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Supporting Online Material for

Amplifying the Pacific Climate System Response to a Small 11-Year Solar Cycle Forcing

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This PDF file includes:

Materials and Methods
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Supporting online material

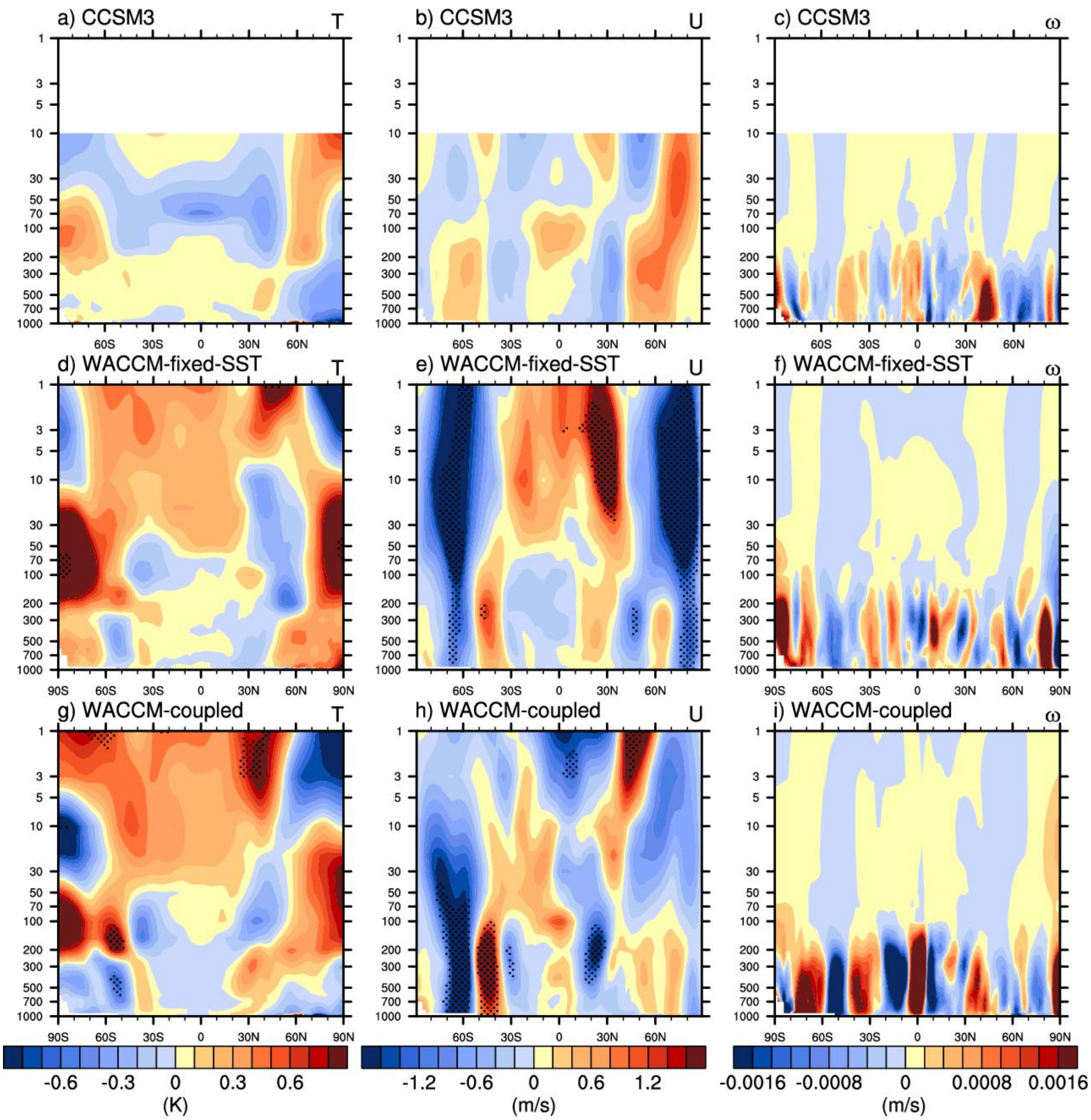

Fig. S1: a) Global zonal mean temperature anomalies (°C) for December composites of peak solar years from the CCSM3, b) same as (a) except for zonal wind (m sec^{-1}); c) same as (a) except for omega (negative signs denote upward vertical velocity anomalies); d) same as (a) except for WACCM run with fixed SSTs; e) same as (d) except for zonal wind (m sec^{-1}); f) same as (d) except for omega (negative signs denote upward vertical velocity anomalies); g) same as (a) except for WACCM coupled to the dynamic ocean; h) same as (g) except for zonal wind (m sec^{-1}); i) same as (g) except for omega (negative signs denote upward vertical velocity anomalies).

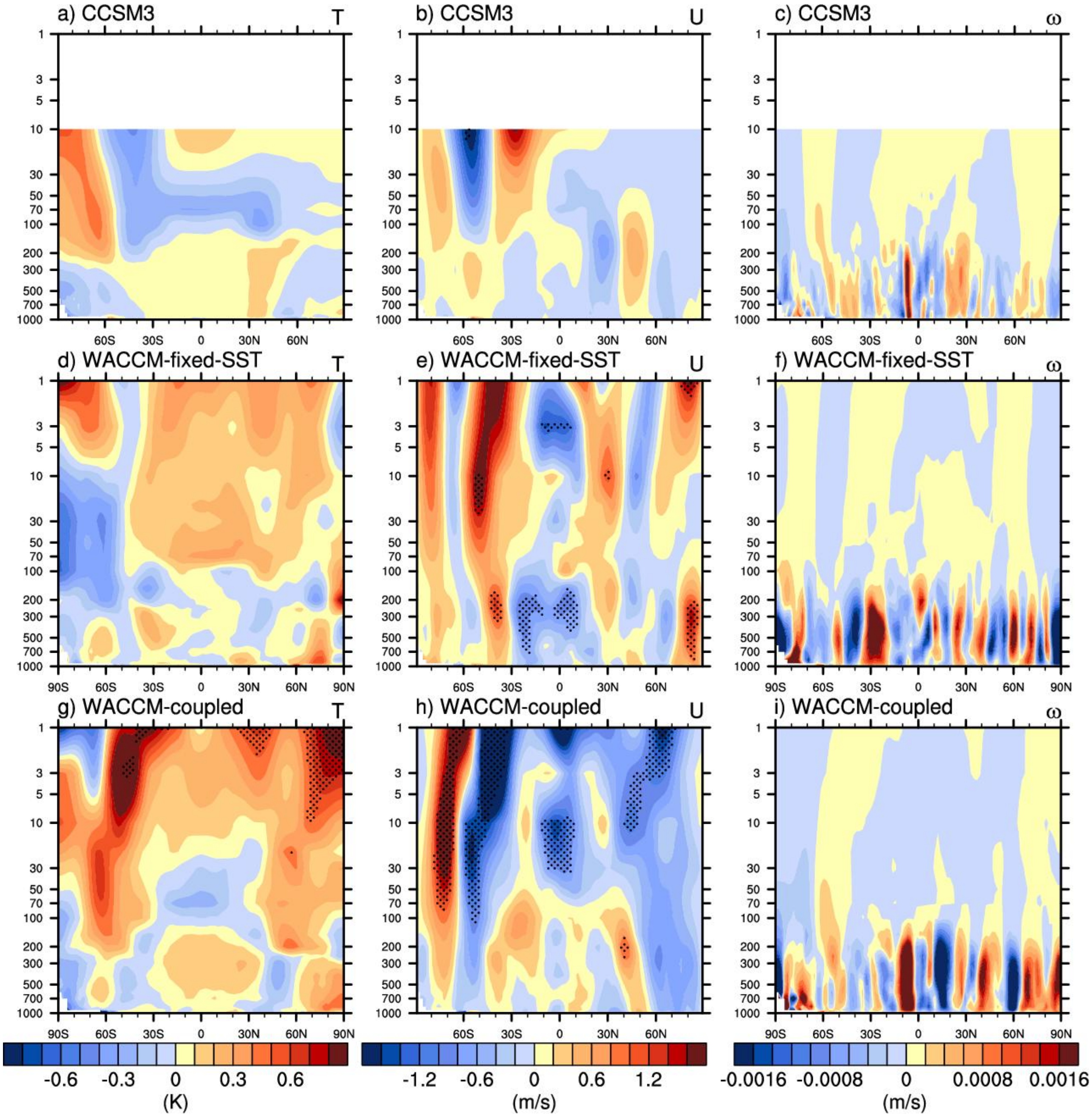

Fig. S2: a) Global zonal mean temperature anomalies (°C) for the June composites following the December composites in Fig. S1 for peak solar years from the CCSM3, b) same as (a) except for zonal wind (m sec^{-1}); c) same as (a) except for omega (negative signs denote upward vertical velocity anomalies); d) same as (a) except for WACCM run with fixed SSTs; e) same as (d) except for zonal wind (m sec^{-1}); f) same as (d) except for omega (negative signs denote upward vertical velocity anomalies); g) same as (a) except for WACCM coupled to the dynamic ocean; h) same as (g) except for zonal wind (m sec^{-1}); i) same as (g) except for omega (negative signs denote upward vertical velocity anomalies).

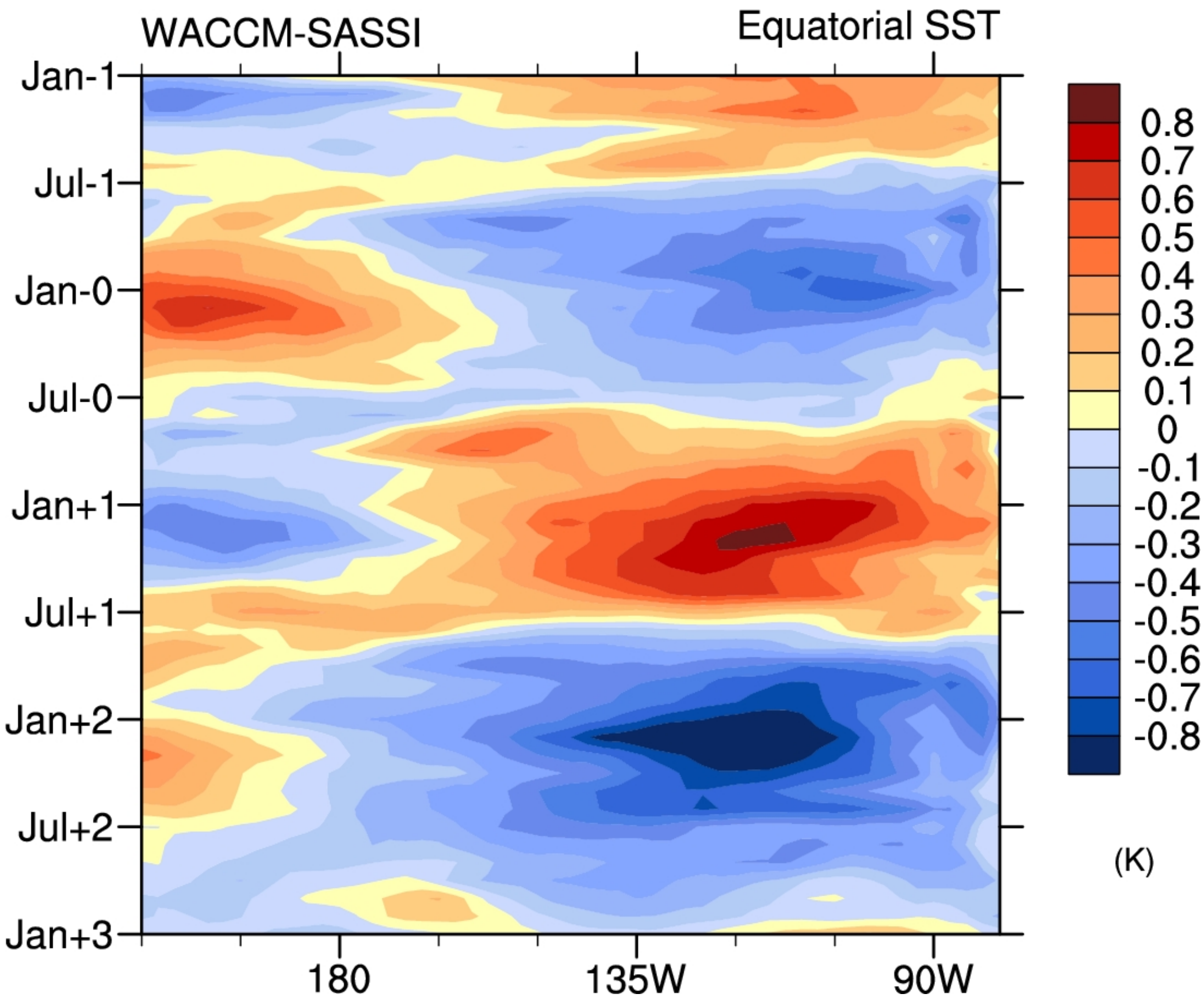

Fig. S3: Time-longitude composite SST (°C) anomaly plot centered at January (Jan0) of peak solar years averaged from about 1°N to 1°S for coupled WACCM showing anomalous negative SSTs during peak solar years in the eastern equatorial Pacific), transitioning to anomalous positive SSTs a year or two later; refer to similar plots for two observational data sets and CCSM3 *(S5).*

Observed data, models, and methods

The observed data used in our study are the NOAA Extended Reconstructed Sea Surface Temperature Version 2 data set from 1854 to 2002, available from http://www.cdc.noaa.gov/cdc/data.noaa.ersst.html with more details given at http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.html *(S1)*. Composites are formed for peak solar years *(S2)* with the January year 0 designated for 11 peak solar years 1883, 1893, 1905, 1917, 1928, 1937, 1947, 1957, 1968, 1979, 1989, relative to a 1854-2002 climatology of years other than peak solar years consistent with the earlier published results *(S2)*. An updated version of this SST data set allows inclusion of the peak solar year 2000, and a composite with 12 peak solar years (including 2000) shows similar results. The global precipitation dataset used here is from the Global Precipitation Climatology Project (GPCP), described at http://cics.umd.edu/GPCP/, and composites are formed for peak solar years 1979, 1989, and 2000 for the January-February season (to be able to include 1979 since the data begin in January, 1979) relative to a 1979-2002 climatology *(S2)*.

Composites are formed picking the peak of the solar cycle after the solar minima (*S2*). Choice of the exact peak year can vary by a year or two since the signal is similar a year or so on either side of the peak and distinct from La Niña events in the Southern Oscillation (*S2*,*S3*,*S4*). The observations and the CCSM3 show that the cold-event-like response gives way to a warm event signal a year or two after the peak solar years (*S5*), and this is the case for the coupled WACCM version (Fig. S3).

The Community Climate System Model version 3 (CCSM3) 20th century simulations analyzed here are from the T85 version of CCSM3, with actively coupled ocean, land and sea ice components (*S6*). The Community Atmospheric Model version 3 (CAM3) is the atmospheric model component (*S6*). Grid points in the atmosphere are spaced roughly every 1.4° latitude and longitude, and there are 26 levels in the vertical with a majority of the levels in the troposphere (model layer midpoints (hPa): 3.5, 7.4, 14.0, 23.9, 37.2, 53.1, 70.1, 85.4, 100.5, 118.3, 139.1, 163.7, 192.5, 226.5, 266.5, 313.5, 368.8, 433.9, 510.5, 600.5, 696.8, 787.7, 867.2, 929.6, 970.6, 992.6). The ocean is a version of the Parallel Ocean Program (POP) with a nominal latitude-longitude resolution of 1° (1/2° Eq. Tropics) and 40 levels in the vertical. Stratospheric ozone depletion in the latter part of the 20th century is prescribed, but no impact of the solar cycle on stratospheric ozone is included. No flux adjustments are used in the CCSM3.

A five member ensemble of CCSM3 20th century simulations is analyzed here. The 20th century simulations were started from different times in the 1870 control run separated by 20 years with the first ensemble member branching from the control run at year 360 and are run with natural and anthropogenic forcings (*S7*). The solar forcing in CCSM3 is a total solar irradiance (TSI) reconstruction that includes the 11 year solar cycle (*S8*). Composites are formed for the same peak solar years as in the observations and compared to a long term model climatology from the 20th century simulations as in previous published work *(S5)*.

The version of WACCM with specified climatological SSTs is run for 110 years with ten repeating climatological 11 year solar cycles. The WACCM version that is coupled to the same ocean, land and sea ice components as CCSM3 is run for 120 years with eleven repeating 11 year solar cycles. This version of WACCM has a slightly modified convection scheme that produces a change in ENSO frequency (*S9*), though this change is not thought to substantively alter the response of the coupled dynamics in the tropical Pacific to solar variability. WACCM has 1.9° latitude by 2.5° longitude resolution and 66 vertical levels from the ground to $4.5X10^{-5}$ hPa (approximately 145 km geometric altitude with a hybrid terrain-following coordinate which becomes purely isobaric above approximately 80 hPa (*S10*)). The vertical resolution is variable, with 3.5 km above 65 km, 1.75 km around the stratopause (50km), and 1.1 to 1.4 km in the lower stratosphere (below 30 km) and at most levels in the troposphere. Spectral solar irradiance is specified over a range of wavelengths, and the model incorporates fully interactive photochemistry and ionospheric processes *(S10,S11*).

The present results are complementary to earlier work (*S12*), in that both argue that the 11 year solar cycle stimulates ENSO-like variability through dynamically coupled feedbacks. The present paper uses un-filtered data and shows only the first several years after peak solar. Using filtered data, by nature extending through more than one solar cycle, earlier work showed stimulation of the third and fifth odd harmonics (*S12*). The frequency response in un-filtered data clearly shows the different timescales of the response in control runs from the different models (*Fig. 1 in S5*). That is, there is a difference among models and observations for how quickly the eastern equatorial Pacific transitions from a La Niña-like response to an El Niño-like pattern a couple of years later (*S5*). Band pass filtering at those frequencies brings out the inherent timescales of ENSO, and that supports the results of the present paper and earlier work (*S12*). However, there could be other processes at work to determine biennial versus somewhat longer term variability in the Pacific due to influences from Indian monsoon sector (*S13*). Because there are low frequency changes involving biennial versus less biennial nature of ENSO variability in the tropical Pacific (*S14*), there are larger issues involved with lags beyond several years of solar forcing which are beyond the scope of the present paper and earlier work (*S12*). Additionally, joint MTM/SVD spectra for Nino3.4 from a long control run from CCSM3, and from an ensemble mean of 20th century simulations that include the 11 year solar cycle forcing (*Fig. 9 in S5)* show significant peaks near 2.2, 2.4, and 2.9 years in the unforced control run indicating the preference of this model to internally generate ENSO variability at those frequencies, with no significant peaks near 11 years as could be expected since there is no solar forcing in the control run. However, in the forced 20th century runs, there are still significant peaks near 2.3-2.4, 2.6 and 2.8 years (consistent with this model's internally generated variability), no enhanced variability near 3.6 years, but significantly increased variability near 11 years. Thus, the solar forced signal comes out in the forced run, but there is no indication of stimulation of the 3.6 year odd harmonic in this model *(S5)*. This is likely consistent with what was documented earlier (*S12*) in that wave packet responses to 11-yr solar forcing in a coupled climate model and a conceptual model are similar. However, the response to ambient noise in the conceptual model yields a weak response to 11 year solar forcing but no higher odd harmonics, while in the coupled climate model it yields no 11 year response but weak higher odd harmonics. Thus higher odd harmonics in the observations may be self-excited or driven by ambient noise but intensified by, and synchronized to, the 11 year solar forcing (*S12*), consistent with earlier results (*S5*) and the present paper that includes additional model versions that include the top-down stratospheric ozone mechanism.

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