The response in the Pacific to the sun’s decadal peaks and contrasts to cold events in the Southern Oscillation

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Abstract

van Loon et al. [2007. Coupled air–sea response to solar forcing in the Pacific region during northern winter. Journal of Geophysical Research 112, D02108, doi:10.1029/2006JD007378] showed that the Pacific Ocean in northern winter is sensitive to the influence of the sun in its decadal peaks. We extend this study by three solar peak years to a total of 14, examine the response in the stratosphere, and contrast the response to solar forcing to that of cold events (CEs) in the Southern Oscillation. The addition of three solar peak years confirms the earlier results. That is, in solar peak years the sea level pressure (SLP) is, on average, above normal in the Gulf of Alaska and south of the equator, stronger southeast trades blow across the Pacific equator and cause increased upwelling and thus anomalously lower sea surface temperatures (SSTs). Since the effect on the Pacific climate system of solar forcing resembles CEs in the Southern Oscillation, we compare the two and note that, even though their patterns appear similar in some ways, they are particularly different in the stratosphere and are thus due to separate processes. That is, in July–August (JA) of the year leading into January–February (JF) of the solar peak years, the Walker cell expands in the Pacific troposphere, and the stratospheric wind anomalies are westerly below 25 hPa and easterly above, whereas this signal in the stratosphere is absent in CEs. Thus the large-scale east–west tropical atmospheric (Walker) circulation is enhanced, though not to the extent that it is in CEs in the Southern Oscillation, and the solar influence thus appears as a strengthening of the climatological mean regional precipitation maxima in the tropical Pacific. Additionally, CEs have a 1-year evolution, while the response to solar peaks extends across 3 years such that the signal in the Pacific SLP of the solar peaks is similar but weaker in the year leading into the peak and in the year after the peak. The concurrent negative SST anomalies develop during the year before the solar peak, and after the peak the anomalies are still present but are waning. In the stratosphere in solar peaks, the equatorial quasi-biennial oscillation (QBO) is amplified when it is in its westerly phase in the lower stratosphere and easterly phase above; and the QBO is suppressed when in its easterly phase below–westerly phase above. Such an association is not evident in CEs.

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1. Introduction

A previous study (van Loon et al., 2007, hereafter referred to as vLMS) described the mean effect over
the Pacific Ocean in northern winter of the decadal solar oscillation (DSO) at its peak. It was noted that there were similarities to a cold event (CE) in the Southern Oscillation. Subsequently, Camp and Tung (2007) also have documented this pattern as a response to peaks in the DSO. Since it could be possible that an apparent response to solar forcing, which has a CE-type response in the troposphere, could indeed just be a CE and not a response to solar forcing, the purpose of this paper is to review the patterns of response in sea level pressure (SLP) and sea surface temperature (SST) in the Pacific in summer and winter, using a longer data record to document how the response to solar forcing differs from CEs, and to show how the effects of solar forcing and CEs are different in the stratosphere.

vLMS showed that the response to peak years of the DSO appears as an enhancement of the climatological mean patterns of SST and precipitation in the Pacific region, including an intensification and poleward displacement of the tropical climatological rainfall regions in the Intertropical Convergence Zone and South Pacific Convergence Zone. A possible coupled radiative-air–sea mechanism that could produce this response was first proposed by Meehl et al. (2003) to explain an apparent CE-like response coincident to vLMS for the observations. Both models showed a CE-like response coincident to peaks in the 11-year solar cycle forcing (Meehl et al., 2008).

As in van Loon et al. (2004), for the northern summer season there is a strengthening of the South Asian monsoon rainfall. Kodera (2004) suggested this monsoon response could also be driven in part from the changes in the stratosphere. However, as discussed above, both the stratosphere and coupled surface responses work in the same direction to produce a similar response and could both be at work.

Solar forcing also affects the stratosphere through the indirect dynamic result of interaction between ultraviolet radiation (UV) and ozone in the upper stratosphere (Balachandran et al., 1999; Shindell et al., 1999). The effects on tropical convection appear to act in the same sense as the surface coupled mechanism of Meehl et al. (2003, 2008), such that the changes in the stratosphere at peaks in solar forcing enhance vertical motion and precipitation, consistent with the climatological precipitation maxima (Lean and Rind, 2001; Haigh, 2003; Kuroda and Kodera, 2002; Rind, 2002; Matthes et al., 2006). Thus, the total atmospheric reaction to solar forcing could be the sum of several processes in the troposphere and stratosphere acting to produce similar responses. The combined effect of these different processes thus likely produces a measurable response as noted in the previous studies cited above. Additionally, the effects in the stratosphere will be shown to be quite different in peak solar years compared to CEs in the Southern Oscillation.

The hypothesis involved with all mechanisms of atmospheric response to solar forcing is that there is a positive reaction, that is, the peaks in solar forcing produce a response in the atmosphere as opposed to the solar minima. Though it could be imagined that perhaps the “normal” state of the system is that in the solar maximum, and solar minima provide the anomalies, composites formed in a similar way to those in vLMS except using solar minima show little coherent signal. This indicates, as argued by vLMS, that it is the peaks in the solar forcing that are producing the response of the climate system, and during minima there is little actual “response” to the lack of solar forcing.

The anomalies are measured against the mean of the years 1968–1996, as done in the re-analyses in the websites from the Climate Diagnostics Center (CDC, NOAA, see Acknowledgements). Forming the reference climatology in different ways (e.g. excluding solar peak years) shows similar results. The SLP and SST and other data are all available in the websites provided by the CDC. The earlier SLP data must rely on spatial reconstructions using the more limited data, but, as will be seen, consistent patterns emerge even with the addition of these more uncertain data.
2. Multi-year aspects of the response to solar forcing

The solar influence on the SLP is seen in Fig. 1a, which is a composite of the SLP anomalies in 14 solar peaks (compared to 11 solar peak years in vLMS), the first one being in 1860 and the last in 2000. The solar signal in Fig. 1a consists of above normal pressure in the Gulf of Alaska and south of the equator; the latter is associated with anomalously larger pressure gradients toward the equator and thus stronger than normal SE trades in the equatorial belt. Fig. 1b, c demonstrates that the anomaly pattern begins to develop in the winter before and lasts, though waning, into the following winter. Thus the response to solar forcing is largest in the peak year in this longer record, but is present in the year before and the year after with smaller magnitude. Though this result was implied in vLMS when they divided the shorter record into sub-parts and saw the same signal, there is a stronger case to be made for including a longer record and still obtaining the same signal. As in vLMS, the SLP anomalies in the North Pacific greater than about 2 hPa are statistically significant. Consistent with vLMS, if one CE year and one warm event year in the composite are not included, a similar pattern emerges (not shown).

With regard to the negative SST anomalies in the composite of the solar peaks along the west coast of North America (Fig. 2a), they are associated with the anomalous northerly component of the wind implied in the positive SLP anomalies in the Gulf of Alaska (Fig. 1a). The positive SST anomalies at 30–40°N relate to the easterly to southerly wind anomalies to the south of the highest SLP anomalies in the Gulf.

As a consequence of the strengthening SE trades, there is larger than normal upwelling of cool water in low latitudes (Fig. 2a; values over about 0.4 °C are significant as in vLMS) and persistent negative SST anomalies the year before and the year after solar peaks (Fig. 2b, c). As suggested in vLMS, this pattern of SLP and SST anomalies is the preferred one in the Pacific Ocean in northern winter at solar peaks, whereas in other years the atmosphere and ocean presumably are not influenced as in the solar peaks, and warm extremes, cold extremes, and neutral conditions can occur without any preference.

A lagged response that resembles a warm event happening 2 or more years after the CE-like response at the solar peak can be found in the filtered data of White et al. (1997). This will be the subject of a subsequent paper.
Figs. 1 and 2 imply that the Walker circulation (the large-scale, tropical zonal and vertical circulation in the atmosphere) and the meridional vertical Hadley circulation are affected by the sun in the solar peaks, as shown in vLMS. In this continuation of vLMS, we extend the analysis of the Walker circulation from its reaction to the solar peaks and to a comparison of this response with that of the cold extremes in the Southern Oscillation in the troposphere and stratosphere.

3. The Walker cell and the QBO in solar peak years

As demonstrated in vLMS, the solar signal is robust and appears in sub-periods of the 150-year sample. Fig. 3, for instance, shows the mean SLP anomalies of the past five solar peaks, and the pattern is the same as the mean for all 14 peaks in Fig. 1a although it is more intense, and this may be related to the fact that these recent peaks were the largest since 1750, or due to better atmosphere and ocean data in recent times, or to both. Since the shape of the solar signal in the DSO peaks since the 1950s is representative of that of the long-term solar signal, the derived data in the NCEP/NCAR re-analyses—available since 1948 in the CDC websites—such as winds, rainfall, and vertical motion, can provide a more detailed picture of the solar effect than earlier periods.

The climatology of the part of the Walker Cell, which lies between 120°E and 70°W, is represented by the average zonal winds between 2°N and 2°S in Fig. 4a. The mean easterlies in the lower half of the troposphere extend as far west as 160°E, and the mean westerlies in the upper half reach 175°W. The easterlies below meet westerlies to their west in the western branch of the Walker Cell, and the westerlies in the upper part of the troposphere face easterlies to their west.

The zonal wind anomalies below 100 hPa in the five solar peaks (Fig. 4b) show that the solar forcing accelerates the Pacific branch of the Walker Cell and expands it westward, with easterly anomaly winds below and westerly anomalies above as far west as 120°E. This anomaly pattern is established already in the previous summer (Fig. 7a), and lasts with small variations through the winter of the peak year. In the uppermost troposphere and the lower to middle stratosphere at the height of the northern winter (January–February (JF) in Fig. 4c), easterly anomalies are found above 40 hPa, above the westerly anomalies in the upper troposphere and lower stratosphere.

This distribution of zonal wind anomalies is probably a solar effect that, in peak years, is characterized by a strengthening and broadening...
of the Walker circulation in the Pacific Ocean with concomitant effects in the SLP and SST (Figs. 1–3). Solar forcing thus influences the quasi-biennial oscillation (QBO) in the equatorial stratosphere in the sense that at solar peaks in northern winter the QBO, when in its westerly phase (westerlies below/easterlies above), will be strengthened, whereas the opposite occurs in its easterly phase when the easterlies below and westerlies above will be weakened.

4. Comparison with cold extremes (CEs) in the Southern Oscillation

The SLP and SST anomalies in solar peaks have some traits in common with those in the cold extremes (CEs, also referred to as La Niña events) in the Southern Oscillation, but there are essential differences, which will be pointed out in this section. Fig. 5a shows the SLP anomalies in JF in 12 CEs and can be compared with the SLP anomalies in the 14 solar peaks in Fig. 1a. There are stronger zonal (west–east) pressure gradients in the CEs, from the bottom to the top of the map. The positive SLP anomalies west of North America are weaker in the CEs and extend northwest to southeast. The positive anomalies south of the equator are larger in the CEs and the pressure gradient anomalies thus steeper, so that the trades crossing the equator must consequently be stronger in the CEs than at solar peaks. Therefore, the negative SST anomalies are markedly stronger in the CEs (cf. Figs. 2a and 5b).

The zonal wind anomalies in the lower equatorial troposphere (the Walker Cell anomalies) in Figs. 4b and 5c are larger in the CEs but not as extensive as those in the solar peaks. In the upper troposphere, the westerly anomalies in the solar peaks, though weaker than those in the CEs, span the whole figure, whereas they are concentrated in the center in the CEs.

In the stratosphere in JF (Figs. 4c and 5d), the differences between CEs and peak solar years are
notable and remarkable. Whereas the solar peaks have easterly anomalies above and substantial westerly anomalies below, the CEs have westerly anomalies above, separated by a thin layer of easterly anomalies from the westerly anomalies in the troposphere. The latter reach no higher than the top of the equatorial tropopause layer (about 70 hPa), in contrast to the tropospheric westerly anomalies in the solar peaks that extend to 40 hPa.

The difference in the vertical distribution suggests that the CE anomalies in the troposphere are forced from the surface and are confined mainly to the troposphere, whereas the tropospheric anomalies in the solar peaks to a large extent are linked to the stratosphere. This suggests that the mechanisms discussed earlier could be a combination of coupled processes at the surface and stratospheric response to solar (mainly UV) forced changes in ozone, both acting in the same direction to produce the strengthening of the regional precipitation maxima in the tropics.

5. The solar signal in the northern summer

van Loon et al. (2004) documented general characteristics of the response to solar forcing in northern summer, and features similar to northern winter were present in summer such as a strengthening of the tropical precipitation maxima including the northern hemisphere monsoon regimes (also noted in model simulations by Meehl et al., 2003).

Here we re-visit those results with the longer data record, and relate the multi-year nature of the solar response to northern summer seasons before and after the solar peaks. Fig. 1a–c indicates that the effect on the SLP of the solar peaks builds up during JF the year before and wanes during the year after the largest JF anomalies in the pressure. This development is also evident in the JF SST anomalies (Fig. 2a–c). The influence of solar forcing is evident in other years about the solar peak years: in July–August (JA) in the years before the peaks of the DSO (Fig. 6a), the shape of the SST anomaly pattern is nearly the same for JA as for JF in the

Fig. 4. (a) Vertical zonal section (1000–100 hPa) of the mean zonal wind component (m s\(^{-1}\)) in the region between 2\(^\circ\) S and 2\(^\circ\) N, from 120\(^\circ\) E to 70\(^\circ\) W in January–February; (b) anomalies of the zonal wind over the region of (a) in January–February of the years 1957, 1968, 1979, 1989, 2000; (c) the same as in (b), but for the levels 100–10 hPa.
Fig. 5. (a) Anomalies of sea level pressure, January–February, in 12 cold extremes of the Southern Oscillation (cold events): 1873, 1887, 1890, 1904, 1939, 1943, 1950, 1971, 1974, 1976, 1999; (b) the same as in (a) except for SST; (c) the same as in Fig. 4b, but for the cold events in (a); (d) the same as in Fig. 4c, but for the cold events in (a).
peak solar years (Fig. 2a). After the maximum amplitude of SST anomalies during JF, in JA this pattern wanes (Fig. 6b), leading to weak but still negative anomalies in JF after the peak years (Fig. 2c). The SLP anomalies for the JA season for peak solar years and 1 year following are characterized by a southward shift of the anomalously high pressure seen in the JF season in the Gulf of Alaska, extending from the dateline to North America at about 30–40°N (Fig. 6c, d).

As noted above, we showed aspects of the solar signal in the tropics in the northern summer since 1979 in van Loon et al. (2004), and besides adding here the long-term SST anomalies in JA (Fig. 6a), we also show the Walker circulation and stratosphere anomalies (Fig. 7a, b). The Walker circulation anomalies are similar to those for the northern winter in Fig. 4b, which is not surprising considering the marked negative SST anomalies in Fig. 6a. There is in JA an extension and amplification of the Walker circulation, and an extension of the tropospheric westerly anomalies into the stratosphere as high as the 25-hPa level, where they are overlain by easterly zonal-wind anomalies. As in northern winter, this vertical distribution of wind anomalies means that at solar peaks in the northern summer when the QBO is westerly below and easterly above it is enhanced by the sun, and when it is easterly below–westerly above it is diminished by the sun.
6. Discussion and conclusion

As noted in vLMS and confirmed here with a longer observational record, at peaks in the DSO, the SLP in the Gulf of Alaska and south of the Pacific equator tends to be above normal. Thus the southeast trade winds crossing the equator are stronger than average and increased upwelling of cooler water produces negative SST anomalies. This situation occurs with a strengthening of the climatological mean precipitation and wind patterns, and is seen here in a longer record than in vLMS. The signals in SLP and SST are present in the year before and after the solar peak in both the northern summer and winter, in contrast to the typical 1-year duration of CEs in the Southern Oscillation.

The branch of the Walker Cell in the Pacific is strengthened and extends westwards at solar peaks, and the upper tropospheric westerly anomalies extend into the stratosphere as high as 40 hPa, in northern summer to 25 hPa. Above these anomalies are easterly anomalies. Thus the QBO is affected by the solar peaks in the sense that when it is in its westerly phase (westerlies below, easterlies above), the QBO is enhanced, whereas it is suppressed when in its easterly phase. The cold extremes in the Southern Oscillation do not have a similarly noticeable effect on the stratosphere. This indicates that, even though the coincident response to solar forcing has some elements of a CE, the solar response and CEs arise from somewhat different processes. CEs are internally generated by coupled dynamics in the Pacific climate system, whereas the CE-like response results from solar forcing that triggers similar coupled processes and ends up producing a similar pattern. However, the differences in the response in the stratosphere between solar response and CEs suggest an additional role for stratospheric processes related to UV (and associated ozone changes) to supplement the coupled responses at the surface. Thus, there are indications that both types of mechanisms work in the same direction to produce the total climate system response to solar forcing in the troposphere and stratosphere.

The response of the atmosphere and ocean in the Pacific is thus a preference for an enhanced mean circulation in the peaks of the DSO. In all other years, the area is not constrained or particularly influenced by the sun, and the circulation can vary from warm to cold extremes in the Southern Oscillation. Thus, though there are similarities in the surface patterns of SLP and SST anomalies in CEs and peak solar years, the latter have a lower amplitude and longer duration, with effects that extend into the stratosphere where CEs have little effect.

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