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High and Low Frequency 11-year Solar Cycle Signatures

in the Southern Hemispheric Winter and Spring

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26   **Abstract**: We have studied the characterization of the 11-yr SC signals in the Southern Hemisphere

27   (SH) during the winter and spring using ECMWF daily and monthly data from 1979 to 2009. By

28   separating the response into high (< 6 months) and low (>36 months) frequency domains, we have

29   found spatially different 11-yr SC signals exist for high and low frequency domains. In the stratosphere,

30   the high and low frequency responses tend to enhance each other near the equator and subtropics while

31   they oppose one another at high latitudes. The high frequency response is marked by a strengthened

32   stratospheric jet during winter and the response is not static but tracks with the centre of the polar

33   vortex. In the lower stratosphere, the positive response of temperature to the 11-yr SC is dominated by

34   its low frequency component, which extends from the North Pole to the South Pole. The low frequency

35   tropospheric response is latitudinally symmetric about the equator and consistent with the modeled

36   responses to temperature perturbation in the lower stratosphere. The signals are found to be sensitive to

37   contamination from the 2002 sudden stratospheric warming event and major volcanic eruptions but the

38   general spatial pattern of the responses remain similar. A significant projection of the 11-yr SC onto the

39   SAM can only be detected in the stratosphere and in the high frequency component. The signature is

40   marked by a strengthening of the stratospheric SAM during winter and a weakening of the SAM in the

41   uppermost stratosphere during spring.

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1. Introduction

Studies have shown that changes associated with the 11-year solar cycle (SC) have detectable
effects on the stratospheric and tropospheric circulation (*e.g.* Gleisner and Thejll 2003; Haigh 2003;
Coughlin and Tung 2004; Hood 2004; Salby and Callaghan 2006; Lu *et al.* 2007; van Loon *et al.* 2007).
The 11-yr SC signature in stratospheric temperature is characterized by positive correlation at low
latitudes with a vertical double-peaked structure, one in the lower stratosphere and another in the upper
stratosphere (Crooks and Gray 2005; Keckhut *et al.* 2005; Claud *et al.* 2008; Frame and Gray 2010;
Gray *et al*. 2010). In zonal-mean zonal wind, it is marked by a strengthening of the subtropical jet in the
upper stratosphere and a poleward and downward movement of westerly anomalies (Kuroda and Kodera
2002; Kodera *et al.* 2003; Gray *et al.* 2004; Matthes *et al.* 2004; ; Gray et al. 2010).

As the total solar irradiance varies by only ~0.1% over an 11-year solar cycle (11-yr SC), it has
been suggested that larger variations of solar ultra violet (UV) radiation (~5-8% over an 11-yr SC) and
its absorption by stratospheric ozone could provide a detectable solar link to variation of the global
circulation (Haigh 1994; 2003). Thermal structure change caused by the associated heating in the upper
stratosphere may lead to a modulation of the stratospheric polar vortex and cause a dynamical feedback
in the lower stratosphere (Kodera and Kuroda 2002). The enhanced equatorial heating due to solar UV-
ozone interaction results in anomalously stronger westeries in the upper stratosphere/lower mesosphere,
in thermal wind balance with an enhanced pole-to-equator temperature gradient. The stronger westerlies
may deflect planetary waves poleward and cause a further strengthening of the polar vortex (Kodera *et
al*. 2003). The solar UV induced wind anomalies move poleward and downward as the winter
progresses (Kodera and Kuroda 2002; Kodera *et al*. 2003; Matthes *et al*. 2004).

Perturbation of the stratosphere by UV radiation variations followed by downward propagation of
the resulting circulation anomalies to the surface has been proposed to explain the observed tropospheric
solar signals (Haigh *et al*. 2005; Hameed and Lee 2005; Matthes *et al.* 2006). Changes to the winter
stratospheric polar vortex may influence the underlying tropospheric circulation. In addition, idealized

71   model simulations have suggested that a solar modulation of the equatorial lower stratosphere, which

72   affects the equator-to-pole temperature gradient may also modulate the synoptic scale wave activity

73   (Haigh and Blackburn 2006; Simpson *et al.* 2009). GCMS studies also suggest that solar UV induced

74   change in the Brewer Dobson (BD) circulation in the upper stratosphere can cause a suppression of

75   tropical convection during solar maximum (Kodera 2004; Kodera and Shibata 2006; Matthes *et al.*

76   2006). One thing in common with the above proposed mechanisms is that they all involve a

77   stratospheric influence on the tropospheric circulation and they are consequently referred to as "top-

78   down' mechanisms (Gray *et al.* 2010).

79   Another mechanism of solar influence over an 11-year cycle is through air-sea-radiative coupling

80   at the ocean surface in the tropics whereby the spatial asymmetries of solar forcing, induced by cloud

81   distributions, result in greater evaporation in the subtropics and consequent moisture transport into the

82   tropical convergence zones (Meehl *et al.* 2003). Higher solar forcing may cause stronger upward motion

83   in the winter hemispheric subtropics and enhanced downward motion in the summer hemisphere

84   subtropics (van Loon *et al.* 2004; Meehl *et al.* 2008). As it involves near surface processes and because

85   significant responses have been detected in models without a stratosphere, it is consequently referred to

86   as the "bottom-up" mechanism (*Gray et al.* 2010). For a recent review of all proposed mechanisms of

87   solar influence on the climate, see Gray *et al.* (2010).

88   It is possible to study each individual mechanism separately using models but it is very difficult to

89   separate the responses associated with different mechanisms using observational data. This presents a

90   substantial challenge to interpret the solar signals of different origin/cause based on the observational

91   signature. Proposed mechanisms involve fast processes such as wave mean flow interaction and/or slow

92   processes such as temperature change induced by redistribution of ozone in the lower stratosphere and

93   differential ocean heating. For instance, the wave driven dynamic response to the 11-yr SC tends to

94   change on sub-monthly time-scales (*e.g.* Kodera 2004; Matthes *et al.* 2006; Lu *et al.* 2009) while the

95   radiative response is more likely to be static over an extended period, especially in the lower

96   stratosphere, and hence can be detected in the annual mean (*e.g.* Keckhut *et al.* 2005; Claud *et al.* 2008;

97   Frame and Gray 2010). It is natural to think that the responses associated with fast processes may show

98   signals with a high frequency component within the atmospheric data while processes with slow

99   responses may be detected better in the low frequency domain.

100   In an attempt to refine the traditional way of analyzing the atmospheric response to the 11-yr SC,

101   here we separate the atmospheric data into high and low frequency domains, so that we are able to

102   examine the characterization of the solar signal in terms of fast *versus* slow processes, direct *versus*

103   indirect effects, radiative *versus* dynamic responses and their possible links to "top-down" and/or

104   "bottom-up" mechanisms. We focus on the Southern Hemispheric (SH) winter and spring where the

105   polar vortex is stronger and longer-lived than its NH counterpart due to weaker planetary wave forcing.

106   This implies that radiative interaction is likely to play a relatively larger role in the SH winter than in the

107   Northern Hemispheric (NH) winter, and the solar signals in the SH have been found to be different to

108   those in the NH (Labitzke 2002; Salby and Callaghan 2006). The dynamically "calm" SH winter may in

109   fact present a better environment to differentiate high and low frequency responses as the signals are

110   less likely to be affected by transient events such as stratospheric Sudden Warmings (SSWs). For

111   example, the modeling study of Cnossen *et al*. (2011) showed that the high latitude stratospheric and

112   tropospheric responses differ significantly for the SSW condition and non-SSW conditions. By

113   focusing on the SH winter and spring, we can understand more how the 11-yr SC signal behaves under

114   non-SSW conditions.

115   Though our main focus is on detecting high and low frequency solar responses in the Earth's

116   atmospheric temperature and zonal wind and to study how those signals might be linked to previously

117   proposed mechanisms, we also study whether or not the 11-yr SC may project onto the Southern

118   Annular Model (SAM) more clearly if the data are separated into high and low frequency components.

119   Because the stratospheric effects on the troposphere may be realized through the SAM and the coupling

120   depends primarily on wave activity (Thompson *et al*. 2005; Limpasuvan and Hartmann 2000), it is

121   expected that the high frequency component plays a more important role than the low frequency

122   component. In this study, we shall check if it is also the case for the 11-yr SC signal on the SAM.

123   Previous studies have shown that the large-scale structure of the late winter and spring SAM is

124   modulated by the 11-yr SC (*e.g.* Kuroda and Kodera 2004, 2005; Kuroda *et al*. 2007; Kurada and

125   Yamazaki 2010). These authors have shown that the 11-yr SC modulates the spatial structure of the

126   SAM from October through to December. In solar maximum years, the solar influence on the SAM

127   extends vertically from the surface to the upper stratosphere while it is capped within the troposphere

128   during solar minimum years. Using a coupled chemistry-climate model, Kuroda and Shibata (2005)

129   found that increases in solar UV radiation led to a stronger signal of the SAM in the Antarctic

130   stratosphere than during low UV runs. Unlike those previous studies, our main focus here is detecting

131   the 11-yr SC signals in the atmospheric variables including the SAM rather than the modulating effect

132   of the 11-yr SC on the SAM signature. More precisely, we do not study how the spatial extent of the

133   SAM signature in wind or temperature changes under high and low solar conditions. Instead, we study

134   how much of the interannual variability of the SAM may be directly linked to the 11-yr SC variation

135   and at what frequency and altitude such a linkage may be statistically significant.

136   The rather sparse observational network before the satellite era (*i.e.* pre- September 1978) in the

137   Southern Hemisphere (SH) limits the accuracy of the ERA-40 reanalysis before 1979. As a result, few

138   observational studies of the atmospheric response to the 11-yr SC have been undertaken for the SH

139   winter and spring. With a relatively short record length, it is important to consider the influence of other

140   major physical disturbances. Stratospheric sudden warmings (SSWs) have so far been recorded in the

141   SH on only one occasion, which was in 2002. Consequently in the 2002 winter and spring, the

142   stratospheric wind and temperature are distinctly anomalous to the other years (Charlton *et al*. 2005;

143   Scaife *et al*. 2005). In addition to the primary focus of this study, the dynamic features of 2002 will be

144   briefly discussed in the context of the atmospheric response to solar forcing. Also, the possible

145   contamination of results by the temporary warming associated with volcanic aerosols will also been

146   examined by comparing results after excluding and including two years of data following two major

147   eruptions (*i.e.* El Chichón in March 1982, and Pinatubo in June 1991). Due to the limited sample size,

148   the modulating effect of the equatorial Quasi-biennial Oscillation (QBO) will not be explicitly studied

149 here as statistical significance cannot be reliably established with any further sub-sampling, though the

150 possible effect of the QBO on the detected solar signals will be briefly discussed.

2.   Data and Methods

152   Data used by this study are daily mean zonal winds and temperatures blended from the ECMWF

153 ERA-40 Reanalysis (January 1979 to August 2002) and ECMWF Operational analyses (September

154 2002 to December 2009), as employed by Frame and Gray (2010). The ERA-40 dataset was assimilated

155 using direct radiosonde and satellite measurements and has a horizontal resolution of 1.125º in both

156 latitude and longitude on 23 pressure levels from 1000 hPa to 1 hPa (Uppala *et al.* 2005). The ECMWF

157 Operational data were output from the ongoing analyses produced by the most recent ECMWF

158 Integrated Forecasting System (IFS) model. Data from September 2002 to the present day are available

159 on the same 1.125º grid but on 21 pressure levels (before 07/11/2007) and 25 pressure levels (since

160 07/11/2007). The ERA-40 and the Operational data sets share 21 of the pressure levels, the exceptions

161 being four levels in the lower troposphere (*i.e.* 600, 775, 900, and 950 hPa). For simplicity, only the data

162 for those 21 pressure levels are used here. Both ERA-40 and Operational datasets extend to 1 hPa (~50

163 km), thus allowing an examination of the solar signals throughout the stratosphere. While it is not ideal

164 to merge two datasets derived from different data assimilation models, we have done this here in order

165 to maximize the length of the data set, as needed for the study of 11-yr SC signals.

166   The daily data have not previously been used for this purpose; therefore this work is

167 complementary to earlier analyses by providing a more detailed temporal resolution on the timing of the

168 solar signals and their propagation pathways. Before the satellite era (*i.e.* before September 1978), the

169 scarcity of SH radiosonde measurements and lack of direct measurement at altitudes above 10 hPa result

170 in unreliable estimations in ERA-40, particularly in the upper stratosphere. To better capture solar

171 perturbation of the stratosphere by UV variations and the downward propagation of the resulting

172 circulation anomalies, only data from January 1979 onwards are used. The entire period of 1979-2009

173 covers 31 years and about three 11-yr SCs.

174   Daily observed 10.7-cm solar radio fluxes were obtained from the National Geophysical Data

175   Center (NGDC) website and are used as a proxy for the 11-yr SC. Their power spectrum shows that the

176   variability in the daily 10.7-cm solar radio fluxes is dominated by two frequency bands, one around 26-

177   28-days and another around 9.5-11.5 years. In order to focus on the 11-yr SC, a 365-day low-pass filter

178   was applied to the solar radio fluxes. The filtered daily time series is denoted as F_s hereafter and were

179   used in the analysis. Qualitatively similar results can be obtained if a running average window of 1-12

180   months is applied to the daily solar data. Noisier but qualitatively similar results can also be obtained by

181   using the raw daily fluxes. Similar to Lu *et al*. (2007; 2009), we use $\overline{F_s} < -0.25$ and $\overline{F_s} > 0.25$ to define

182   low solar (LS) and high solar (HS) activity when deriving composites where $\overline{F_s}$ stands for the

183   normalized values of F_s; transition years where $|\overline{F_s}| \leq 0.25$ are excluded. Under this definition, 11 years

184   (*i.e.* 1979-1982, 1989-1992, and 1999-2001) were HS years and 15 years (*i.e.* 1984-1987, 1994-1998,

185   and 2004-2009) were LS years for June to October mean.

186   A possible projection of solar signal onto the Southern Annular Mode (SAM) is studied by using the

187   SAM index derived from two different sources. The first is the daily SAM index derived as the leading

188   empirical orthogonal function (EOF) of daily zonal-mean zonal wind over 20°–90°S, from the blended

189   ECMWF ERA-40 reanalysis and operational data for the same period. Details about this method can be

190   found in Baldwin and Thompson (2009). The second type of SAM index is the station-based SAM

191   index, which is estimated as a monthly mean difference between the mean sea level pressure anomaly at

192   six stations close to 40°S and six stations close to 65°S (Marshall 2003, available at

193   www.nercbas.ac.uk/icd/gjma/sam.html). By only using long-term stations and surface pressure

194   measurements, this index avoids the possible bias problems when combining the ERA-40 and ERA-

195   operational datasets. Thus, the principal advantages of the Marshall (2003) index are its simplicity and

196   temporal consistency across its entire time-span and between different seasons. As the station based

197   SAM extends back to 1957, it is used to test the robustness of the signals near the surface. For

198   simplicity, these two SAM indices are referred to hereafter as daily ECMWF-SAM and monthly

199   Marshall-SAM, respectively.

200   The main diagnostic tools used are composite analysis and linear regression with standard Student

201   *t*-test being used to test their significance. The analyses were carried out for a range of frequency bands

202   where Chebyshev filters (Smith 1997) are used to separate one band of frequencies from another.

203   Chebyshev type II is used as high-pass filter while Chebyshev type I is used as low-pass filter. The main

204   criteria in designing the filters are a small (i.e. < 0.5%) peak-to-peak ripple and stability for all

205   geographical locations. Through a large number of computational experiments, we found that a high-

206   pass filter with an order of 15-17 and peak-to-peak ripple of 2-5 dB in the normalized passband was

207   optimal for monthly data and an order of 3-5 was sufficient for daily data. For the low-pass and

208   bandpass filter, filter orders in the range of 4-9 for the monthly mean and 1-3 for daily data are

209   sufficient. In the sections below, a ripple magnitude of 2-dB is used throughout. Similar results can be

210   obtained if a Butterworth filter is used though higher order filters are required.

3. Solar Signal during SH Winter and Spring

3.1   Winter and spring mean signals

213   Figure 1 shows composite differences (HS-LS) of June-August averaged zonal-mean temperature

214   (ΔT_{HS-LS}, 1st column) and zonal wind (ΔU_{HS-LS}, 2nd column), in meridional-height cross section. When

215   the entire record is used ((a;e)), significant responses to the 11-yr SC are detected primarily in

216   temperature and in the stratosphere. In temperature, significant positive ΔT_{HS-LS} are found to extend

217   from 90°N to 40°S latitudinally and from 7hPa to 100 hPa vertically. Near the equator, ΔT_{HS-LS} is

218   statistically significant at a 95% confidence level only at ~70 hPa and not significant at other altitudes.

219   In the polar SH, ΔT_{HS-LS} displays an alternating vertical negative and positive pattern, which is most

220   likely to be an artifact of the dataset rather than a real response. Significant ΔU_{HS-LS} is found in the mid-

221   latitude stratosphere in the NH. In the SH, though ΔU_{HS-LS} is marked by westerly anomalies at 15-45°S

222   and easterly anomalies at poleward of 55°S, they are not significant at a 95% confidence level.

223   A similar response pattern can be obtained if selected anomalous data are excluded, *i.e.* 2002 major

224   SSW (b;f), the major volcanic eruptions (c;g) and both the major SSW and the volcanic eruptions,

225   although the magnitude and significance of the differences change slightly. Possible contaminations by

226   the major SSW and the volcanic eruptions can be viewed as enhancement or weakening of the solar

227   signals. When data from 2002 are excluded, the low-latitude temperature response is enhanced and the

228   westerly anomalies at 15-45°S become significant. When the years affected by the major volcanic

229   eruptions are excluded, the temperature response becomes weaker (< 0.3 K) in the lower stratosphere

230   and stronger (~ 0.5 K) in the upper stratosphere. Thus, the positive solar signature in lower-stratospheric

231   temperature is amplified by the bias of the eruptions of El Chichón and Mount Pinatubo. Almost no

232   significant signals can be found in the troposphere except for the westerly anomalies near the equator in

233   the SH.

234   **[[Insert Figure 1 here]]**

235   It has been suggested that the lack of statistically significant solar signals at 5-50 hPa in the tropics is

236   likely due to a contamination effect of the QBO (Smith and Matthes 2008). To examine such a

237   possibility in a simple manner, the same composite analysis is carried out at two distinct frequency

238   domains distinctly away from the typical period of the QBO (~28 months). Figure 2 shows the June-

239   August zonal-mean temperature (a;b;c) and zonal wind (d;e;f) responses to the 11-yr SC when a 6-

240   month high-pass filter (a;d), 36-month low-pass filter (b;e) and linearly detrend plus 36-month low-pass

241   filter are applied to the atmospheric data, respectively. Where a 6-month high-pass filter is applied to the

242   data, the primary feature of the temperature response to the 11-yr SC is positive ΔT_{HS-LS} in the

243   equatorial and subtropical stratosphere and at high latitude in the NH upper stratosphere. In the high

244   latitude SH, there are alternating positive and negative anomalies, but only the negative ones are

245   significant at the 0.05 level (*i.e.* a confidence level of 95% or above), implying a dominated cooling

246   effect in the region under HS condition. A small region near the equator in which a 95% confidence

247   level cannot be achieved is found at ~10-20 hPa, though a positive temperature difference remains there.

248   The accompanying solar signals in zonal wind are marked by westerly anomalies up to 12 m/s in the SH

249   subtropical stratosphere extending downward from 1hPa to 70 hPa and 3 m/s in the NH subtropical

250   stratosphere extending downward from 1hPa to 20 hPa. Easterly anomalies are found in the high-

251   latitude upper stratosphere but are only significant in the NH at 55-75°S, 1-2hPa (see Figure 2(d)). A

252   similar pattern of solar response is obtained if the high-pass cutoff period is in the range of 3 to 12

253   months, and the magnitude and significance of the responses reduce when the cutoff period is either

254   smaller than 3 months or greater than 12 months. With a 36-month low-pass filter (see Figure 2b;e), the

255   temperature response is marked by a general positive ΔT_{HS-LS} in the stratosphere where a significant 11-

256   yr SC signal appears near the equator, in the subtropics and also in the polar region. The corresponding

257   response in the zonal wind is broadly symmetric about the equator. In the upper stratosphere, it is

258   characterized by statistically significant westerly anomalies in the subtropics and partly significant

259   easterly anomalies poleward of 60°. In the middle to lower stratosphere, it is marked by easterly

260   anomalies near the equator and in the region poleward of 60° and by westerly anomalies at mid-

261   latitudes. In the troposphere, it is marked by westerly anomalies near the equator and by easterly

262   anomalies near 30° and in the region poleward of 60°. The clearest vertical connection of the signals is

263   present in the westerly anomalies originating in the subtropical upper stratosphere. The spatial pattern

264   remains similar when the lower cutoff period is anywhere in the range of 12-36 months. However, the

265   equatorial-symmetric signal becomes noticeably stronger and clearer when the cutoff period is greater

266   than 28 months because the contamination of the QBO is suppressed.

267   It is known that there has been a steady decrease of the temperature in the stratosphere and increase

268   of the temperature in the troposphere over the last three decades and the diagnosis of the solar signal is

269   sensitive to the presence of trends in the data (Lu *et al*. 2007; Kodera *et al*. 2008; Frame *et al*. 2010). To

270   account for the effect of the long-term trends, the atmospheric data is first detrended linearly before

271   applying a 36-month low-pass filter (Figure 2c;f). The results of this show that the effects of removing

272   the linear trend give a generally weaker and less significant response in the stratosphere and an

273   enhanced response in the troposphere. In particular, at 30-50° in both hemispheres, a significant positive

274   temperature response (~0.4 K) in the troposphere appears only when the long-term trend is removed.

275   Conversely, only marginal changes in zonal wind response are found to be associated with long-term

276   trend. There is an indication that the high and low frequency responses in tropospheric temperature are

277   of the opposite sign though the high frequency responses are hardly significant at a 95% confidence

278   level. More data are needed to confirm such a cancellation effect. Unlike temperature, the signature in

279   zonal wind is not sensitive to the long-term trends.

280   ## 3.2   Seasonal progression of high frequency signals

281   It has been suggested that the temperature responses in the lower stratosphere are likely to be indirect

282   responses either through a modification of the Brewer-Dobson (BD) circulation, changes in ozone

283   transport or both (Kodera and Kuroda 2002; Hood 2004; Gray *et al*. 2009; Marsh and Garcia 2007;

284   Hood and Soukharev 2006; SPARC CCMVal report 2010). In this section, we focus on the temporal

285   evolution of the high frequency signal which helps the diagnosis of dynamical responses. We also show

286   how the high frequency signals in the upper stratosphere might contribute to those in the lower

287   stratospheric temperature, through a downward propagating mechanism which is likely to be associated

288   with changes in BD circulation. Daily data are used to demonstrate that solar UV forcing in the upper

289   stratosphere may be transferred dynamically through a downward and poleward movement of the

290   signals.

291   ### *3.2.1   Signals in temperature*

292   Figure 3 shows the monthly zonal-mean temperature (T_{clim}) for June to October (1st column) and

293   the corresponding 6-month high-pass filtered temperature differences ΔT_{HS-LS} (2nd and 3rd columns), all

294   displayed in meridional-height cross section with latitude extending from 30°N to 90°S. The

295   corresponding zonal wind signals are described in the next section. In June, a significant positive ΔT_{HS-}

296    $_{LS}$ signal emerges in the equatorial and sub-tropical upper stratosphere (5-10hPa) and in the lower

297   stratosphere (70 hPa). The upper stratospheric signature enhances in July and latitudinally expands and

298   descends towards the lower stratosphere in August. Significant negative values of ΔT_{HS-LS} are found in

299   the high latitude SH in July and August. Such a response pattern in temperature suggests an enhanced

300   equator-to-pole temperature gradient in both the upper and lower stratosphere. The high latitude and

301   lower stratospheric tropical responses would be expected from a weakened BD circulation in solar

302   maximum years or from a strengthened BD circulation during solar minimum years. The temperature

303   responses both at low and high latitudes weaken in spring (September and October) and the high-

304   latitudinal negative signals are replaced by positive temperature responses.

305   **[[Insert Figure 3 here]]**

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306   Figure 4 shows the daily running regression (in K per 100 solar unit) of zonal-mean temperature on

307   F_s averaged over 5°S to 5°N (a;c;e), and 55°S to 65°S (b;d;f), where data from 2002, 1982, 1983, 1991

308   and 1992 are excluded. In Figure 4(a;b), the regression is performed based on raw zonal-mean

309   temperatures at those two latitude bands and daily F_s. It shows that a downward descent of the positive

310   temperature anomalies with maximum magnitude of 3 K per 100 solar unit is found at ~2 hPa near the

311   equator in late June (Figure 4a). The signal descends to 20 hPa in late August. There is a weaker but

312   significant (*i.e.* at the confidence level of 95% or above) temperature response at 70 hPa for the same

313   period which does not show any direct vertical connection with that originating in the equatorial upper

314   stratosphere. A negative temperature response (~6 K per 100 solar unit) appears at various altitudes at

315   55-65°S in July and August (Figure 4b).

316   Figure 4(c;d)) shows the same as Figure 4(c;d) but with a Chebyshev type II high-pass filter having

317   a cutoff-period of 183-days applied to the temperature data. An apparent descent from 20-100 hPa in the

318   case of equatorial temperature and from the stratosphere to the troposphere in the case of high latitude

319   temperature can now be observed. Similarly, Figure 4(e;f)) shows the same as Figure 4(c;d) but with a

320   Chebyshev type II band-pass filter having a bandwidth of 31 to 183 days applied to the temperature

321   data. Downward descent of the solar signals becomes clearer though only the high latitude signal

322   manages to cross the tropospause and move into the troposphere.

323   We found that the downward movement from the upper stratosphere to the lower stratosphere is

324   robust and becomes clearer when either a Chebyshev type I, or type II or Butterworth filter is applied to

325   the temperature data. Together, the signals suggest that during these seasons the high frequency

326   response in the stratosphere is characterized by warming in the tropics and cooling at high latitudes,

327   implying a slowing down of the BD-circulation. They also suggest that the effect moves gradually from

328   the upper stratosphere to the lower stratosphere. However, the downward movement of the signal into

329   the troposphere loses statistical significance when either a Chebyshev type I or Butterworth filter is

330   applied. When the cut-off period of the filter is increased beyond 6-months, the high latitude signals

331   become noticeably weaker (not shown). Thus, it remains to be verified whether or not the high latitude

332   temperature signal actually descends from the stratosphere into the troposphere in reality.

333   **[[Insert Figure 4 here]]**

334   To examine the variability of the solar signals in stratospheric temperature for HS and LS years

335   more closely, time series of the daily temperatures in the upper and lower stratosphere for each

336   individual year are shown in Figures 5 and 6, respectively. In Figure 5, daily mean temperature at 10

337   hPa averaged over the latitude ranges of 10-15°S (top row) and 55-65°S (bottom row) are compared for

338   HS (1st column) and LS (2nd column) conditions, where the averages are weighted by the cosines of the

339   latitudes.

340   **[[Insert Figure 5 here]]**

341   **[[Insert Figure 6 here]]**

342   Figure 5 shows that, in the upper stratosphere, considerable temperature variation exists and the

343   variance is larger for HS years than for LS years. The larger temperature variation under HS may be

344   partially due to the contaminating effects of the major SSW (year 2002, purple line) and the major

345   volcanic eruptions (years 1982, 1991 and 1992; blue lines). The 3rd- 4th columns of Figure 4, display the

346   mean daily temperatures under HS (red) and LS (grey) conditions for no filtering and183-day

347   Chebyshev type II high-pass filter. The shaded regions represent 95% confidence intervals for the mean.

348   When the shaded regions do not overlap, it indicates that the average temperature differences between

349   the HS and LS groups are significant at the 95% confidence level. In order to focus on the 11-yr SC

350   effect, years affected by the SSW and major volcanic eruptions are excluded from the group mean in

351   HS. For equatorial temperature, statistically significant differences between HS and LS conditions are

352   evident for both the raw data and the high frequency component. For high latitude temperature, the

353   difference is only significant for the high frequency component. When the unfiltered data are used, it is

354   barely differentiable.

355   Figure 6 shows the corresponding temperature time series for the lower stratosphere at 50 hPa and

356   for the same latitude ranges as in Figure 5. It shows that higher temperatures existed for the volcanic

357   eruption affected years near the equator and subtropics, due to the warming effect of the volcanic

358   aerosols (Robock and Mao, 1992). In the 2002 winter, substantially lower temperatures are found at low

359   latitudes accompanied by higher temperatures at high latitudes. In the subtropics (top row), significant

360   positive temperature differences between HS and LS exist whether or not a filter is applied. The

361   response obtained by using raw unfiltered daily data is found from April to September while the high

362   frequency response occurs briefly only in August and September. The magnitude of the response is

363   larger in the unfiltered data than in the high frequency component. Conversely, the high latitude

364   temperature differences are only significant in the high frequency domain in July to early September.

365   The lack of significance in unfiltered high latitude temperature in the lower stratosphere is due to a

366   cancellation effect between high and low frequency components (not shown).

367   *3.2.2   Solar signals in zonal wind*

368   Figure 7 is similar to Figure 3 except that the temperature is replaced by the zonal-mean zonal

369   wind. The composite differences are the high frequency zonal-mean zonal wind between HS and LS

370   conditions (ΔU_{HS-LS}). The climatology of the wind field is characterized by a strengthening and

371   poleward movement of the stratospheric westerly jet from June to Mid-August and a gradual weakening

372   and downward movement of the jet thereafter. The high frequency ΔU_{HS-LS} signature is clearly marked

373   by a strengthening of the stratospheric jet as the significant westerly anomaly almost tracks the centre of

374   the jet. The signals originate in the subtropical upper stratosphere and lower mesosphere and then move

375   poleward and downward. There is a symmetric, but weaker, response in the NH subtropics (not shown),

376   which shows little poleward movement. As a whole, the overall structure of high frequency ΔU_{HS-LS} in

377   the stratosphere agrees exceedingly well with that proposed earlier by Kodera and Kuroda (2002) and is

378   consistent with the thermal wind balance in the presence of the anomalous latitudinal temperature

379   differences at 5-10 hPa shown in Figure 3.

380   **[[Insert Figure 7 here]]**

15

381   To examine the high frequency responses and variability of the wind in more detail, Figure 8 shows

382   the daily evolution of the zonal wind at 30-40°S, 5hPa (upper panels), and at 40-50°S, 50hPa (lower

383   panels) for HS (1st column) and LS (2nd column) conditions. Significant positive $\Delta U_{HS\text{-}LS}$ for the

384   unfiltered data exists only in Austral winter and only in the upper stratosphere winds. The difference is

385   noticeably enhanced both in the upper and lower stratosphere if a high-pass filter is applied. $\Delta U_{HS\text{-}LS}$

386   becomes insignificant if data from 2002 are included.

387   **[[Insert Figure 8 here]]**

388   **3.3   Solar signal in the Sothern Annular Mode**

389   It is known that the changes in zonal-mean zonal wind in the tropospheric westerly jet during the

390   SH winter are affected by changes in wave forcing (Limpasuvan and Hartmann 2000; Lorenz and

391   Hartmann 2001) and the effects may be projected onto the large scale atmospheric mode, *i.e.* the

392   Southern Annular Mode (SAM) (Thompson *et al.* 2005). Figure 9 shows the running linear regression

393   (in SAM index per 100 solar unit) using raw daily SAM (a) and 183-day high-pass filtered SAM (b),

394   where the linear trend is removed and the data from 2002 and two years following the major volcanic

395   eruptions are excluded. An almost identical response pattern can be seen in (a) and (b), suggesting that

396   the SAM response to the 11-yr SC is dominated by the high frequency response. In the stratosphere, a

397   positive solar response originates at 1hPa and above in early July and descends towards the lower

398   stratosphere in July and August. A negative response is obtained from October near the stratopause.

399   Noisier but significant responses are also found in the troposphere. They are positive in June-July

400   preceding the stratospheric signal, negative during mid-winter, and positive again form October onward.

401   No consistent signals can be found in the low frequency domain (not shown).

402   **[[Insert Figure 9 here]]**

403   Figure 9 suggests that the 11-yr SC may project onto the tropospheric SAM in early winter or late

404   spring. To test whether there is any definite projection of the 11-yr SC on the SAM in the troposphere,

405   scatter plots of F_s versus the station-based monthly Marshall-SAM from 1957-2009 are shown in Figure

406   10. We found that, in both June and November, the correlations are not significantly separable from

16

407   zero either using the raw data, or in the high or low frequency domains. Similar results were obtained

408   for other months or seasonal averages. We also found that there is no significant difference in the

409   variance and the histogram of the SAM under HS and LS conditions in the SH winter and spring.

410   **[[Insert Figure 10 here]]**

4.   Discussion

412   The most significant solar signature is the positive response of stratospheric temperature, consistent

413   with the theory that the interaction between solar UV and ozone photochemistry increases temperature

414   there (Haigh, 1994). However, the stratospheric signals of the 11-yr SC are sensitive to the

415   contamination of the 2002 SSW event and the major volcanic eruptions and zonal winds are more

416   sensitive than temperature. We have noted that the zonal wind response becomes noticeably clearer and

417   more significant by excluding the data from year 2002 or by separating the analysis into high and low

418   frequency components. The fact that the solar signal in zonal wind is more sensitive to sampling

419   methods than that in temperature implies that temperature is more directly affected by the variation of

420   solar output during the 11-yr SC. This is consistent with the known mechanism of solar UV-

421   stratospheric ozone interaction. In the troposphere, however, the solar signature in temperature is more

422   sensitive to the long-term trends than to the SSW or the major volcanic eruptions. Linearly removing the

423   trends enhances the signal in the troposphere and weakens the signals in the stratosphere. Without

424   removing a linear trend, up to $0.3°K$ of the temperature response in the low-latitude lower stratosphere

425   might be the result of aliasing of a long-term trend onto the solar signal and this is in good agreement

426   with Lu *et al*. (2007) and Frame and Gray (2010).

427   Here we have found that, during the SH winter, the 11-yr SC signals become stronger and

428   statistically more significant when the analysis is carried out at high and low frequencies than when the

429   raw data are used. The difference is more noticeable at high latitude as the high and low frequency

430   responses tend to cancel each other there. The cancelation partly explains why high latitude responses

431   are hard to detect statistically when raw data are used.

432   The difference in high and low frequency responses highlights new aspects of the underlying

433   physical processes. The static low frequency responses in the stratosphere may represent the slow

434   varying temperature and circulation change due to ozone transport induced by solar UV-stratospheric

435   ozone interaction and changes in BD-circulation (Kodera and Kuroda 2002; Gray *et al.* 2009; Gray *et al.*

436   2010). The non-static high frequency responses in temperature, zonal wind and the SAM to the 11-yr

437   SC and the fact that the signals are statistically significant only during SH winter point to a dynamic

438   effect of the 11-yr SC on the stratospheric circulation. These high frequency signals are generally

439   consistent with the dynamic response studied previous (Kodera and Kuroda 2002; Matthes *et al.* 2004;

440   Kuroda *et al.* 2007). It may be interpreted as a possible association between the 11-year solar cycle and

441   the temporal or seasonal persistence of the polar vortex and the BD-circulation. Apart from the known

442   mechanism of *in-situ* solar UV and ozone photochemistry interaction, other mechanisms may also be at

443   play to produce those stratospheric signals. For instance, the signature of the solar wind streaming out

444   from the Sun has also been found in various climate records (Lu *et al.* 2008b; Seppälä *et al.* 2009;

445   Lockwood *et al.*, 2010a,b; Woollings *et al.* 2010). Observational studies have shown that the solar wind

446   induced geomagnetic activity may alter stratospheric chemistry indirectly through energetic particle

447   precipitation (EPP) (Solomon *et al.* 1982; Randall *et al.*, 2005; 2007; Seppälä *et al.* 2007; Siskind *et al.*

448   2007). Chemical-dynamical coupled general circulation models (GCMs) have indicated that odd

449   nitrogen (NO_x) induced by energetic charged particle precipitation during geomagnetic storms may

450   cause temperature changes in both the polar and equatorial regions and in the stratosphere and the

451   troposphere (Langematz *et al.* 2005; Rozanov *et al.* 2005). *Lu et al.* (2007) found that the magnitude of

452   temperature response in the low latitude lower stratosphere to geomagnetic activity was slightly larger

453   than that associated with the 11-yr SC and that the temperature response to the 11-yr SC and

454   geomagnetic Ap index tend to enhance each other. Lu *et al.* (2008b) have shown that there is a robust

455   relationship between solar wind dynamic pressure and the zonal wind and temperature in the northern

456   polar winter. Stratospheric wind and temperature variations are positively projected onto the Northern

457   Annular Mode (NAM) when the 11-yr SC is at its maximum phase, and negatively projected onto the

458   NAM during the 11-yr SC minimum phase. A weakening of the BD-circulation with reduced upwelling

459   into the lower stratosphere at low-latitude under high solar wind forcing is consistent with the behavior

460   of the high frequency response shown here. Our rationale is that, at solar maximum, a warming effect in

461   the low latitude stratosphere due to solar UV-stratospheric ozone interaction together with a cooling

462   effect in the high latitude stratosphere due to solar wind driven geomagnetic activity would enhance the

463   equator to pole temperature gradient. When both mechanisms work together, it would result in a

464   stronger dynamic effect on the stratospheric circulation than that resulting from just one of these two

465   mechanisms. Given that the 11-yr SC signals are found to be opposite at high latitudes, it may therefore

466   be speculated that the high frequency responses represent a combined effect of enhanced solar UV,

467   which causes warming near the equatorial stratosphere, and solar wind driven processes, which cause

468   cooling at high latitude stratosphere. This may also explain the static high frequency temperature

469   response in the lower stratosphere (~70 hPa) which seems to be independent of those originated in the

470   upper stratosphere (see Figures 3 and 4). Nevertheless, it remains to be understood what mechanism has

471   caused the cooling effect in the high latitude stratosphere in relation to solar wind activity. Recent

472   studies have suggested that the EPP-NOx and its downward decent during winter and spring play an

473   insignificant role on stratospheric ozone and circulation (Lu *et al*. 2008a; Salmi *et al*. 2011). Lu *et al*.

474   (2008a) suggested that changes observed in stratospheric winds and temperatures were unlikely caused

475   by photochemistry associated with EPP-NOx and stratospheric ozone but were more likely due to an

476   indirect dynamical link, *e.g*. changes in wave activity, as they found that the spring temperature and

477   wind variations in relation to changes of geomagnetic Ap index have a sign that is opposite to that

478   expected from the NOx-ozone photochemistry mechanism.

479   The modulating effect of the QBO has not been explicitly studied here due to the limited data

480   records. Nevertheless, our analysis indicates that the QBO may add noticeable contamination to the

481   signals in the temperature near the equatorial stratosphere at 20-30 hPa if no high and low frequency

482   separation is made for the solar signature. This agrees well with the findings of Smith and Matthes

483   (2008). Here, we also found that separating the response into high and low frequency components not

484   only allows isolation of the fast and slow responses but also partially eliminates the QBO contamination

485   at those pressure levels. However, unlike the Northern Hemisphere where a significant solar signature

486   can only be detected when the data are subgrouped according to the QBO phases (*e.g.* Labitzke and van

487   Loon 1988; Lu *et al*. 2009), it is not essential to separate the data according to the QBO phases in order

488   to obtain significant 11-yr SC signal in the Southern Hemisphere.

489   The low frequency responses (> 36 months) are found in the lower stratosphere temperature

490   extending from the North Pole to the South Pole with the signal becoming weaker at mid-latitudes.

491   These low frequency responses could be related to slowly-varying transported ozone anomalies as

492   suggested by Austin *et al*. (2008) and Gray *et al*. (2009). They may also be partially associated with a

493   downward movement of ozone-UV interaction in the upper to middle stratosphere due to a change in the

494   BD-circulation and such a process could account for up to 1 K per solar unit in the observed increase in

495   temperature near the equatorial lower stratosphere (see Figure 4(a;c;e)). Other slow processes such as

496   thermal inertia of the oceans may also play a role (Austin *et al*. 2008; *White et al*. 2003; White and Liu

497   2008).

498   In the troposphere, we found the zonally averaged solar signals are generally more fragmented than

499   those in the stratosphere. At high frequency, there are some indications of downward propagation of

500   solar signals from the stratosphere into the troposphere at high latitudes (see Figure 4 and 7). However,

501   the most significant signal in temperature is a positive response at 30-50° and this can only be obtained

502   when the long-term trend is removed (see figure 2) and is consistent with previous studies (van Loon

503   and Labitzke 1998; Haigh *et al*. 2005; Gleisner and Thejll 2003; Crooks and Gray 2005; Lu *et al.* 2007;

504   Frame and Gray 2010). A significant signal in tropospheric zonal winds was found only in the low

505   frequency domain. The signal is characterized by a weakening of the sub-tropical jet and the effect is

506   symmetric about the equator, consistent with Haigh *et al.* (2005). The magnitude and spatial structure of

507   the signal in tropospheric zonal wind (~1-2 m/s) is in general agreement with the model simulations of

508   Haigh *et al*. (2005; 2006) and Simpson *et al.* (2009), where a positive equator-to-pole temperature

509   gradient was applied in the lower stratosphere. Nevertheless, we have noted that the positive signal in

510   the tropical lower stratosphere / troposphere is much weaker in ECMWF data than those imposed in the

511   model simulations.

512   It has also been suggested that higher solar forcing may cause stronger upward motion in the winter

513   hemisphere subtropics and enhanced downward motion in the summer hemisphere subtropics (van Loon

514   *et al.* 2004; Meehl *et al.* 2008). This response is associated with the "bottom-up" mechanism that is not

515   symmetric about the equator and is longitudinally varying and confined mostly to the Pacific Ocean

516   (Meehl *et al.* 2003; van Loon *et al.* 2007). As our analysis here has mainly focused on the zonal pattern

517   of the signals, our results cannot be directly compared to those reported by Meehl *et al.* (2003; 2008).

518   Using a stratosphere-troposphere coupled GCM, Meehl *et al.* (2009) show that both "top-down" and

519   "bottom-up" mechanisms may work together to induce positive feedbacks in the ocean-atmosphere

520   system that may amplify the response to solar irradiance variations. Further studies are needed to

521   understand how the stratospherically originating changes may amplify the longitudinal variations

522   associated with air-sea interaction in the tropical troposphere.

523   Linear regression between the 11-yr SC and the SAM shows that the solar signal is marked by a

524   strengthening of the stratospheric SAM during winter and a weakening of the SAM in the uppermost

525   stratosphere during spring. However, an 11-yr solar cycle influence in the stratosphere as a cause of

526   change in the tropospheric SAM cannot be established directly or linearly for the extended period of

527   1957-2009; other modulating factors, *e.g.* the QBO, must be taken into account to reveal any significant

528   solar effect on the tropospheric SAM. This is consistent with the results of Roscoe and Haigh (2007)

529   based upon multi-regression analysis where they also used station based Marshall SAM and found that

530   the 11-yr SC signal is not significant. However, a QBO modulation of the polar vortex may itself be

531   modified by the 11-year cycle of solar activity (Labitzke 2003; Salby and Callaghan 2006) and this

532   combined solar-QBO effect has been detected in the SAM by using a composite solar–QBO (SQBO)

533   index for the period of 1958-2006 (Roscoe and Haigh 2007). They showed that SQBO was able to

534   capture more variance in the SAM than the QBO and the 11-yr SC alone and suggested that the effect of

535   the 11-yr SC on the tropospheric SAM is non-linear and is modulated by the QBO. Indeed, the

536   modulation effects of the QBO and the 11-yr SC on the SAM have been studied by Kuroda and Kodera

537   (2005), Kuroda and Shibata (2006) and Kuroda and Yamazaki (2010). As our primary goal here is to

538   study whether or not there is a direct projection of the 11-yr SC on the SAM and also as we are limited

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539 by the amount of data available, we have not studied the *modulation* effects either by the 11-yr SC or by

540 the QBO on the SAM. Therefore, our results are not directly comparable to either the signal of SQBO

541 shown by Roscoe and Haigh (2007) or the QBO or solar modulated SAM patterns studied by Kuroda

542 and co-authors. In addition to aliasing effects of the QBO, long-term trend, volcanoes and the 2002-

543 SSW, the signals could also be affected by ENSO, which may be also related to non-linear effects (*e.g.*

544 Marsh and Garcia, 2007; Calvo *et al*. 2009). Again, due to the limited data available, those effects were

545 not studied here.

546   To check whether or not the signals presented here may have been affected by merging two

547 different data sets together, we have also performed the same analysis by excluding the ECMWF

548 Operational data from our analysis and have found that the results remain qualitatively similar. For the

549 high frequency response, both temperature and zonal wind responses in fact become larger in magnitude

550 though the significant regions remain similar due to a smaller sample size. For the low frequency

551 response, the spatial pattern of the response remains similar but the regions covered by the 95%

552 confidence levels reduce. We also performed the same analysis by including data back to 1968 as

553 Kuroda and Yamazaki (2010) had done. Again the spatial patterns of the solar signals are generally

554 similar though the magnitude of the high frequency response reduces significantly. Thus, the results

555 presented here should be verified in the future, when longer data sets become available. This applies in

556 particular to the upper stratosphere where the impacts of discontinuities are more marked and in the

557 troposphere where the magnitude of the response is small and comparable to the uncertainty range

558 associated with the ECWMF reanalysis data (Uppala *et al*. 2005).

559 5. Conclusions

560   We have studied the characterization of 11-yr SC signals in the SH atmosphere during the winter and

561 spring using ECMWF daily and monthly data from 1979 to 2009. By separating the response into high

562 (< 6 months) and low (>36 months) frequency domains, we have found:

563   1) The 11-yr SC signal is generally more robust in temperature than in zonal wind.

2)   Spatially different 11-yr SC signals exist at high (< 6 months) and low (> 36 months) frequency domains. In the stratosphere, the high and low frequency responses tend to enhance each other near the equator and subtropics, while they oppose one another at high latitudes.

3)   The high frequency response in the stratosphere is marked by an enhanced latitudinal temperature gradient in HS years from the equator to pole and a strengthened stratospheric jet during winter. The response moves poleward and downward from the upper stratosphere to the lower stratosphere by tracking the movement of the stratospheric jet, as noted by Kodera and Kuroda (2002).

4)   In the lower stratosphere, the positive response of temperature to the 11-yr SC is dominated by its low frequency component.

5)   In the stratosphere, the magnitude and the statistical significance of temperature and zonal wind responses to the 11-yr SC are sensitive to the contamination of the 2002 SSW event and major volcanic eruptions but the general spatial pattern of the responses remains similar with or without these data.

6)   In the troposphere, the responses in the high and low frequency domains are of opposite signs but only the low frequency response with warmer temperatures in HS years is significant (figure 2). The low frequency latitudinal temperature gradients and the resulting zonal wind anomalies are consistent with the results of Haigh et al (2005).

7)   In the troposphere, the solar signature in temperature is more sensitive to the long-term trend than to the SSW or the major volcanic eruptions. Linearly removing the trend enhances the signal in the troposphere and weakens the signature in the stratosphere.

8)   A significant projection of the 11-yr SC onto the SAM can only be detected in the stratosphere and in the high frequency component. The signal is marked by a strengthening of the stratospheric SAM during winter and a weakening of the SAM in the uppermost stratosphere during spring.

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597 **References**

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752 **Figure captions**

753 **Figure 1**. Composite differences (high solar –low solar (HS-LS)) of zonal-mean temperature (a;b;c;d)

754 and zonal wind (e;f;g;h) for June-August averages. In cases (a;e), all data from 1979-2009 are included.

755 In cases (b;f), data from year 2002 are excluded. In cases (c;g), years affected by the major volcanic

756 eruptions (*i.e.* 1982, 1983, 1992, and 1993) are excluded. In cases (d;h), data from 2002 and years

757 affected by the major volcanic eruptions are excluded. Statistical confidence levels above 95% are

758 shown as dashed grey contours.

759 **Figure 2**. Composite differences (high solar –low solar (HS-LS)) of zonal-mean temperature (a;b;c) and

760 zonal wind (d;e;f) for June-August averages. In cases (a;d), a Chebyshev type II high-pass filter with a

761 cutoff-period of 6-month is applied. In cases (b;e), a Chebyshev type I low-pass filter with a 36-month

762 cutoff period is used. In cases (c;f), temperature and zonal wind are linearly detrended first and then a

763 Chebyshev type I low pass filter with 36-month cutoff period is applied. Statistical confidence levels

764 above 95% are shown as dashed grey contours.

765 **Figure 3**. Left: monthly climatology zonal-mean zonal temperature (in units of K) for June to October

766 (top to bottom), displayed as lined contour plots in meridional-height cross section from 30°N to 90°N

767 and from 1000 hPa to 1 hPa. Right: same as the left panels but displayed as coloured contour plots for

768 the composite differences of the temperature between high solar and low solar conditions (HS-LS). The

769 areas enclosed within the grey lines indicate that the differences are statistically significant from zero

770 with a confidence level of 95% or above, calculated using a Monte-Carlo trial based non-parametric

771 test. Data which might be affected by the major volcanic eruptions and 2002 stratospheric major

772 warming are excluded.

773 **Figure 4.** Time vs pressure level plot of linear running regression (in K per 100 F10.7-cm solar flux

774 unit) between F_s and equatorial temperature averaged over 5°N to 5°S (a;c;e, where the contour interval

775 is ±0.5 K) and temperature averaged over 55-65°S (b;d;f, where the contour interval is ±2 K). In (a;b),

776 raw daily temperature is used. In (c;d), a high-pass filter with a cutoff-period of 183-days is applied to

777 the daily temperature. In (e;f), a bandpass filter with a bandwidth of 31 to 183 days is applied to the

778   daily temperature. An order 6 Chebyshev type II with passband ripple of 2 decibels is used for (c;d;e;f).

779   For all cases, the temperatures are linearly detrended first and the data from 2002, 1982, 1983, 1991 and

780   1992 are excluded from the regression. Statistical confidence levels above 90% and 95% are shown as

781   light and dark shadings.

782   **Figure 5.** Daily averaged zonal-mean temperatures (K) at 10 hPa, averaged over 0-5°S (1st row) and

783   over 55-65°S (2nd row), for HS (1st column), LS (2nd column) together with daily mean values for HS

784   (the line with red shading) and LS (the line with grey shading) conditions (3rd column). The daily mean

785   values for HS and LS at high frequency (< 183-days) estimated using a Chebyshev type II filter (4th

786   column) are also shown. The shaded regions represent the 95% confidence intervals of the mean. In the

787   HS group, the years in which data might be affected by the major volcanic eruptions are shown as blue

788   lines and the 2002 data are shown as the purple line. The daily mean values are calculated by excluding

789   major volcanic eruptions affected year and 2002 data.

790   **Figure 6**. As in Figure 5 but for temperatures at 50 hPa, averaged over latitude ranges of 10-15°S (1st

791   row) and 55-65°S (2nd row).

792   **Figure 7**. As in Figure 3 but the zonal-mean temperature is replaced by the zonal-mean zonal wind in

793   units of m s^{-1}.

794   **Figure 8**. As in Figure 5 but for zonal-mean zonal wind (m s^{-1}) at 30-40°S, 5hPa (1st row), and at 40-

795   50°S, 50hPa (2nd row).

796   **Figure 9**. As in Figure 4 but for the SAM derived from ECMWF daily data. (a) uses the raw daily

797   SAM; (b) a 183-day high-pass filter is applied to the SAM. The treatment of data and use of filter, lines

798   and shadings are the same as for Figure 4 and the contour interval is 0.25 SAM index per 100 solar unit.

799   **Figure 10**. (a;b) Scatter plot of F_s and July Marshall-SAM index. (c;d) Scatter plot of F_s and November

800   Marshall-SAM index. For (a;c) no filtering is applied to the data; for (b;d) a high-pass filter of 6-month

801   is applied to the data.
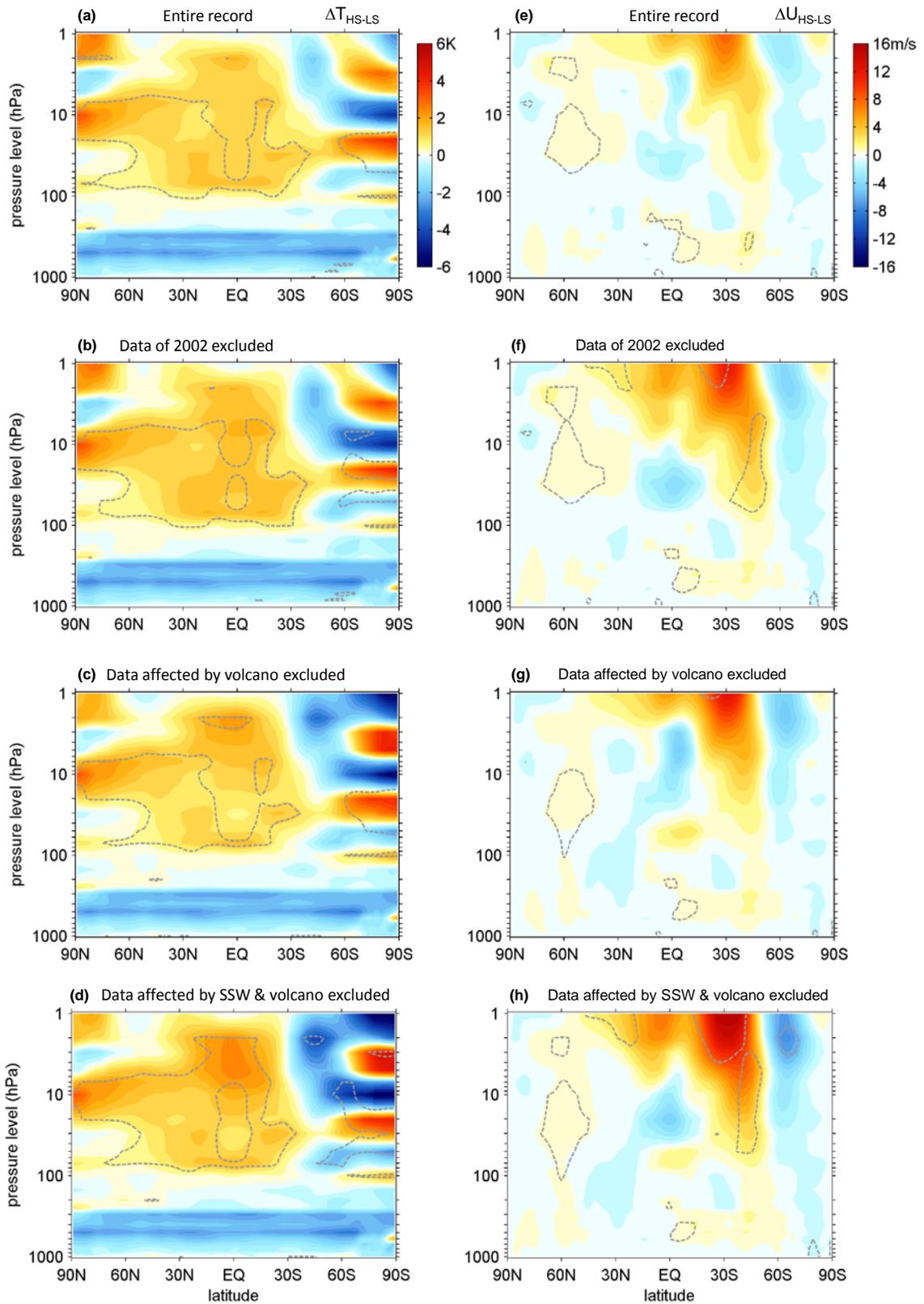
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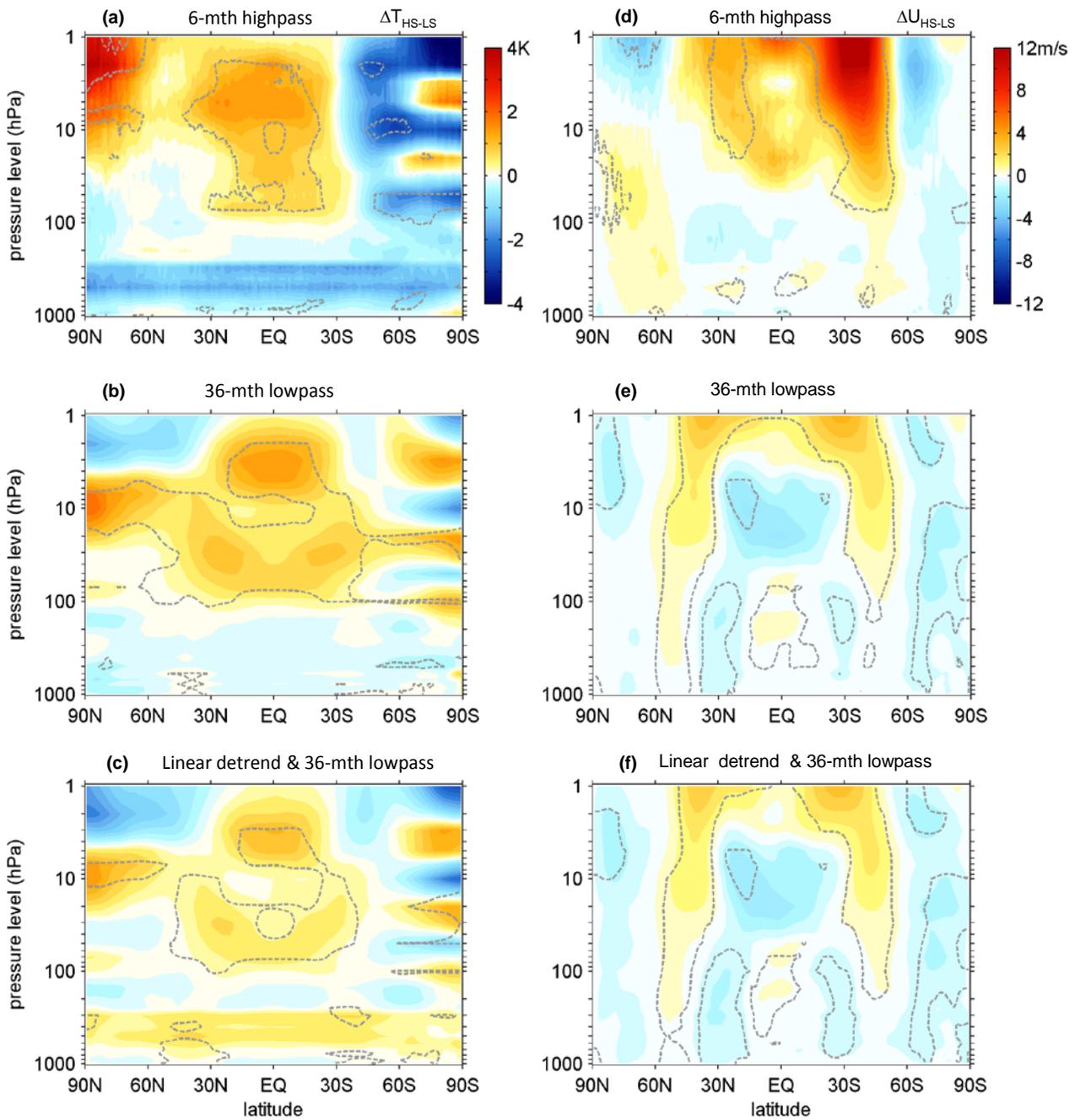
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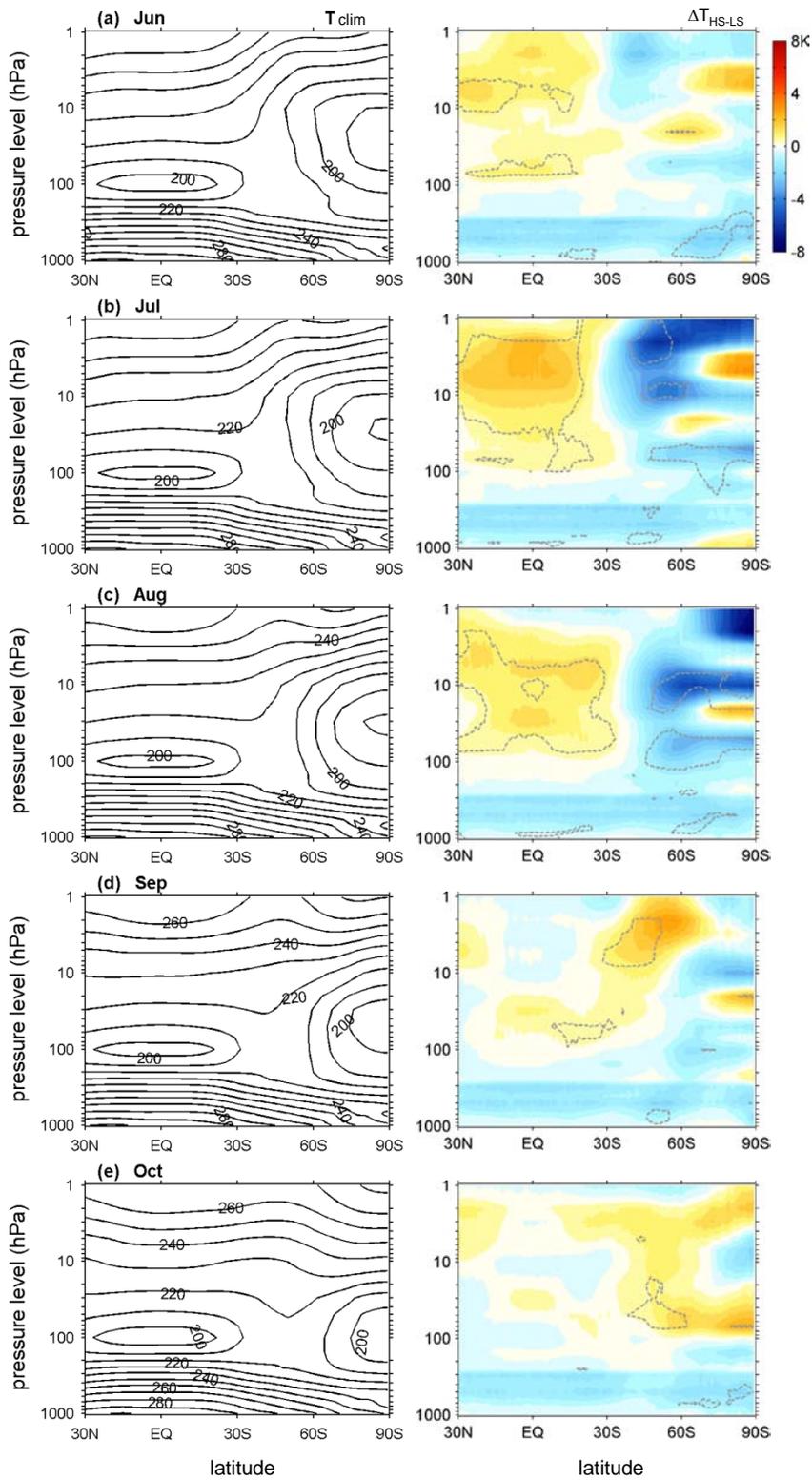
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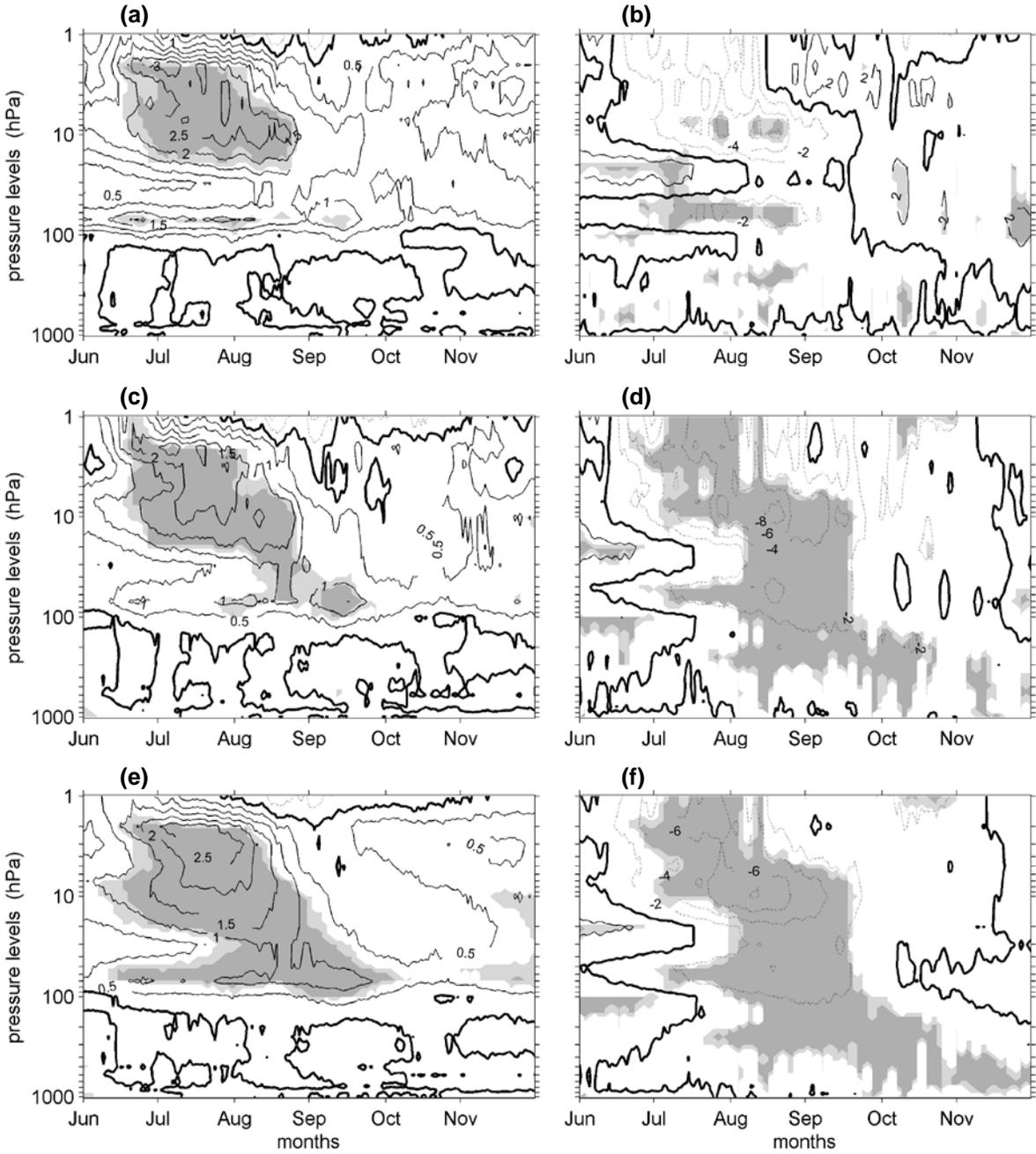
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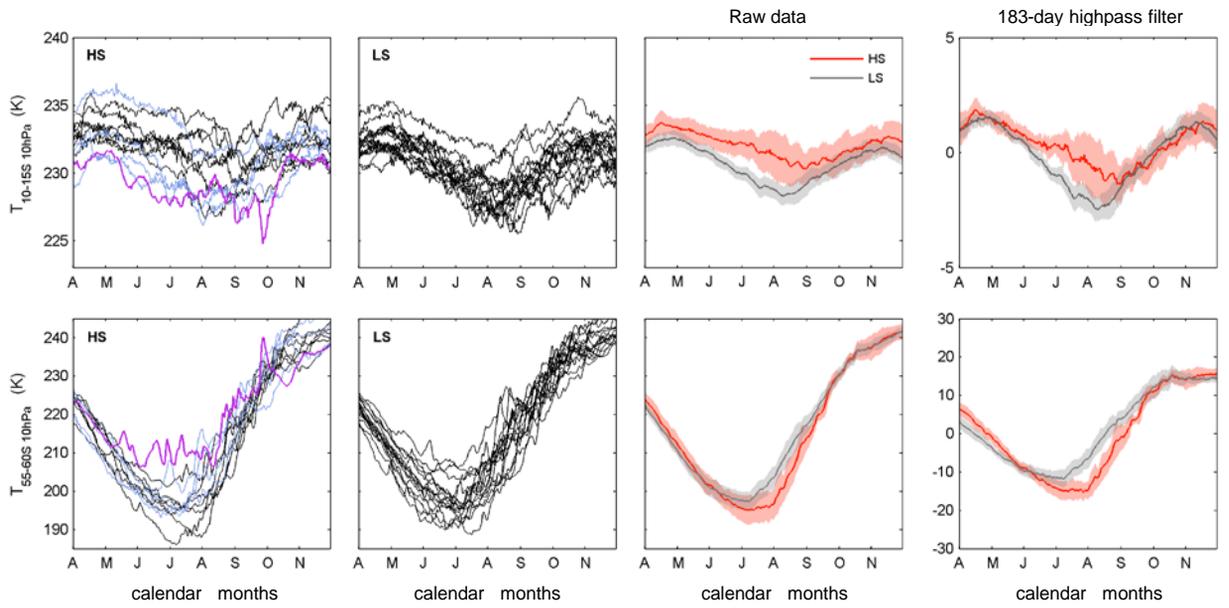
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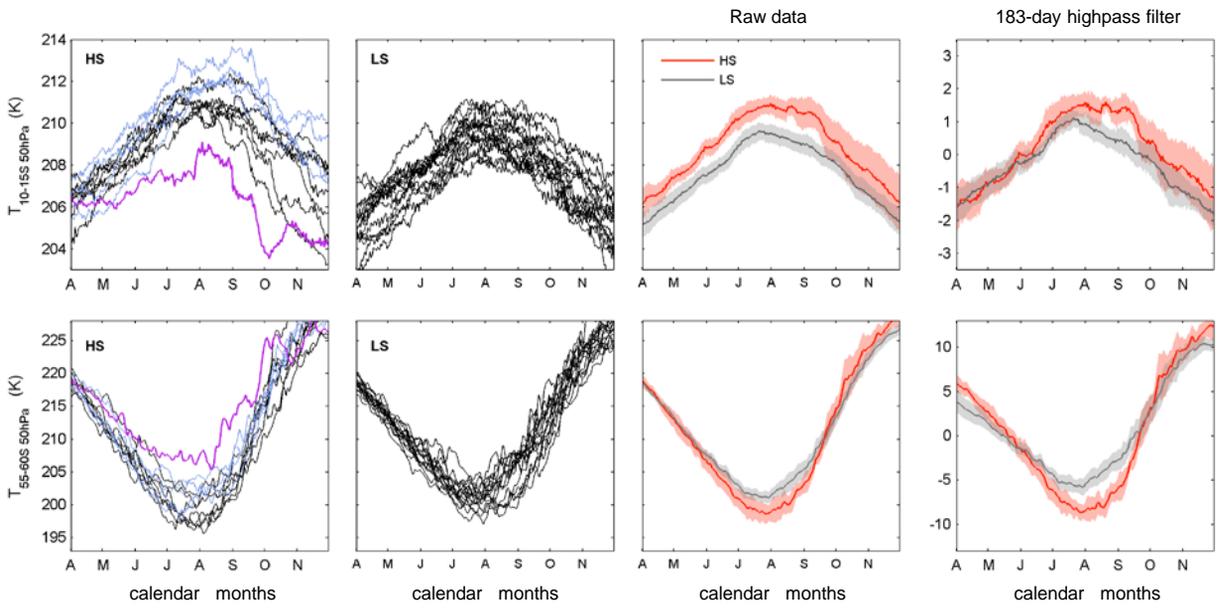
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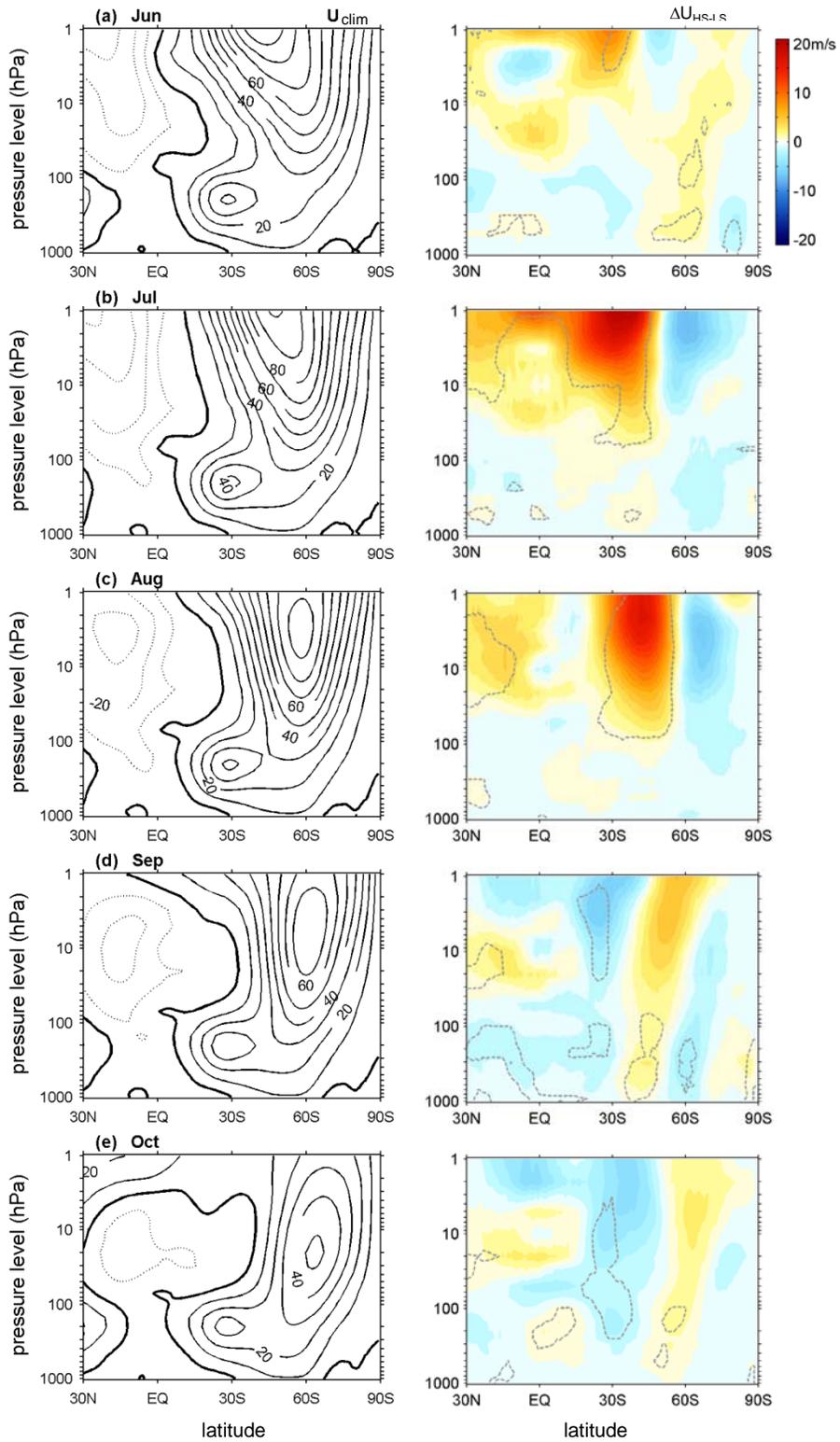
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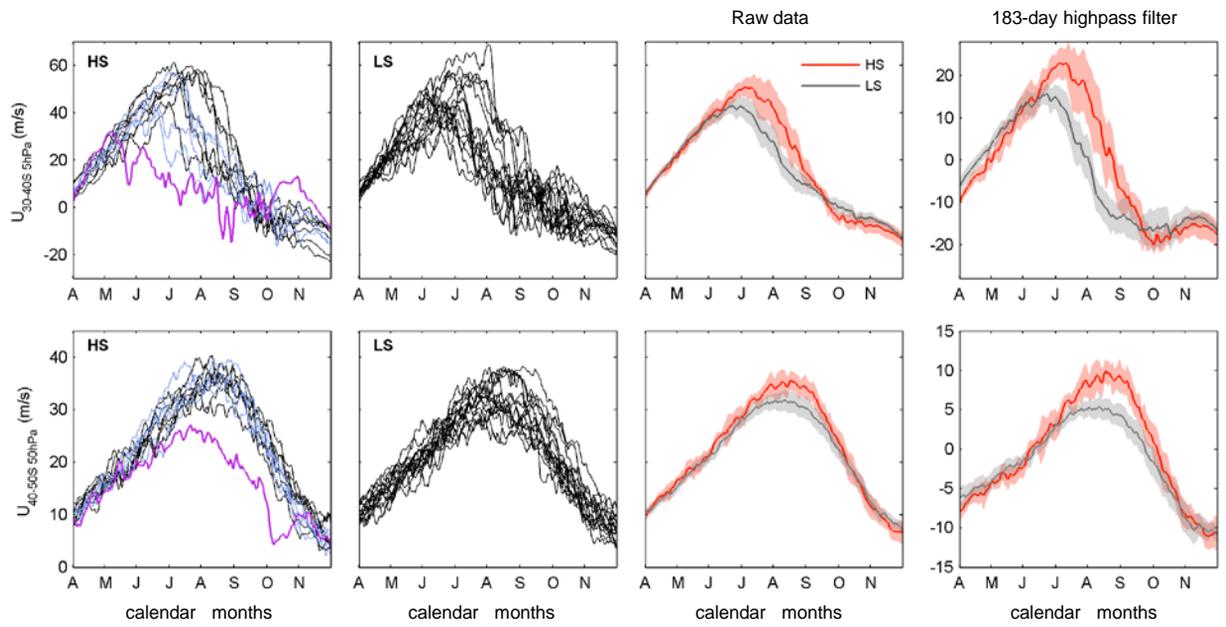
Figure 8

Figure 9

Figure 10