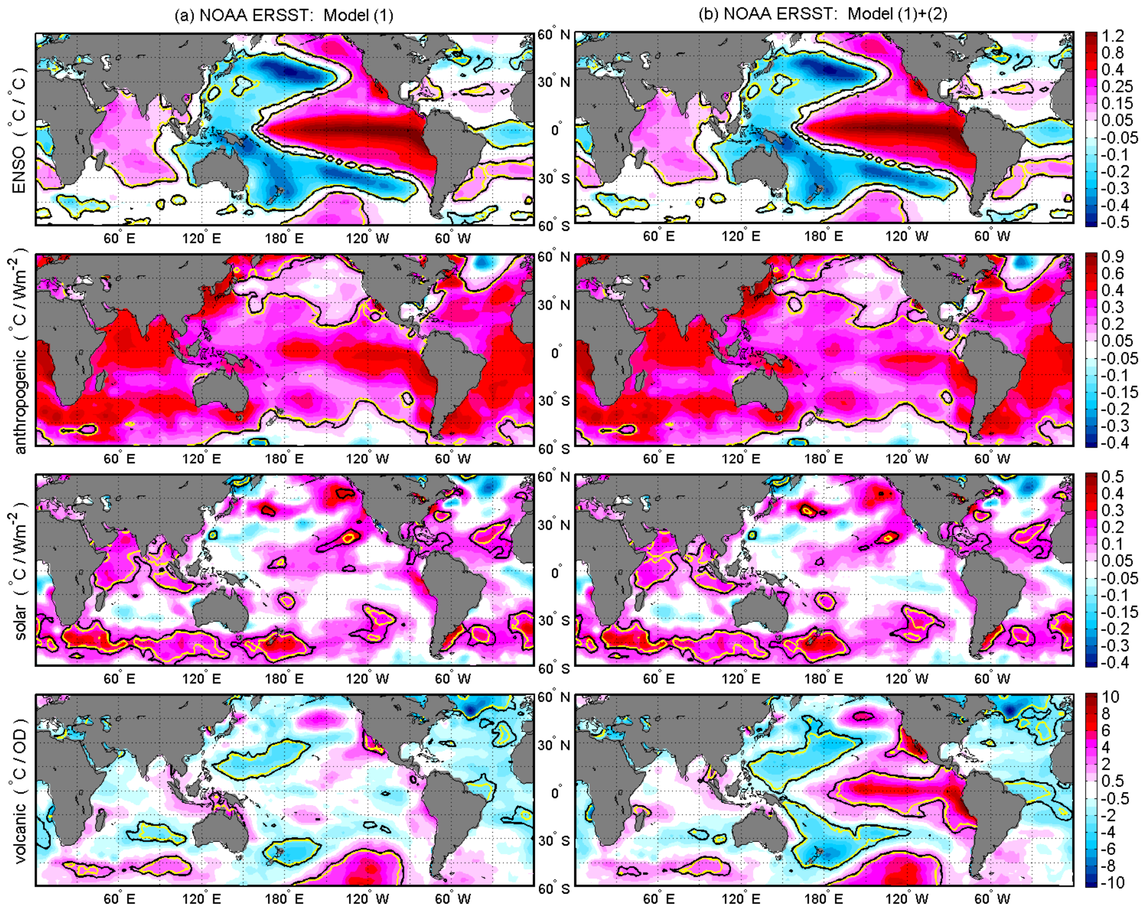
Figure 2. Same as Figure 1, except obtained using HadISST data.

Figure 3. Seasonal anthropogenic responses from model (1)+(2), using ERSST data (left panels) and HadISST data (right panel) for (1882-2008). Monthly data for SST and the indices were used in the multiple regression except that the anthropogenic forcing *G* was only available in annual mean. Monthly data are not available before 1882 for the TSI.

Figure 4. Same as Figure 3, but for the solar response.

Figure 5. Same as Figure 3, but for the volcano response.

Figure 6. Durbin-Watson test on the residual in the original data (left panel), which is shown to be positively auto-correlated (PAC), and after one stage prewhitening (right panel), which then becomes neither positively autocorrelated nor negatively autocorrelated (NAC). ERSST data are used in the top panels, and HadISST in the lower panels.



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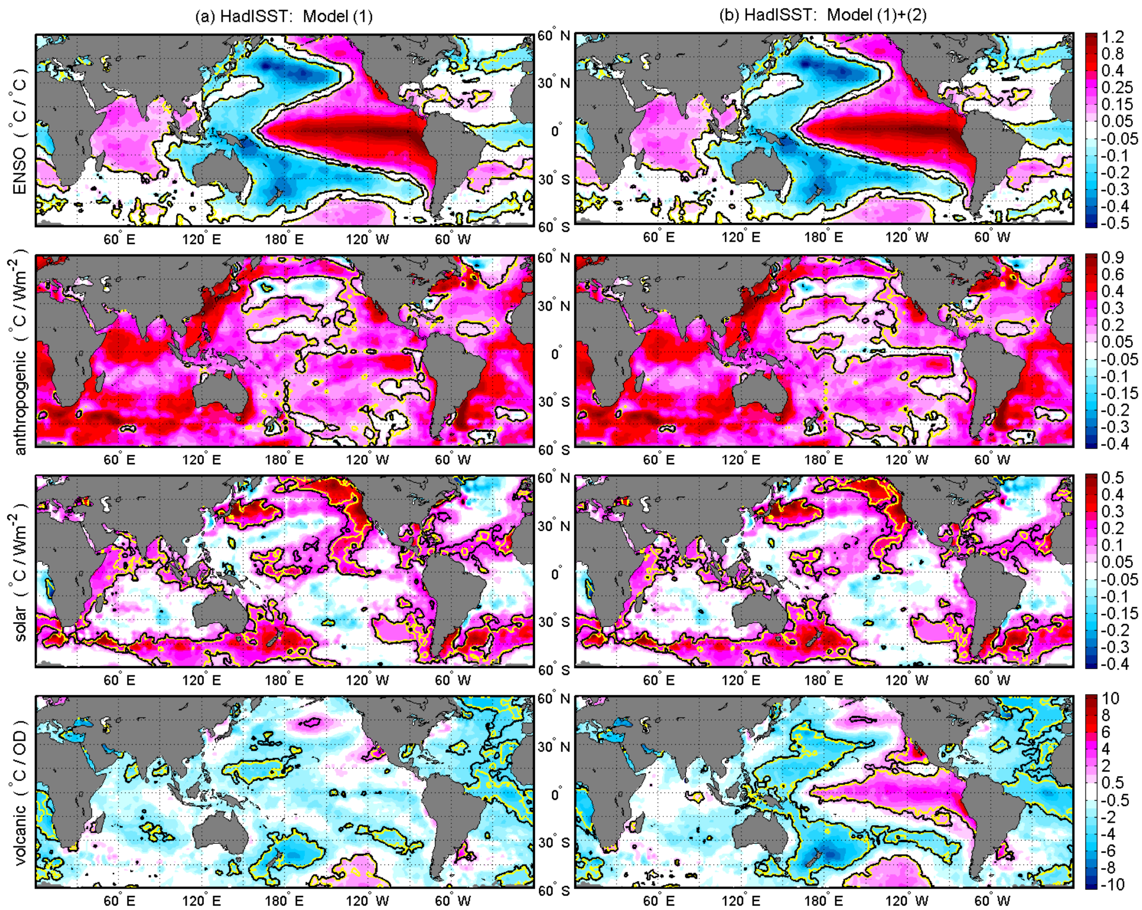

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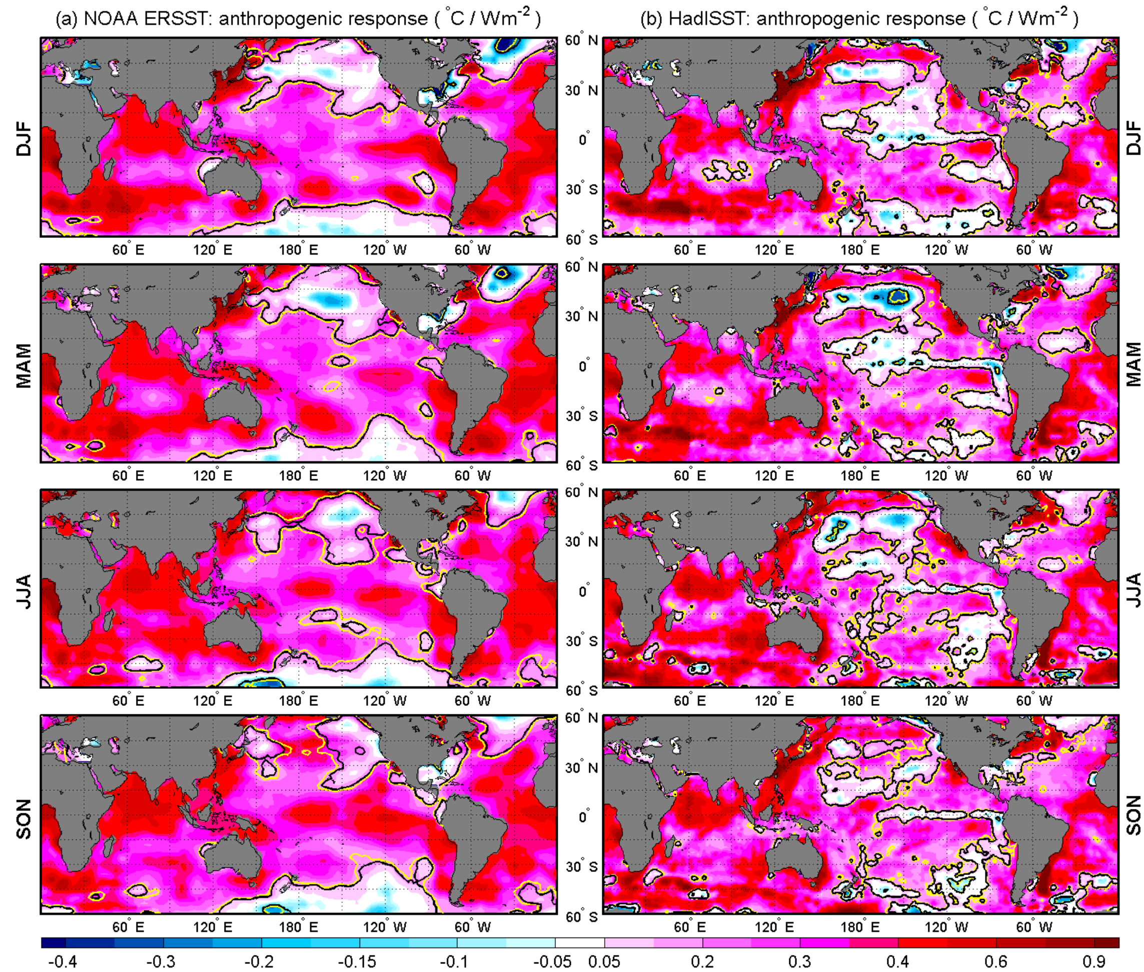

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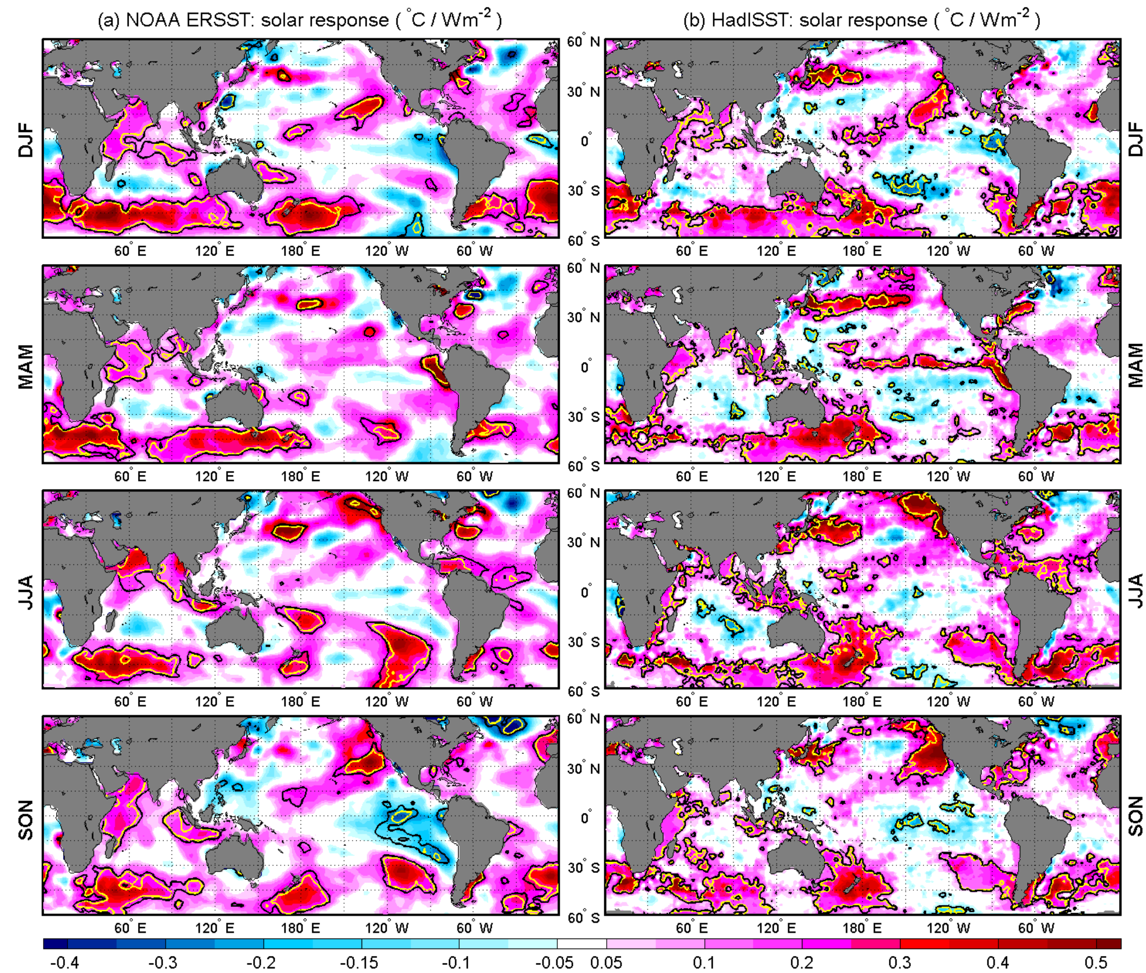

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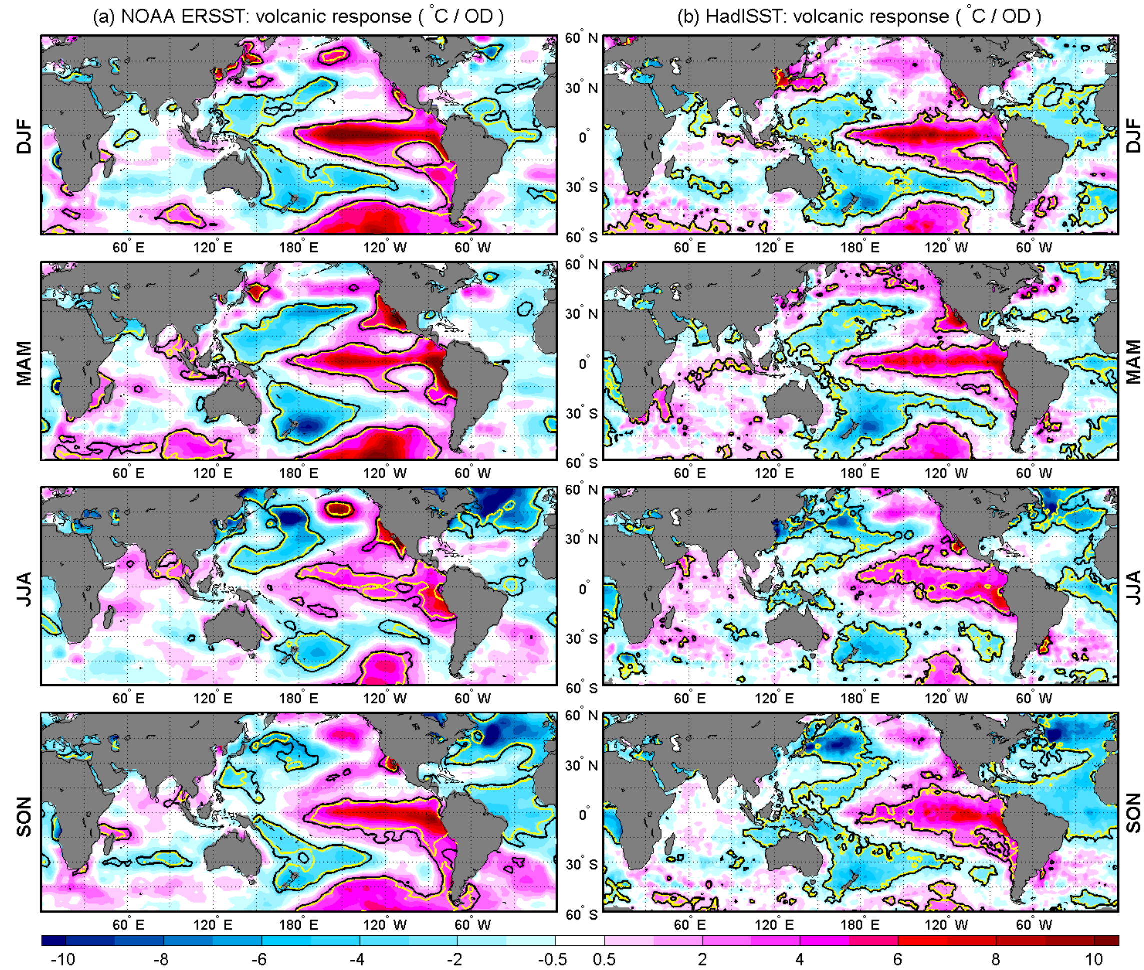

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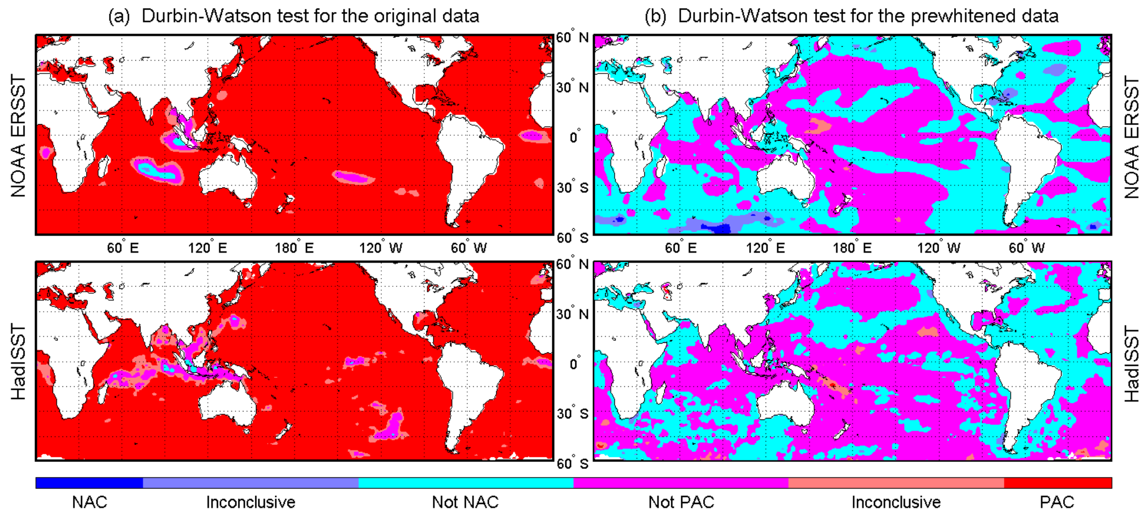

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