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Coupled air-sea response to solar forcing in the Pacific region during northern winter

Harry van Loon,[1,2] Gerald A. Meehl,[3] and Dennis J. Shea[3]

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[1] Observations since the middle of the 19th century show that the decadal solar oscillation at its peaks strengthens the major convergence zones in the tropical Pacific (Intertropical Convergence Zone, ITCZ, and South Pacific Convergence Zone, SPCZ) during northern winter. Through an amplifying set of coupled feedbacks, a set of processes is described that link solar forcing and its response in the tropical Pacific with reductions in precipitation in the northwest United States. The process begins with an increase in solar forcing which results in a strengthening of the major convergence zones in the tropical Pacific. This then increases the precipitation in those regions and increases the southeast trade winds. Stronger trades increase the upwelling of colder water in the eastern equatorial Pacific and extend the cold tongue westward, thus reducing precipitation in the western Pacific. This redistribution of diabatic heating and associated convective heating anomalies thus produces anomalies in the tropical Hadley (north-south) and Walker (east-west) circulations. The former weakens as subsidence in equatorial latitudes is enhanced; the latter strengthens and extends westward. Additionally, the resulting anomalous Rossby wave response in the atmosphere, and consequent positive sea level pressure anomalies in the eastern region of the Aleutian low in the North Pacific that extends to western North America, is associated with reductions of precipitation in the northwest United States. The response of the climate system to solar forcing is manifested as a strengthening of the climatological precipitation maxima in the tropics.

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1. Introduction

[2] One of the long-standing problems in climate science is the effect on the earth's climate system of the small amplitude variations in the approximately 11-year solar cycle (also termed the decadal solar oscillation) [*Haigh*, 2001; *Lean and Rind*, 2001; *Rind*, 2002; *Lean*, 2005]. Recent analyses of observations have shown that, in addition to the influence of the decadal solar oscillation in the stratosphere [*van Loon and Labitzke*, 2000], it is evident that the troposphere [*van Loon and Labitzke*, 1998; *van Loon and Shea*, 1999, 2000; *Douglass and Clader*, 2002; *Gleisner and Theijll*, 2003; *Haigh*, 2003; *van Loon et al.*, 2004; *Tourpali et al.*, 2005; *Crooks and Gray*, 2005; *Wang et al.*, 2005; *Gleisner et al.*, 2005] and ocean [*White et al.*, 1997, 1998; *Bond et al.*, 2001; *Weng*, 2005] are also affected by the oscillation. A solar effect in the tropics and subtropics of the troposphere was noted in radiosonde station data with a positive correlation between solar forcing and stratospheric temperature, little or negative correlation at the tropopause, and positive correlations in the troposphere [*van Loon and Labitzke*, 1993, 1994]. Furthermore, it was shown that in northern summer the difference between solar maxima and minima in the tropical rainfall over the eastern Indian and western Pacific Oceans was positive in the eastern, and negative in the western parts of the region, consistent with differences in vertical motion and outgoing longwave radiation, and suggesting a solar influence on the Hadley and Walker circulation cells, the major large-scale north-south (Hadley) and east-west (Walker) atmospheric circulations in the tropics [*van Loon et al.*, 2004]. Attempts to model the solar influence on climate have yielded some measure of success [e.g., *Meehl et al.*, 2003, 2004; *Cubasch et al.*, 2006]. However, it could be argued, as it has been in the past, that these associations are coincidental, and that without mechanisms to account for them, they could be accidental.

[3] In the past few years mechanisms have been suggested by modeling studies that could explain some of these linkages. One involves variations in stratospheric ozone in response to solar ultraviolet (UV) variability, such that changes in the vertical and horizontal temperature structure result in dynamical responses in the stratosphere and troposphere [*Haigh*, 1996; *Balachandran et al.*, 1999; *Shindell et al.*, 1999]. This type of communication of forcing from the stratosphere downward to the troposphere

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[1] Colorado Research Associates, NorthWest Research Associates, Inc., Boulder, Colorado, USA.

[2] Also at National Center for Atmospheric Research, Boulder, Colorado, USA.

[3] National Center for Atmospheric Research, Boulder, Colorado, USA.

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was also posed by *Hameed and Lee* [2005]. Another mechanism from a modeling study relates to air-sea-radiative coupling at the surface in the tropics whereby the spatial asymmetries of solar forcing, induced by cloud distributions, result in greater evaporation in the subtropics and consequent moisture transport into the tropical convergence zones, thus producing higher precipitation through dynamically coupled ocean-atmosphere interaction (*Meehl et al.* [2003, Figure 8] show the cold event–like response for the DJF season to increased solar forcing in the context of the physical mechanism described here).

[4] These two mechanisms are not mutually exclusive and suggest that both could be acting together to enhance the response. Thus, consistent with the earlier observational results, there could be an intensification of the tropical climatological precipitation maxima during peaks in the solar cycle, and this should be evident in the observational record. The latter mechanism above indicates that the strengthening of the trade winds and the convergence zones would lead to a set of amplifying coupled feedbacks and conditions that could resemble a cold event (sometimes referred to as La Niña; the two terms refer to the same phenomenon) in the Southern Oscillation, with lower sea surface temperatures (SSTs) in the equatorial Pacific. The consequent convective heating anomalies associated with the precipitation changes in the western equatorial Pacific would then produce cold event–like teleconnections over the North Pacific at the solar peaks. Such a set of anomalies was seen in the global coupled climate model mentioned above so that, for an increase in solar forcing from early to mid 20th century, there was a cold event–like pattern in the Pacific [*Meehl et al.*, 2003]. Here we look in observations for such influences of the decadal solar oscillation during the past 150 years, and report on the results in northern winter over the Pacific Ocean. A previous paper has documented these similar processes for northern summer involving a strengthening of the climatological monsoon precipitation regimes [*van Loon et al.*, 2004], as also noted subsequently by *Bhattacharyya and Narasimha* [2005].

[5] In the results to follow, we denote statistical significance from a t test and some areas are significant by that measure indicating the relative size of the anomalies compared to the noise. Though the signals are relatively small compared to warm and cold event anomalies (about half to two thirds the size), the physical consistency of the response across independent variables from different data sets supports the hypothesis that the climate system response to solar forcing is indeed an enhancement of the climatological precipitation maxima in the tropics documented here for northern winter, and by *van Loon et al.* [2004] for northern summer.

[6] The data we have used are the reanalyses by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), sea surface temperature and sea level pressure data sets from the Hadley Centre in the UK, and the Global Precipitation Climatology Project (GPCP) precipitation data. They can be obtained in websites from the Climate Diagnostics Center, NOAA, established and maintained by Ms. C. Smith. The sea level pressures (SLP) from the Hadley Centre are available from 1871 to 1998. We use these data instead of other reconstructions because they cover land as well as sea. Solar cycle data are available from ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/MONTHLY. The global precipitation data set used here is the Global Precipitation Climatology Project (GPCP) described at http://cics.umd.edu/GPCP/. The gridded land precipitation data set is the Hulme Monthly Precipitation from the Climatic Research Unit (CRU), available from http://www.cru.uea.ac.uk/~mikeh/datasets/global/.

2. Features at the Surface

[7] During the period of available SLP data, there were 11 peak years in the decadal solar oscillation: 1883, 1893, 1905, 1917, 1928, 1937, 1947, 1957, 1968, 1979, and 1989. We use the peak years because these years show the strongest signal. The years immediately prior to and following the peak years also show similar signals but of smaller magnitude (not shown). The fact that the peak years of solar forcing show the largest signals indicates that the coupled processes responsible for these signals operate on the timescale of less than 1 year, consistent with the concept discussed below that these coupled processes are similar to those that produce cold events in the Southern Oscillation with timescales on the order of months.

[8] The composite SLP anomalies (solar peak year composites minus mean climatology for the period 1950–1979) for these 11 years, for the months of December-February (the year being January: 1883, 1893, etc., Figure 1a) show positive anomalies just south of the equator, which results in anomalously strong SE-trade winds across the equator (not shown), because small changes in gradient so close to the equator produce large change in wind. There are negative SLP anomalies stretching from 35°N eastward toward North America, and positive, statistically significant (greater than 95% confidence) anomalies over the eastern half of the domain of the Aleutian low in the Gulf of Alaska.

[9] Though the largest anomalies in this pattern are statistically significant by a Student t-test indicating the anomalies are large compared to the noise, perhaps more important is that the pattern is physically consistent with the coupled anomalies in the tropical Pacific, as will be shown below for SST and precipitation. Additionally, if this is a robust anomaly pattern it should also appear if we subdivide the SLP data set into shorter subperiods. Indeed, by dividing the set of solar peak years in half, the anomalies from the two subperiods (Figures 1b and 1c) show similar patterns, which resemble that observed during cold events [*van Loon and Madden*, 1981]. Since there could be the chance that cold events are driving this signal, we note that in the 11 solar peak years considered, there was only one cold event (1989) and one warm event (1905) (year zero, the year of the development of the event [*Kiladis and Diaz*, 1989]). If either is removed, the pattern remains the same (not shown). Therefore this pattern is not associated with extremes in the Southern Oscillation, but likely is the response to solar forcing.

[10] The SLP and surface wind anomalies (i.e., stronger trade winds across the equatorial Pacific) during peaks in the decadal solar oscillation are associated with negative SST anomalies in the central and eastern equatorial Pacific that also resemble those during years zero in cold events (Figure 2a). The solar effect is thus an enhancement of the

climatological SST pattern in the tropical Pacific since the SE trades normally blow across the equator and cause upwelling of cool water in the region. With stronger trades there is enhanced upwelling in the equatorial Pacific.

[11] SST anomalies separately from three more solar peaks (1860, 1870, and 2000, not covered by the period of the Hadley SLP data, none of these are cold events in the Southern Oscillation, Figure 2b), show that the cold event-like pattern is the same as for solar peaks from the other period (Figure 2a). This attests to the robustness of the tropical Pacific response to the solar signal in the peaks of the decadal solar cycle.

[12] Gridded precipitation data for the globe are available after 1978. Considering the consistency of the solar signal in both sea level pressure and sea surface temperature for different time periods, it is possible to use the post-1978 data to show the mechanism behind the solar signal, representative not only of the solar peaks since 1979 but of the other peaks as well [*van Loon et al.*, 2004]. The mean tropical rainfall anomalies in the 3 solar peak years 1979, 1989, and 2000 (Figure 3a) are negative in the equatorial belt and positive in the convergence zones on either side of it. As is observed during cold events, there is an expansion of the equatorial cold tongue such that the positive precipitation anomalies in the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ) to the north and southwest, respectively, are shifted somewhat farther away from the equator. However, the main climatological structures of the ITCZ and SPCZ are enhanced with greater solar forcing. Therefore, taken together with the SST anomalies (Figure 2), this shows that there is essentially an enhancement of the climatological average circulation, with above-normal precipitation in the mean convergence zones over the ocean (the ITCZ north of the equator and the SPCZ in the tropical southwest Pacific) and with lower than normal SSTs in the equatorial cold tongue extending farther west, leaving the dry zone in that region drier than normal. The anomalies of the precipitation rate from the reanalysis data from a longer time period (including December-January-February for 5 solar peak years, Figure 3b) and anomalies from a different gridded precipitation data set (Figure 3c) have a similar pattern.

[13] Such a pattern of precipitation anomalies, particularly the negative precipitation anomalies in the equatorial western Pacific, produces negative convective heating anomalies there and positive SLP anomalies in the far North Pacific (Figure 1) through anomalous atmospheric Rossby wave response [*Branstator and Haupt*, 1998]. Thus a physically consistent picture emerges, connecting the response to the solar peaks with the mechanism that involves coupled anomalies of lower equatorial Pacific SSTs, stronger trades, greater precipitation in the tropical convergence zones, and positive SLP anomalies in the North Pacific extending over North America.

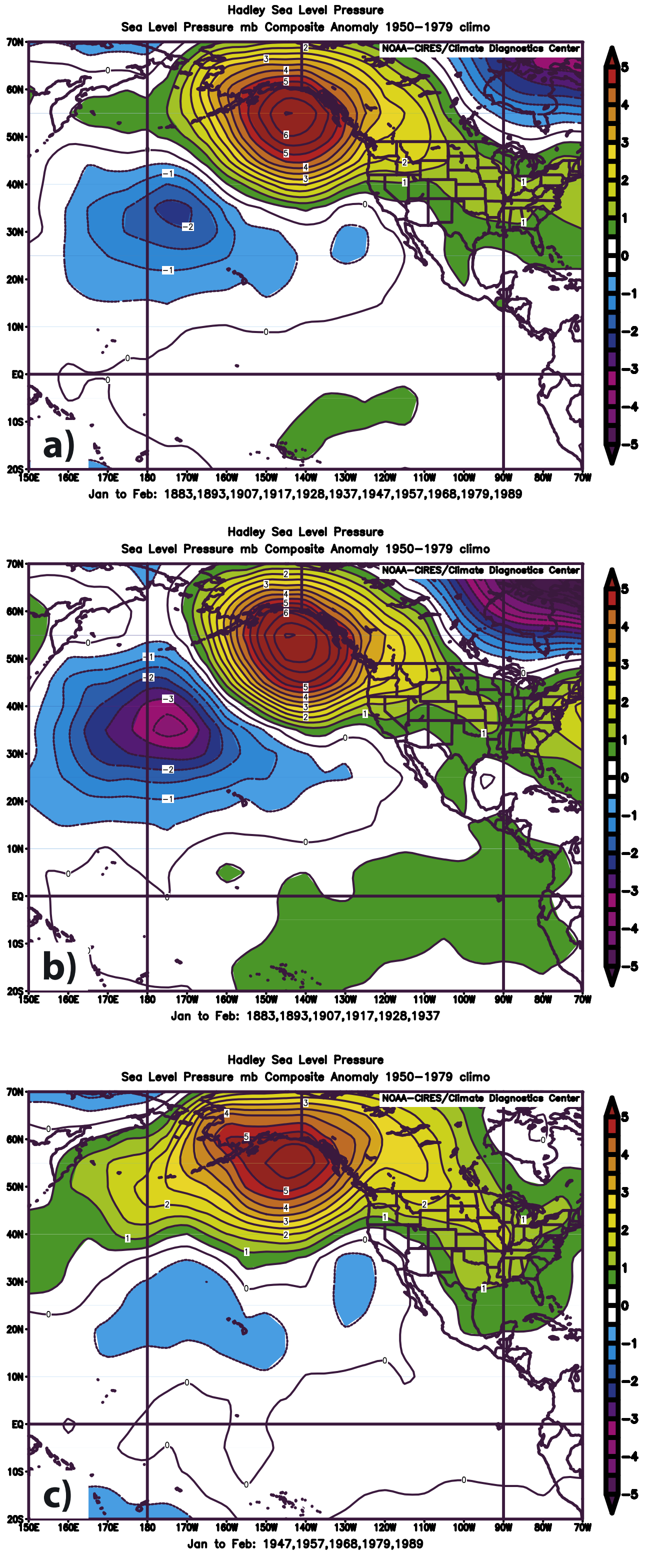

Figure 1. (a) Average anomalies of sea level pressure in 11 solar peak years: 1883, 1893, 1905, 1917, 1928, 1937, 1947, 1957, 1968, 1979, and 1989 (hPa), January–February season averages computed relative to a 1950–1979 base period. Differences greater than about 2 hPa are significant at the 95% level, indicating the relative magnitude of the anomalies compared to the noise. (b) Same as Figure 1a except for the first 6 peak years, 1883, 1893, 1905, 1917, 1928, and 1937 (hPa), January–February season averages. (c) Same as Figure 1a except for the second 5 peak years, 1947, 1957, 1968, 1979, and 1989 (hPa), January–February season averages. Splitting the record into two parts shows the consistency of the anomalies in different time periods.

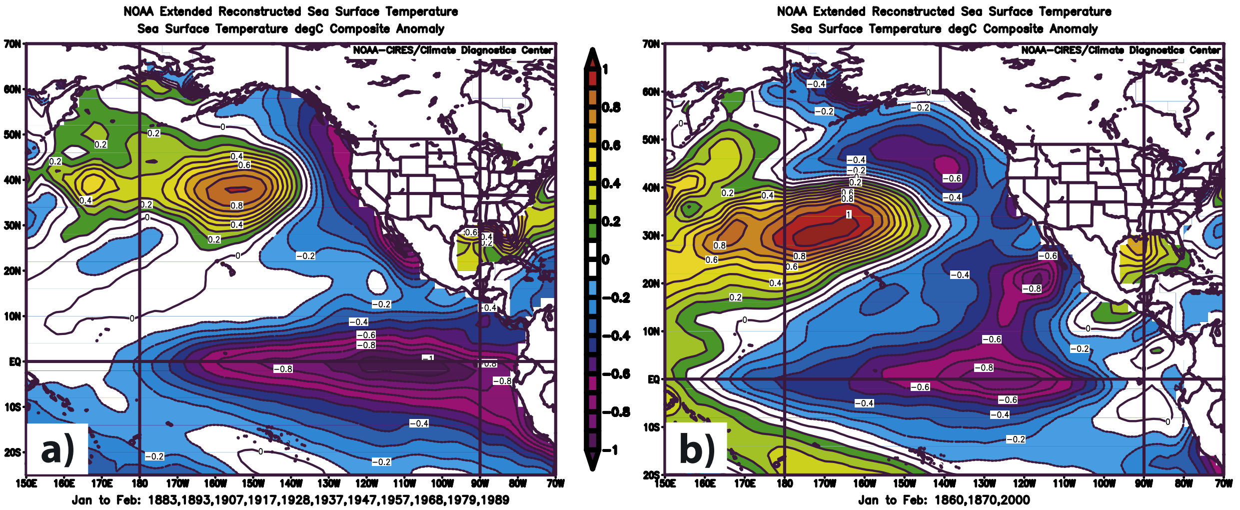

Figure 2. (a) Average anomalies of sea surface temperature in the 11 solar peak years in Figure 1 (°C) from the Hadley SST data set, January–February season averages using the NOAA Extended Reconstructed Sea Surface Temperature data set, available from http://www.cdc.noaa.gov/cdc/data.noaa.ersst.html with more details given at http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.html. Areas of magnitude greater than −0.5°C are generally significant at and above the 95% level, indicating the relative magnitude of the anomalies compared to the noise. (b) Same as in Figure 2a except for January–February averages for additional solar peaks not included in Figure 2a for the years 1860, 1870, and 2000.

[14] The positive SLP anomalies over the northwestern United States (Figure 1) are associated with decreases in precipitation in that region in the 9 solar peak years from 1900 to 1998 covered by the Hulme Monthly Precipitation from the Climatic Research Unit (Figure 4). Negative precipitation anomalies cover areas of the western United States, with significant decreases of about 1 mm d^{-1} (roughly 30% to 50% of the seasonal mean values) over much of northern California, Oregon, and Washington. Data from weather stations with longer records than in the gridded precipitation data set in the northwest United States (in the regions of the largest precipitation reductions from solar forcing, Figure 4), are consistent with this pattern. San Francisco and Sacramento have data from the mid-1850s to 2003 that include 14 peak solar years. Both show significant decreases of winter precipitation of 0.7 and 1.0 mm d^{-1}, respectively (long term means are 1.2 and 1.5 mm d^{-1}, so the anomalies amount to 58% and 67% decreases, which are significant at greater than the 98% level). Another station with a long record from that region, Portland (starting in 1871, yielding 12 solar peak years), shows a decrease of 0.8 mm d^{-1} (a 28% decrease, which is significant at greater than the 90% level). Again, these decreases of precipitation, though statistically significant by the Student t-test, become compelling in the context of the physically consistent processes reaching to the midlatitudes from the coupled anomalies in the tropical Pacific due to peaks in solar forcing.

3. Tropospheric Circulation Features

[15] The climatological ITCZ north of the equator and the SPCZ south of the equator are part of the tropical vertical circulation motions in the large-scale east-west Walker circulation, and the north-south Hadley circulation. For dynamical consistency, the rainfall anomalies in the solar peaks must therefore be associated with comparable vertical motion anomalies in these circulation cells.

[16] The mean Walker circulation in the northern winter along the equator in the Pacific has rising air (negative values) west of about 150°W, especially over Indonesia, and sinking air to the east (Figure 5a). In the solar peaks, the anomalies of vertical motion are such that the upward motion is suppressed over the whole equatorial Pacific region, especially in the west (Figure 5b). Similarly, in the meridional or Hadley circulation between about 30°S and 20°N, climatological mean rising motion occurs north of the equator in the ITCZ and south of the equator in the SPCZ (Figure 6a). For peak solar years, anomalous sinking motion predominates in the equatorial belt, and to its north and south there is anomalous upward motion indicative of a poleward-shifted and intensified ITCZ and SPCZ (Figure 6b) consistent with the results noted above for precipitation. Thus this evidence from a data set independent from the precipitation data shows physical consistency in the response to the decadal peaks in solar oscillation, with areas of enhanced vertical motion and positive precipitation anomalies in the convergence zones of the ITCZ and SPCZ, and suppressed vertical motion where there are negative precipitation and SST anomalies in the equatorial Pacific cold tongue/dry zone. Though *Gleisner and Theijll* [2003] use annually averaged data, their Figure 2 shows a similar relationship with omega in the Pacific and solar forcing.

4. Discussion and Conclusions

[17] There are cold events in the Southern Oscillation in years other than in solar peaks, so they are not necessarily always forced by the sun. However, one can conclude that in the year of peak activity of the decadal solar oscillation, a

circulation pattern is preferably forced by the sun, which resembles that of a cold event in the Southern Oscillation. When the sun is not at its peak, the atmosphere is unconstrained so that both warm and cold events can occur. This is consistent with another study that found that the tendency in the period 1727–1983 was marked for warm events in the Southern Oscillation to occur mainly at decreasing solar activity and in minima of the decadal solar oscillation [*Mendoza et al.*, 1991]. We postulate that solar forcing and climate system response are unrestrained during solar

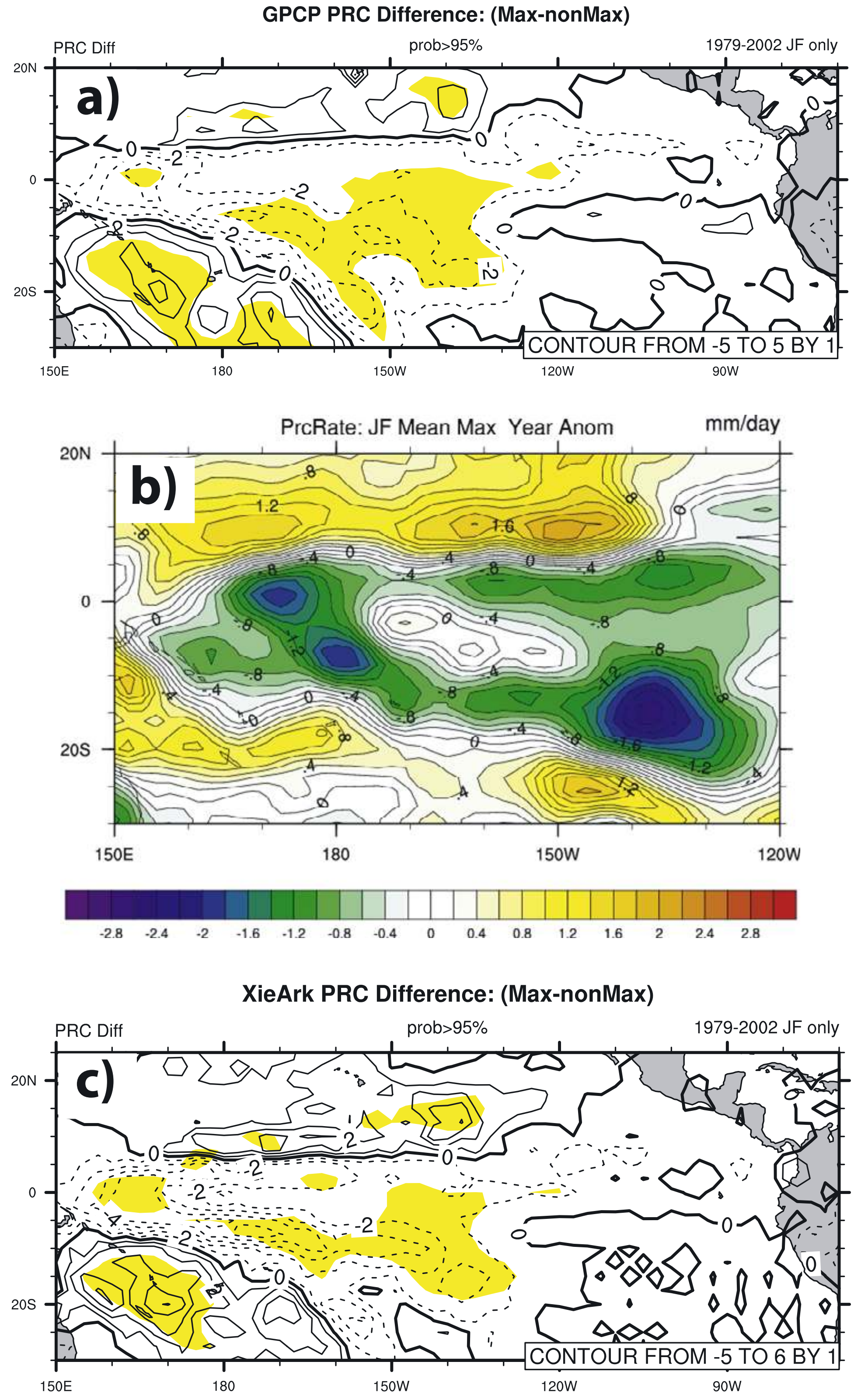

Figure 3

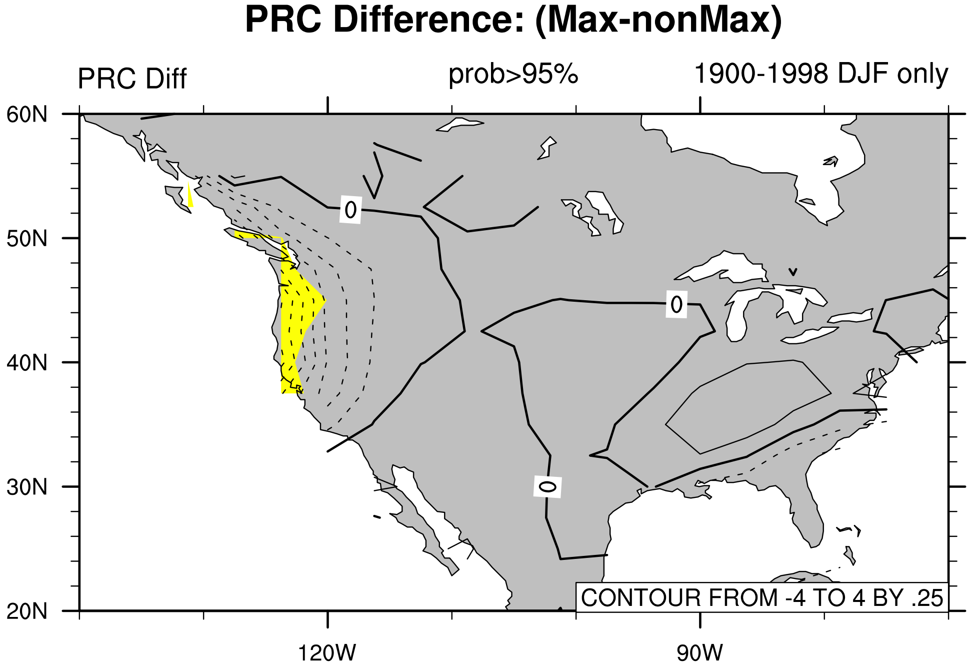

Figure 4. Average rainfall anomalies in the 9 solar peak years of 1905, 1917, 1928, 1937, 1947, 1957, 1968, 1979, and 1989 (mm d^{-1}), December–January–February averages, over the continental United States from a gridded precipitation data set over land areas only (Hulme Monthly Precipitation from the Climatic Research Unit, University of East Anglia). Yellow areas denote significance at and above the 95% level indicating the relative magnitude of the anomalies compared to the noise. Negative values are dashed contours, and positive values are solid. Using only January–February gives a comparable pattern with somewhat larger significance areas.

minima, so warm events are as likely to occur as cold events. However, during solar maxima the system is being forced to increase the odds of the appearance of the cold event–like response, with less chance of warm events to occur.

[18] On the timescale of the last 1000 years, there is evidence that there is a cold event–like pattern during multidecadal periods of high solar forcing [*Mann et al.*, 2005]. Additionally, our results for the sea level pressure (Figure 1) are in agreement with a study that showed the Aleutian low moved westward and the Pacific subtropical high moved northward in solar maxima during the period 1900–1994 [*Christoforou and Hameed*, 1997]. Since there are increased chances of a cold event-like response during peak solar years, there is the possibility that this could be taken into account as a factor in ENSO forecasting (presuming that an accurate forecast of upcoming solar variability could be obtained). Other results show that cold event-like SST anomaly patterns contribute to drought in parts of the United States [e.g., *Cole et al.*, 2002], and a dynamically coupled air-sea tropical-midlatitude mechanism for such relationships has been posed in a modeling study [*Meehl and Hu*, 2006]. However, the exact areas affected, the seasonality, and the timescale of these relationships with regard to solar forcing [e.g., *Cook et al.*, 1997] need to be further investigated.

[19] The current results show that the maximum response of the climate system to solar forcing occurs on the timescale of months (both peak in the same year) suggesting that coupled air-sea interaction in the tropical Pacific have similar amplification mechanisms to cold events that also act on the timescale of months. There have been indications that such a coupled air-sea mechanism is operative in a global coupled climate model [*Meehl et al.*, 2003]. Further analysis indicates these mechanisms act on the timescale of the solar cycle in two global coupled models (G. A. Meehl et al., A coupled air-sea response mechanism to solar forcing in the Pacific region, submitted to *Journal of Climate*, 2006, hereinafter referred to as Meehl et al., submitted manuscript, 2006).

[20] Such studies and the results presented here indicate that the sun at its peaks reinforces the ITCZ and SPCZ,

Figure 3. (a) Average tropical rainfall anomalies in the solar peak years of 1979, 1989, and 2000 (mm d^{-1}), January–February averages from the GPCP gridded precipitation data set in comparison to all other years. Yellow areas denote significance at and above the 95% level, indicating the relative magnitude of the anomalies compared to the noise. Negative values are dashed contours, positive are solid. (b) Average surface precipitation anomalies (mm d^{-1}) from the NCEP/NCAR reanalysis for the solar peak years 1947, 1957, 1968, 1979, 1989, and 2000, January–February season averages, mean anomalies from 1968–1996 climatology (from http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.derived.html#surface_gauss). (c) As in Figure 3a except using the CMAP gridded precipitation data set, the Climate Prediction Center's Merged Analysis of Precipitation (CMAP) (sometimes referred to as the Xie-Arkin data set), described at the NOAA website http://www.cdc.noaa.gov.

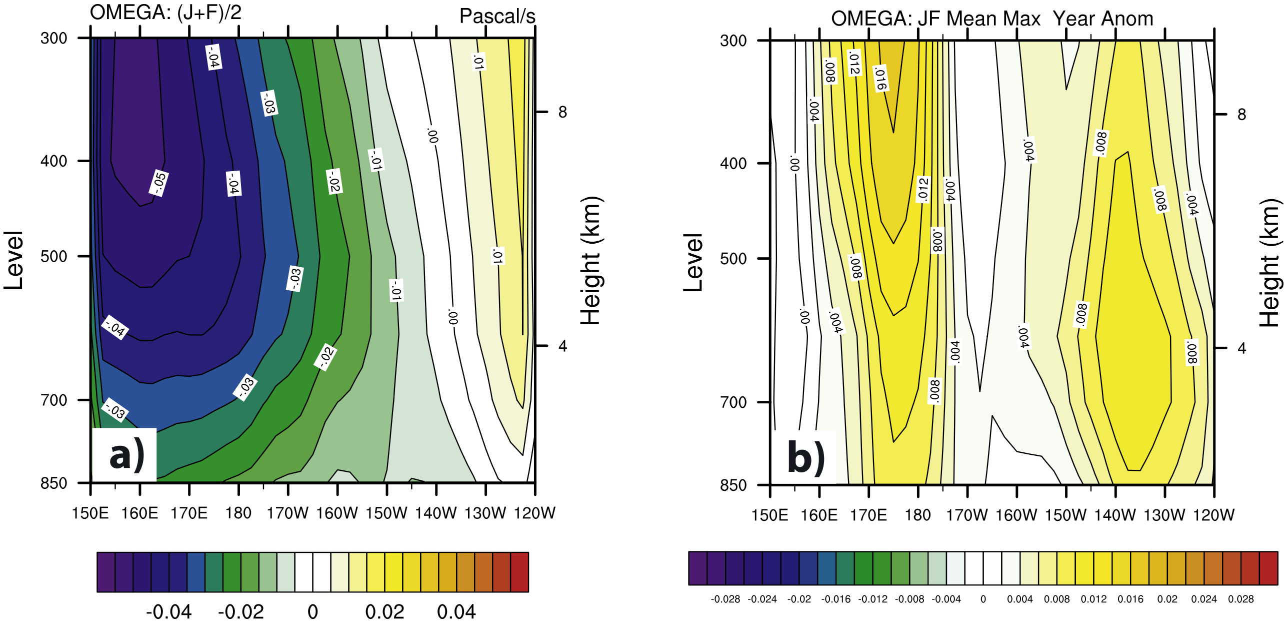

Figure 5. (a) Mean vertical motion (omega) in the eastern part of the Walker Cell in January–February (Pa s^{-1}) between 10°S and 5°N. Negative values denote upward vertical motion.(b) Average anomalous vertical motion (omega) in the Walker Cell in the solar peak years of 1979, 1989, and 2000 (Pa s^{-1}) between 10°S and 5°N, January–February. Negative values denote anomalous upward vertical motion.

enhances the downward motion between the two convergence zones, strengthens the SE trade winds, reduces SSTs in an expanded equatorial Pacific cold tongue that extends farther west, and produces above normal pressure in the North Pacific over the eastern half of the Aleutian low and North America. Similar processes occur to strengthen the climatological monsoon rainfall maxima in northern summer [*van Loon et al.*, 2004]. These sets of coupled interactions amplify a relatively small decadal solar forcing, and produce an enhancement of the mean circulation in the Pacific that is independent of cold events in the Southern Oscillation. A subsequent modeling study (Meehl et al., submitted manuscript, 2006) will show that in certain clear-sky areas in the tropics, the increase of net solar radiation at

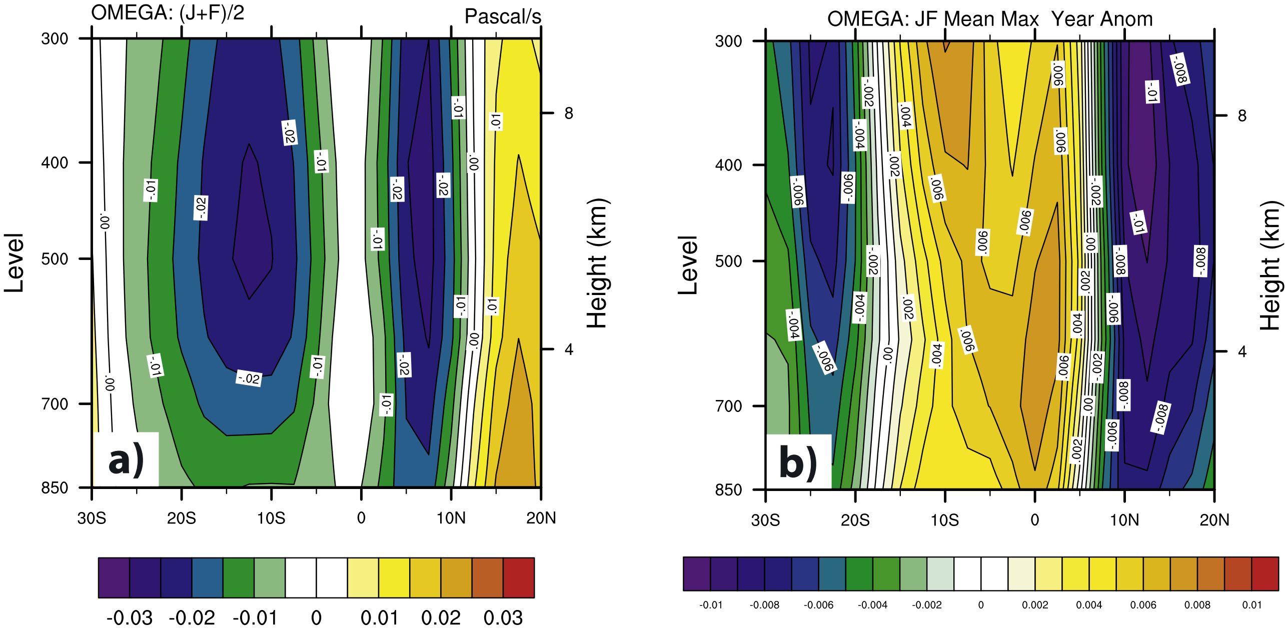

Figure 6. (a) Climatological mean vertical motion (1958–2003) in the Hadley circulation, averaged from 150°E eastward to 100°W (Pa s^{-1}), January–February. Negative values denote upward vertical motion. (b) Same as Figure 6a except for the mean anomalous vertical motion in 1979, 1989, and 2000 in the Hadley circulation.

the surface for solar maximum can be on the order of 1 $\mathrm{Wm^{-2}}$. The amplitude of the solar cycle in total solar irradiance is on the order of 2 $\mathrm{Wm^{-2}}$, which typically is cited as a globally averaged solar forcing at the top of the atmosphere of about 0.2 $\mathrm{Wm^{-2}}$ [*Lean et al.*, 2005]. However, in tropical areas where there are few clouds and the sun is more directly overhead, there can be net surface shortwave fluxes an order of magnitude larger than the globally averaged solar forcing. This then is physically consistent with the mechanisms that link solar forcing to a strengthening of the climatological mean circulation and precipitation features in the tropical Pacific.

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G. A. Meehl and D. J. Shea, National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA. (meehl@ncar.ucar.edu)

H. van Loon, Colorado Research Associates, NorthWest Research Associates, Inc., 3380 Mitchell Lane, Boulder, CO 80301, USA.