Energetic particle forcing of the Northern Hemisphere winter stratosphere: comparison to solar irradiance forcing

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Variation in solar irradiance is considered an important factor in natural climate forcing. Variations in the solar UV in particular are now regarded as a major source of decadal variability in the stratosphere, influencing surface climate through stratosphere–troposphere coupling. However, by analyzing meteorological re-analysis data we find that the magnitude of the solar controlled energetic particle forcing signal in stratospheric zonal mean zonal winds and polar temperatures is equivalent to those arising from solar irradiance variations during the Northern Hemisphere polar winter months. We find that energetic particle forcing drives warmer polar upper stratospheric temperatures from early winter leading to an anomalously strong polar night jet via modulation of the vertical temperature gradient. By midwinter the stratosphere–troposphere coupling pathway becomes analogous to the solar UV impact at high latitudes. This not only highlights the importance of the energetic particle forcing contribution to stratospheric circulation, but enables us to understand the pathways responsible for the previously reported energetic particle forcing impacts on the troposphere in terms of the coupling of solar UV forcing to dynamics in the latter part of the winter.

Keywords: energetic particle precipitation, stratosphere, dynamics, stratosphere–troposphere connection, solar forcing, solar cycle, solar variability

1. INTRODUCTION

Understanding the role of the Sun and solar variability as a source of external forcing to the atmosphere has become increasingly important with the need to understand all factors, both natural and anthropogenic, contributing to the Earth's climate. The focus has been on the atmospheric effects of climate variability arising from solar total and spectral irradiance variations (the latter most importantly in the UV) and these are known to drive changes on both annual and seasonal scales [1–3]. Recently the role of direct solar as well as solar activity controlled magnetospheric energetic particle forcing [4, 5] (here denoted as EPF for Energetic Particle Forcing, this includes electrons of auroral to relativistic energies, i.e., tens of keV up to few MeV, as well as protons.), in the form of electron and proton precipitation into the atmosphere, has sparked interest due to it's potential influence on stratospheric circulation [6–11]. EPF effects on middle atmosphere chemistry through NO_x and HO_x production and their impact on atmospheric ozone balance are well recorded in the literature [see e.g., review by 7]. These effects tend to be particularly focused on the winter polar hemisphere where the impact on atmospheric chemical balance can last for months. The first idealized model study looking beyond stratospheric chemical changes arising from EPF [6] suggested that the impact on stratospheric and tropospheric temperatures, even on annual scales, might be comparable to those arising from solar UV variations between the solar maximum and solar minimum, but the physical mechanisms linking the EPF influence on chemical changes in the middle atmosphere

to stratospheric and tropospheric circulation and dynamics have remained elusive.

Stratospheric circulation shows largest variability during the winter when planetary scale atmospheric waves interact and disturb the polar vortex [12], which is generated from the equator-to-pole temperature gradient. This so called wave–mean flow interaction provides a way for the stratosphere to significantly influence tropospheric climate and it has been shown that stratospheric circulation anomalies can be used to improve and extend the range of tropospheric weather forecasts [13–16]. This provides a direct application and motivation to improve understanding of mechanisms contributing to stratospheric circulation.

Variations in total solar irradiance (TSI) and solar UV are considered to be the main sources of natural climate forcing [1]. In this paper, we contrast Northern Hemisphere winter-time dynamical and circulation conditions between times of high energetic particle forcing, solar irradiance minimum, and solar irradiance maximum conditions. We focus on the Northern Hemisphere where longer reanalysis datasets are available than for the Southern Hemisphere. We present a mechanism of energetic particle forcing driving dynamical changes in the atmosphere that are as intense as those arising from the known solar irradiance variations. Our results show how these changes propagate through the stratosphere. Contrasting our results with previous work we are able to provide an explanation of how the stratospheric signals can ultimately reach all the way to the surface via stratosphere–troposphere coupling. We focus on the winter

months when stratospheric anomalies are more likely to propagate to the surface [17].

2. MATERIALS AND METHODS

For our meteorological data analysis we use zonal mean zonal wind (U) and zonal mean temperature (T) from the blended ERA-40 [18] and ERA-Interim [19] reanalysis dataset from 1958 to 2012 (switch to Interim data in Jan 1989). For separation of the solar irradiance and energetic particle forcing signals we group the ERA data using solar radio flux (F10.7 cm) observations and geomagnetic/particle precipitation activity indices as detailed below.

Variation in EPF is more linked to transient phenomena in the Sun and solar wind than the progression of the solar cycle, which controls solar irradiance variations. EPF also shows larger variability over time than irradiance variations do from solar maximum (max) to solar minimum (min). **Figure 1** presents how the overall solar irradiance (F10.7 cm) varied over 4.5 recent solar

cycles, contrasting how EPF levels, as proxied by the geomagnetic activity index A_p, varied during the same time period. A pronounced feature is the 2–3 year lag of the main peak in the EPF forcing relative to the solar cycle. Thus, EPF can provide a way of influencing regional climate which is out of phase with the solar cycle. For EPF we use the geomagnetic activity index A_p as a proxy. As no continuous particle observations are available for the period concerned, this approach is widely used [see 8].

We average both the solar irradiance cycle and EPF proxies over the 4 month winter period Oct–Jan. The averaged data are also shown in the figure. Following the method of thirds used by Ineson et al. [2] for the solar irradiance signals, we determine solar minimum and solar maximum as the lower and upper thirds of the mean solar radio flux (F10.7 cm). The solar maximum (1959, 1969, 1979, 1980, 1982, 1983, 1989, 1990, 1991, 1992, 2000, 2001) and minimum (1964, 1966, 1996, 1997, 2007, 2008, 2010, 2011) years are shown in **Figure 1** as red and blue bars, respectively. The years are also listed in **Table 1**. We note that defining
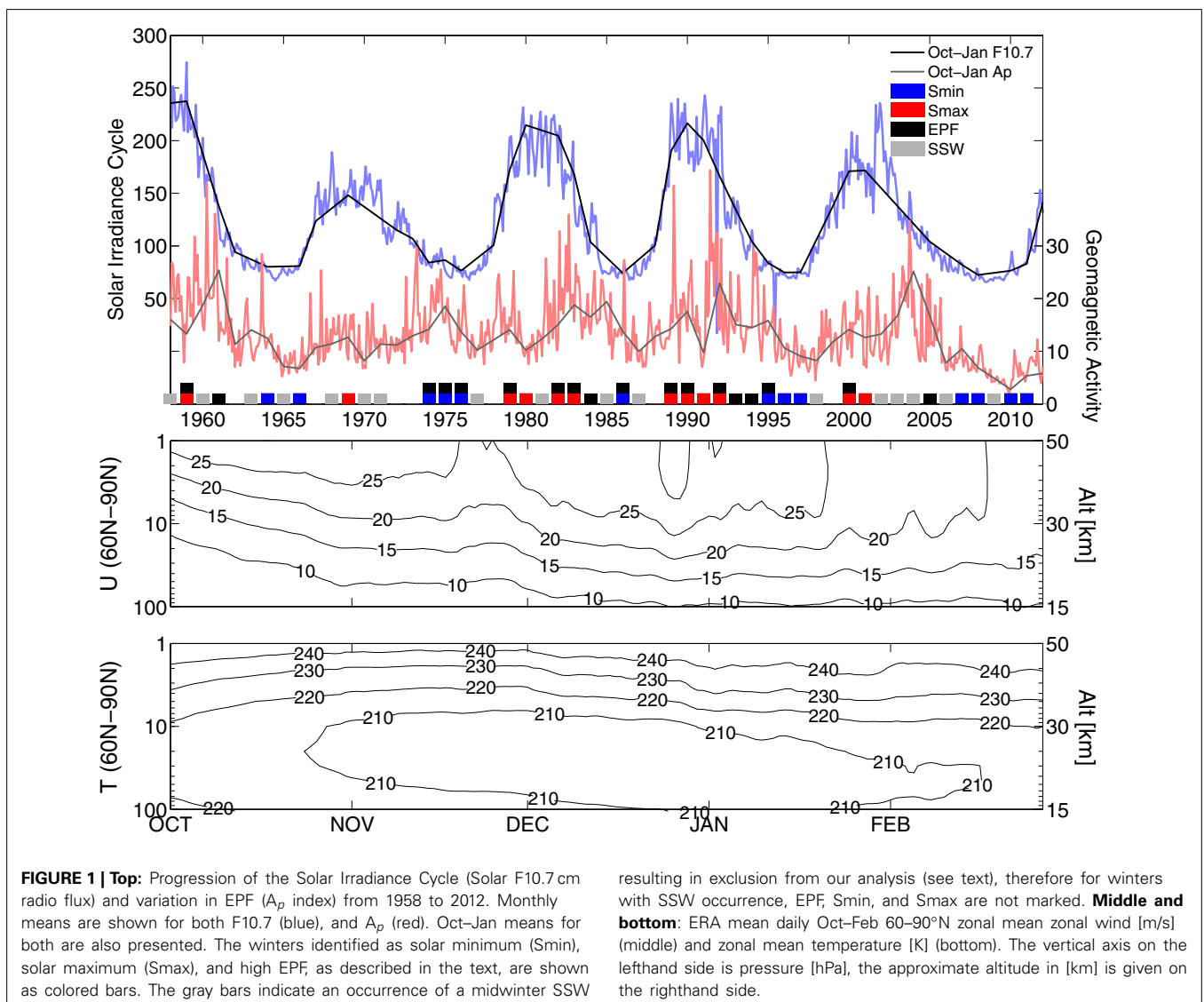

FIGURE 1 | Top: Progression of the Solar Irradiance Cycle (Solar F10.7 cm radio flux) and variation in EPF (A_p index) from 1958 to 2012. Monthly means are shown for both F10.7 (blue), and A_p (red). Oct–Jan means for both are also presented. The winters identified as solar minimum (Smin), solar maximum (Smax), and high EPF, as described in the text, are shown as colored bars. The gray bars indicate an occurrence of a midwinter SSW

resulting in exclusion from our analysis (see text), therefore for winters with SSW occurrence, EPF, Smin, and Smax are not marked. **Middle and bottom**: ERA mean daily Oct–Feb 60–90°N zonal mean zonal wind [m/s] (middle) and zonal mean temperature [K] (bottom). The vertical axis on the lefthand side is pressure [hPa], the approximate altitude in [km] is given on the righthand side.

Table 1 | Years included in the analysis.

Case	Years
Solar maximum	1959, 1969, 1979, 1980, 1982, 1983, 1989, 1990, 1991, 1992, 2000, 2001
Solar minimum	1964, 1966, 1996, 1997, 2007, 2008, 2010, 2011
High energetic particle forcing	1959, 1961, 1979, 1982, 1983, 1984, 1989, 1990, 1992, 1993, 1994, 2000, 2005

Years correspond to the end of the Northern Hemisphere winter season, i.e., "1979" = Oct 1978–Feb 1979.

solar maximum and minimum based on means or medians leads to quantitatively similar results as the thirds.

High EPF conditions are determined as those where the Oct–Jan A_p index is above the median of the 1958–2012 period. Using medians is very suitable for the highly varying A_p [9] index, although quantitatively similar results are obtained when using means. The high EPF years (1959, 1961, 1979, 1982, 1983, 1984, 1989, 1990, 1992, 1993, 1994, 2000, 2005) are shown in **Figure 1** as black bars. Overlapping years for EPF and solar minimum were additionally removed (shown the figures as overlapping black and blue bars). Some overlap remains for EPF and solar maximum (overlapping black and red bars).

We exclude years during which midwinter sudden stratospheric warmings occur (**Figure 1**, gray bars) as previous work has shown that the stability of the polar vortex is important for observing the coupling of EPF to dynamical parameters [8, 9, 20]. It is important to note that also QBO, volcanoes, and ENSO, among others, influence the stratosphere. Separation of all factors is challenging with a limited reanalysis dataset, however, the role of these in connection to EPF has been discussed e.g., by Lu et al. and Seppälä et al. [9, 20].

All reanalysis variables in **Figures 2**, **3** are shown as differences from the blended ERA dataset mean (this is referred to as anomaly). Statistical significance is included, with details given in the Figures. For reference purposes, the two bottom panes in **Figure 1** present the daily blended ERA dataset mean polar zonal mean zonal wind and zonal mean temperature. The use of anomalies instead of composite differences (e.g., Solar maximum–Solar minimum) enables us to contrast the propagation of the signals in three different cases, which would not be possible if using composite differences. For composite differences for high and low EPF see e.g., [9, 21].
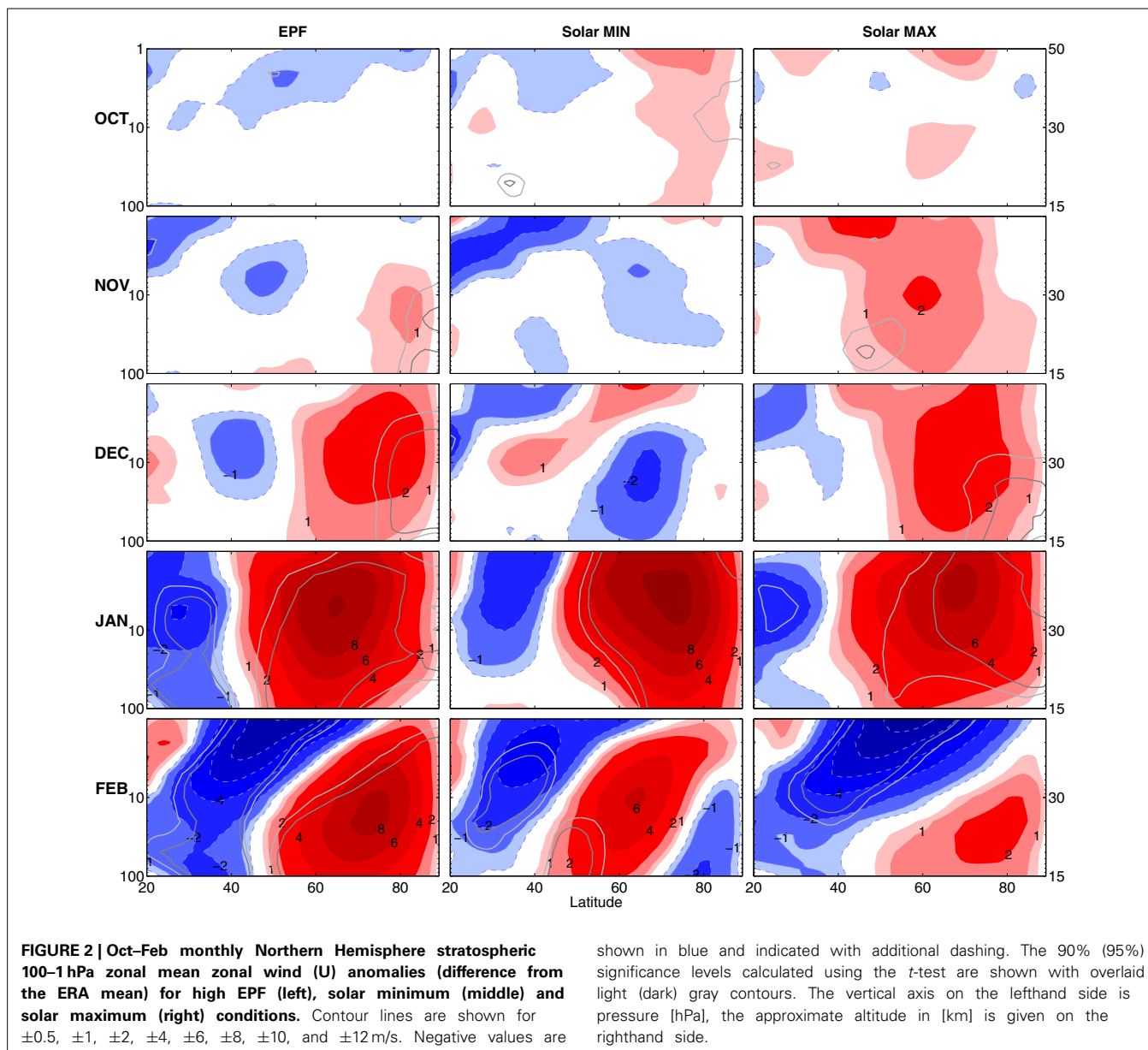
3. RESULTS AND DISCUSSION

Figure 2 shows the monthly October to February zonal mean zonal wind (U) anomalies for the high EPF, solar min and solar max conditions. The EPF case highlights strengthening winds at high polar latitudes (north of 70°N) from November onwards. Such signals are not present in the October mean and are very weak even at daily scales as presented later. The EPF response is notably different from the solar max conditions, which characteristically shows a stronger sub-tropical upper stratospheric jet in November with a gradual poleward and downward propagation into a stronger high latitude polar night jet as the winter progresses [12, 22]. For both EPF and solar min the stronger polar

night jet persists longer than during solar max, with the EPF case featuring anomalously high polar winds across the stratosphere. The key difference between EPF and solar max is the direct influence on the polar latitudes for EPF, instead of the early winter sub-tropical upper stratospheric jet enhancement seen at solar max.

The underlying cause for the initial circulation anomalies driven by variations in solar irradiance is understood to arise from the modulation of atmospheric temperatures via direct heating and additional stratospheric ozone feedback [1]. This is also visible from **Figure 3** which shows the propagation of polar temperature anomalies from October to February for the three cases. The polar upper stratosphere around 2–3 hPa shows slightly more persistent cooling from October to November during solar max than during solar min as expected [22], but the response to EPF in early winter is the opposite, with a warmer upper stratosphere above ∼5 hPa from mid-October onwards. In a manner similar to solar min, this will weaken the equator-to-pole temperature gradient. However, under high EPF conditions, heating the upper stratosphere will also increase the stratospheric vertical temperature gradient. Modulation of the vertical temperature gradient can further influence the horizontal momentum flux [23]. The momentum flux anomalies reveal that this is taking place for high EPF in October with increasing northward momentum as October progresses. The changes in the momentum flux act to drive the zonal flow resulting in the delayed response in the zonal winds as seen in **Figure 2**. The strengthened zonal wind will further have an influence on wave propagation which will provide another wave-mean flow feedback to the winds and further down to the troposphere [9]. Despite different initial causes for the EPF and solar UV zonal wind anomalies, the similar end effect on the polar night jet can lead to coupling into the troposphere in both cases.

This suggest that, similarly to the better understood solar UV effects on troposphere [see e.g., 1, 2, 12], the proposed EPF effects on the troposphere [see e.g., 6, 8, 10, 24] are likely to be arise from top–down coupling. The results of Seppälä et al. [9] and Lu et al. [25] have already shown that the wave-mean flow interaction plays a critical role in transferring the signal, and our results now suggest that the propagation of the zonal mean zonal wind and zonal mean temperature signals from December onwards is comparable to the top–down coupling signals arising from solar UV for solar maximum conditions [12]. This comparison, of course, does not include any possible lagged tropospheric effects from solar UV variations, but rather we are addressing the role of the stratosphere in the top–down coupling.

Our results show that the dynamical responses are initiated early in the Northern polar winter season, with first temperature anomalies appearing in the upper stratosphere as early as mid-October, and zonal wind anomalies occurring from November. Recent observational results [26] have demonstrated that even moderate geomagnetic storms are able to drive sufficient levels of EPF into the atmosphere to cause significant ozone loss near and above the stratopause. As these types of storms are much more frequent than those arising solely from large eruptions in the Sun (i.e., Solar Proton Events) [27], it is now proving likely that EPF has more long term influence over middle atmosphere
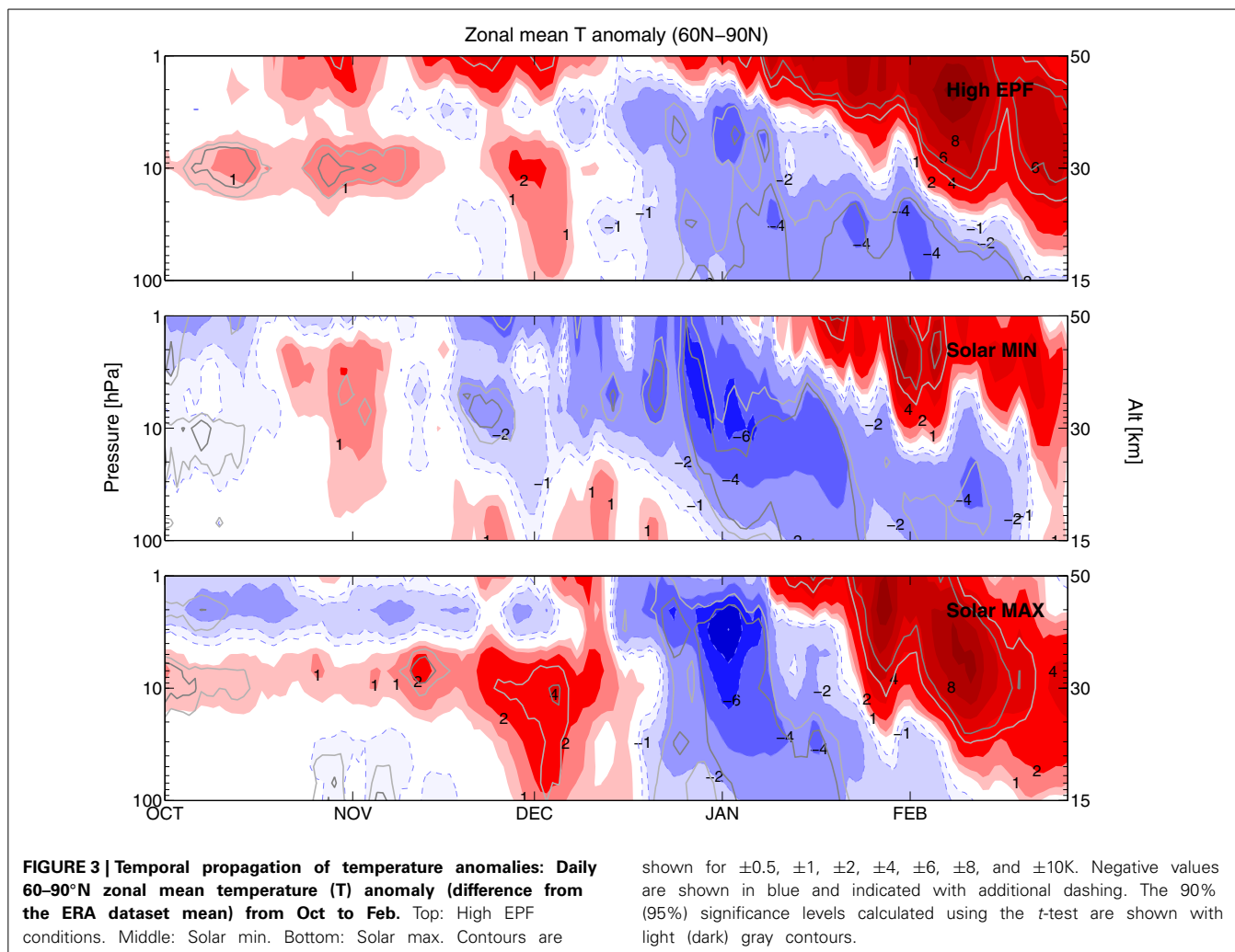
FIGURE 2 | Oct–Feb monthly Northern Hemisphere stratospheric 100–1 hPa zonal mean zonal wind (U) anomalies (difference from the ERA mean) for high EPF (left), solar minimum (middle) and solar maximum (right) conditions. Contour lines are shown for ±0.5, ±1, ±2, ±4, ±6, ±8, ±10, and ±12 m/s. Negative values are shown in blue and indicated with additional dashing. The 90% (95%) significance levels calculated using the *t*-test are shown with overlaid light (dark) gray contours. The vertical axis on the lefthand side is pressure [hPa], the approximate altitude in [km] is given on the righthand side.

ozone balance than previously expected. Reduced ozone levels at these altitudes at high latitudes during the polar winter season could result in positive temperature anomalies as the ozone radiative effect is not dominated by the solar short wave heating, but rather terrestrial long wave cooling [9, 28, 29], although it is important to note that while this temperature effect from the EPF impact on ozone has been suggested, it has thus far not been confirmed from observations.

Scaife et al. [30] proposed a 1–3 year lagged North Atlantic climate (North Atlantic Oscillation) response to the solar irradiance cycle via extended memory of the ocean heat content. While this mechanism would impact the climate at the surface level, it is unclear how, or to what extent, the stratosphere could be affected. In this context it is interesting to note that Baumgaertner et al. [10] found in model simulations that geomagnetic activity

controlled mesospheric EPF NO_x production, and the consequent ozone loss lead to more positive Northern Annular Mode (NAM) for high geomagnetic activity. The NAM and the North Atlantic climate are closely related [31]. It should be noted here that a potential link between geomagnetic activity and the North Atlantic Oscillation has also been discussed by several others [see e.g., 32, and references therein]. Therefore it could be possible that several factors, both top–down, as in the EPF case, and bottom–up (the lagged signal from solar irradiance via ocean heat memory) could be contributing to the observed annual variability in the Northern Hemisphere polar region.

4. CONCLUSIONS

We show that the Northern winter hemisphere stratosphere is influenced by solar activity driven energetic particle forcing at

FIGURE 3 | Temporal propagation of temperature anomalies: Daily 60–90°N zonal mean temperature (T) anomaly (difference from the ERA dataset mean) from Oct to Feb. Top: High EPF conditions. Middle: Solar min. Bottom: Solar max. Contours are shown for ±0.5, ±1, ±2, ±4, ±6, ±8, and ±10K. Negative values are shown in blue and indicated with additional dashing. The 90% (95%) significance levels calculated using the t-test are shown with light (dark) gray contours.

a level that is comparable to that of the solar irradiance forcing. Our results show that this effect starts early in the winter season. Furthermore, with a comparable effect on stratospheric polar night jet, the further late winter EPF influence on the troposphere presented by Rozanov et al. and Seppälä et al. [6, 8] and Baumgaertner et al. [10] could be understood along the lines of the solar UV top–down coupling propagating downwards via the stratosphere–troposphere connection at high latitudes in later winter. Even though the initial effects on stratospheric dynamics differ, both influence the stratospheric polar night jet—key for providing the downwards coupling to the troposphere. Since the irradiance and particle forcing driven by the Sun typically have different magnitudes and phases of variation during the solar cycle, energetic particle forcing could provide an out-of-phase forcing mechanism from the Sun to the climate of the Earth's winter hemisphere.

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