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• **Letter** •

Decadal Variation of the Impact of La Niña on the Winter Arctic Stratosphere

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ABSTRACT

The impact of La Niña on the winter Arctic stratosphere has thus far been an ambiguous topic of research. Contradictory results have been reported depending on the La Niña events considered. This study shows that this is mainly due to the decadal variation of La Niña's impact on the winter Arctic stratosphere since the late 1970s. Specifically, during the period 1951–78, the tropospheric La Niña teleconnection exhibits a typical negative Pacific–North America pattern, which strongly inhibits the propagation of the planetary waves from the extratropical troposphere to the stratosphere, and leads to a significantly strengthened stratospheric polar vortex. In contrast, during 1979–2015, the La Niña teleconnection shifts eastwards, with an anomalous high concentrated in the northeastern Pacific. The destructive interference of the La Niña teleconnection with climatological stationary waves seen in the earlier period reduces greatly, which prevents the drastic reduction of planetary wave activities in the extratropical stratosphere. Correspondingly, the stratospheric response shows a less disturbed stratospheric polar vortex in winter.

Key words: La Niña, stratospheric polar vortex, decadal variation, planetary waves

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1. Introduction

Processes through which ENSO (El Niño–Southern Oscillation) influences the stratospheric polar vortex have been examined in many studies. It is now well known that El Niño has a significant warming and weakening effect on the winter Arctic stratosphere (Sassi et al., 2004; Manzini et al., 2006; Garfinkel and Hartmann, 2008; Ren et al., 2012; Xie et al., 2012; Hu et al., 2014a, 2016; Rao and Ren, 2016). The primary pathway through which El Niño disturbs the stratospheric circulation is its tropospheric teleconnection, which is akin to the PNA (Pacific–North America) pattern (Garfinkel and Hartmann, 2008). The El Niño teleconnection enhances the propagation of planetary-scale wave activity and the convergence of wavenumber-1 Eliassen Palm (EP) flux in the polar stratosphere and leads to a weak polar vortex.

However, compared with that of El Niño, the impact of La Niña on the Arctic stratosphere is relatively controversial. Although it has been said that, in general, La Niña corresponds to a negative PNA pattern and has a similar but opposite effect on the winter Arctic stratosphere (Garfinkel and Hartmann, 2007; Rao and Ren, 2016), it has been argued that the amplitude of Arctic La Niña anomalies is much smaller than that of El Niño (Manzini et al., 2006; Free and Seidel, 2009; Butler et al., 2014). Based on the composite results of the four coldest La Niña events during the period 1980–99, Manzini et al. (2006) even pointed out that the stratospheric response to La Niña is negligible. In view of this, most relevant studies have focused only on the El Niño signal in the stratosphere. The objective of the current study, therefore, is to revisit La Niña's impact on the winter Arctic stratosphere, based on a longer reanalysis time series that is now available. We show that there is a decadal variation of La Niña's impact on the winter Arctic stratosphere from the late 1970s that is largely responsible for the aforementioned issue.

2. Data and method

This paper uses daily and monthly data derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis, covering January 1950 to December 2015 (Kalnay et al., 1996). We focus

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on the detrended data fields with the linear trend for each day or seasonal mean over 1951–2015 removed. However, the main conclusions remain steady when the long-term trend is considered.

A La Niña event is identified when the November–March mean sea surface temperature anomaly from the Hadley Centre (Rayner et al., 2003) over the Niño 3.4 region (5°N–5°S, 170°–120°W) drops below −0.5 K from the 1951–2015 climatology. There are in total 22 La Niña events during the period 1951–2015, with 10 during 1951–78 (1950/51, 1954/55, 1955/56, 1964/65, 1967/68, 1970/71, 1971/72, 1973/74, 1974/75, 1975/76) and 12 during 1979–2015 (1983/84, 1984/85, 1988/89, 1995/96, 1998/99, 1999/00, 2000/01, 2005/06, 2007/08, 2008/09, 2010/11, 2011/12).

Different to the composite methods used in previous literature, during which La Niña events were chosen subjectively either from a relatively short period like 1980–99 (e.g., Manzini et al., 2006) or from the whole period from 1958 to 2005 (e.g., Free and Seidel, 2009), we separate the La Niña events identified from the period 1951–2015 into two groups: one during the period 1951–78 and the other during the period 1979–2015. Then, composite analyses associated with these La Niña events during each period are performed. Such an approach is mainly inspired by two relatively new and independent studies. Firstly, Zhou et al. (2014) found that the tropospheric El Niño teleconnection over the PNA region shifts eastwards in a warmer climate. They pointed out that, compared to that in 1949–78, the El Niño-related Aleutian low shifted eastwards into the Gulf of Alaska in the period 1979–2008. This motivates us to infer a similar decadal variation in the tropospheric La Niña teleconnection since the late 1970s. More importantly, Butler et al. (2014) show that the frequency of stratospheric sudden warming events during La Niña winters after 1979 is much higher than that before 1979 (also see Table S1 and Text S3). Thus, it is reasonable to separate the whole period of 1951–2015 into two sub-periods, in consideration of the significant effect of stratospheric sudden warming events on the intraseasonal variability of the extra-

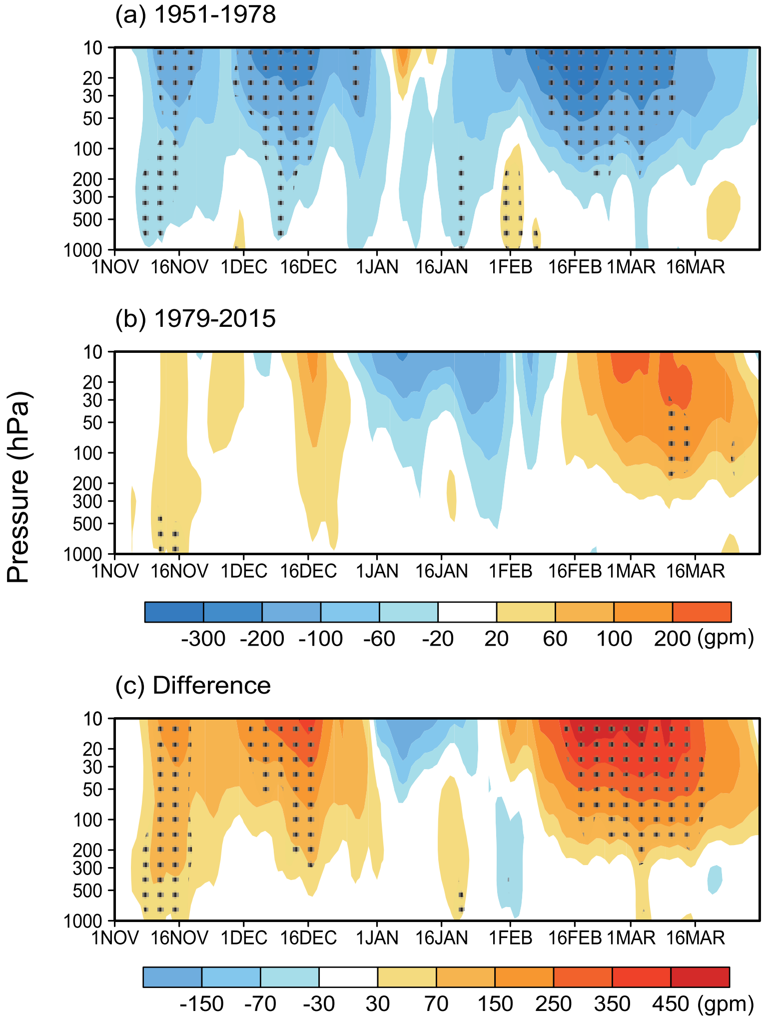

Fig. 1. Temporal evolution of the geopotential height anomalies over the polar region (70°–90°N, 0°–360°), composited for La Niña events during the periods (a) 1951–78 and (b) 1979–2015, and (c) their difference (later minus early). The areas where the anomalies exceed the 90% confidence level are dotted [based on a two-tailed Student's *t*-test (the same for the other figures, below)].

tropical stratospheric circulation (e.g., Charlton and Polvani, 2007; Hu et al., 2014b, 2015).

3. Results

3.1. *Decadal variation of the winter Arctic stratospheric La Niña anomalies*

Figure 1 shows the daily evolution of the polar mean geopotential height anomalies associated with La Niña events during each period. It is apparent that La Niña clearly strengthens the winter Arctic stratosphere during the period 1951–78 (Fig. 1a). Negative height anomalies are observed through almost the entire time period from November to March. In contrast, the La Niña anomalies during the period 1979–2015 generally exhibit an out-of-phase relationship with those during the period 1951–78, but the amplitudes of the anomalies are much weaker (Fig. 1b). The most pronounced differences between the two periods are present from mid-February to mid-March (Fig. 1c). Significant positive anomalies are also found around mid-November and mid-December.

To further demonstrate this contrast, the composite DJFM (December–March) mean geopotential height anomalies related to La Niña at 30 hPa are illustrated in Fig. 2. We can see that, during the period 1951–78, the 30-hPa stratosphere exhibits a strong vortex with significant negative height anomalies dominating the polar region (Fig. 2a). However, the 30-hPa La Niña-related polar vortex is relatively weak during the later period of 1979–2015; both positive and negative height anomalies are observed in the polar region (Fig. 2b). The difference in height anomalies between the two periods is statistically significant in the Arctic Ocean–Northern Eurasia sector (Fig. 2c).

3.2. *Dynamical cause for the decadal variation*

The primary pathway through which both El Niño and La Niña disturb the stratospheric circulation is their tropospheric teleconnection over the PNA region (Sassi et al., 2004; Garfinkel and Hartmann, 2008; Xie et al., 2012, 2014; Rao and Ren, 2016). To examine the dynamical cause for the decadal variation of the stratospheric La Niña signal, Fig. 3 shows the DJF (December–February) mean geopotential height anomalies at 500 hPa associated with each group of La Niña events. It can be seen that, during the period 1951–78, the mid-tropospheric La Niña teleconnection shows a significant negative PNA pattern, with the anomalous high across the North Pacific and the anomalous low over northwestern Canada, although the anomalous high over the southeastern United States is barely distinguishable (Fig. 3a). The spatial correlation coefficient between this typical La Niña teleconnection and the DJF climatological eddies over the extended PNA region [(30°–90°N, 120°E–100°W); purple boxes in Fig. 3] reaches −0.44 (significant at the 99% confidence level). According to the linear interference mechanism in Garfinkel et al. (2010), the North Pacific high destructively interferes with the climatological stationary trough and leads to a dramatic decrease in the planetary wavenumber-1 in the extratropical stratosphere, and thus a strengthened polar vortex (Figs. 1a and 2a). However, during the period 1979–2015, the La Niña teleconnection changes greatly, showing a dipole in the PNA region, with the anomalous high confined to the northeastern Pacific and anomalous low over the Arctic Ocean (Fig. 3b). The spatial correlation coefficient is only −0.03 during this period. Furthermore, the differences in the tropospheric teleconnections between the two periods are generally in phase with the climatological eddies (Fig. 3c; $r = 0.55$, significant at the 99% confidence level). This could prevent the drastic reduction of planetary-wave activities in the extratropical stratosphere seen in the earlier period and weaken La Niña's effect on the stratospheric polar vortex in the later period. As expected, a relatively weak stratospheric polar vortex is observed during the period 1979–2015 (Figs. 1b and 2b).

Finally, we examine the vertical component of EP (EP_z) flux to further illuminate the cause of the decadal varia-

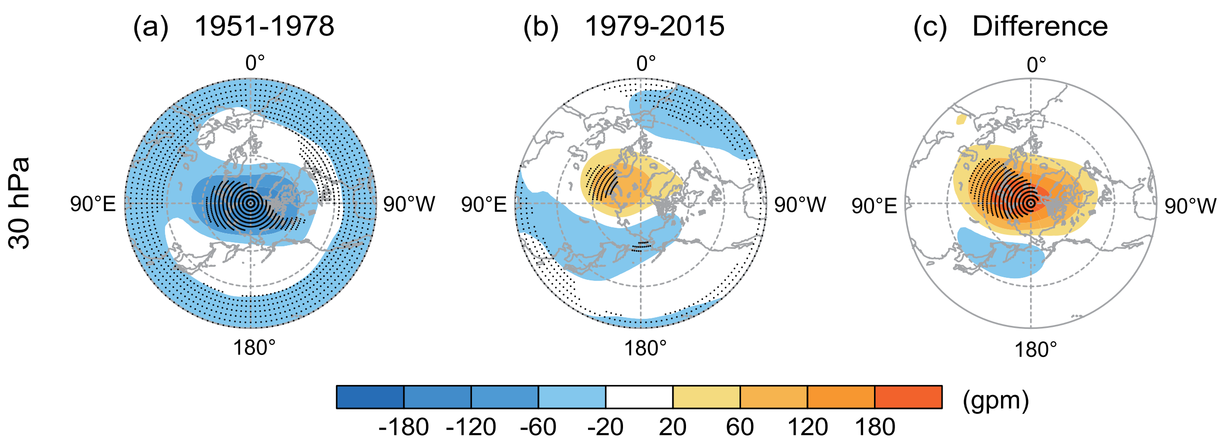

Fig. 2. DJFM mean 30-hPa geopotential height anomalies, composited for La Niña events during the periods (a) 1951–78 and (b) 1979–2015, and (c) the difference between the two periods (later minus early). The areas where the anomalies exceed the 90% confidence level are dotted.

tion of La Niña signals in the Arctic stratosphere. Figure 4 shows the daily evolution of extratropical EP_z flux. It is obvious that, associated with the decadal variation of the tropospheric La Niña teleconnection, the evolution of stratospheric EP_z flux anomalies by planetary waves (wavenumber-1 to wavenumber-3) also exhibit an out-of-phase relationship between the period 1951–78 and 1979–2015 (Figs. 4a and c). We find that the EP_z flux variability corresponds well to that of the height anomalies, with the former leading the latter by several days (Figs. 4a and c vs Figs. 1a and b). For example, the significant negative EP_z flux anomalies from mid-January to mid-February play a crucial role in strengthening the stratospheric polar vortex from mid-January to early March during the period 1951–78 (Figs. 4a and 1a). Similarly, during the period 1979–2015, the relatively weak and upward EP_z flux anomalies from mid-January to late February are followed by positive height anomalies with small amplitudes from mid-February to late March (Figs. 4c and 1b).

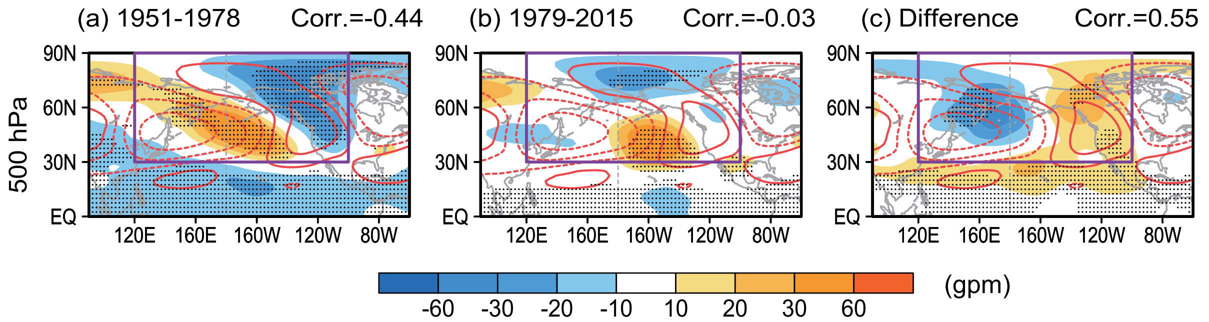

Fig. 3. As in Fig. 2, but for DJF mean 500-hPa geopotential height anomalies. The areas where the anomalies exceed the 95% confidence level are dotted. The red lines represent the zonal deviations of climatological DJF mean geopotential height and are shown at ±20, ±70, and ±150 gpm. Purple boxes mark the regions for spatial correlation analysis. The spatial correlation coefficients between composite geopotential height anomalies and the zonal deviations of climatological DJF mean geopotential height are shown in the title of each figure.

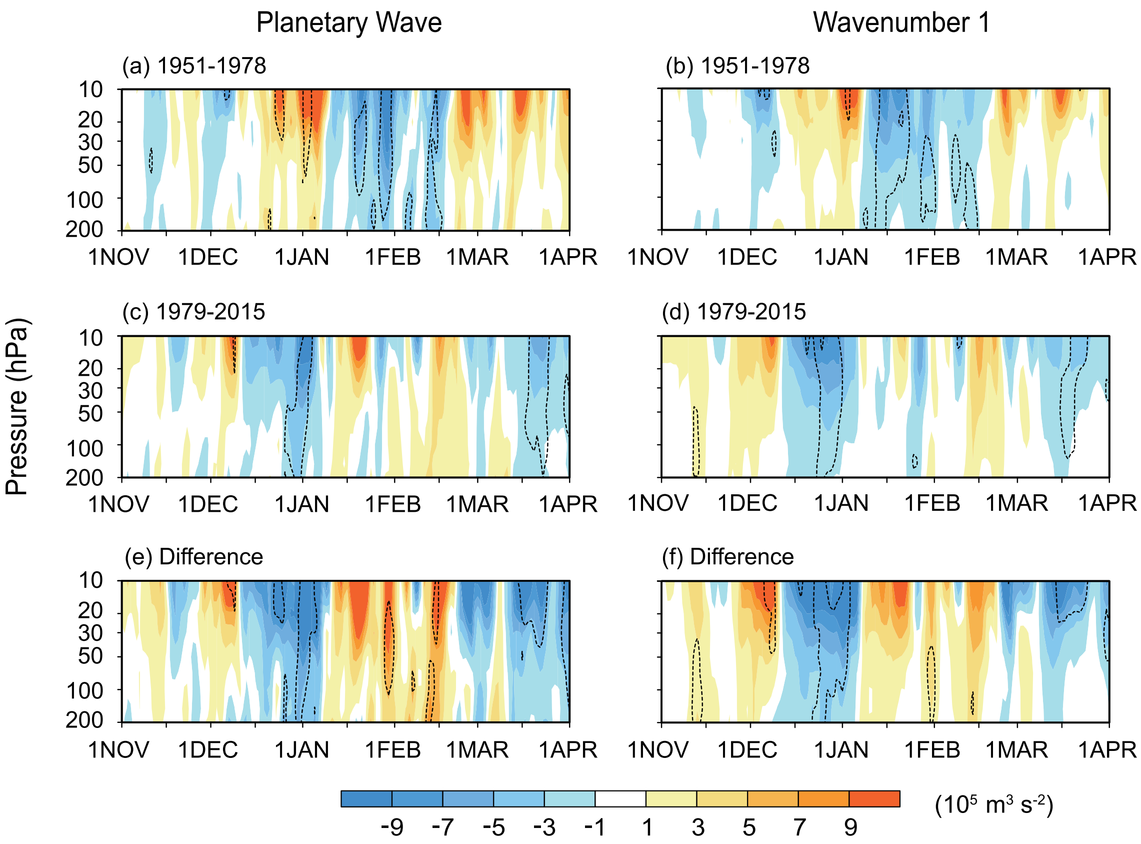

Fig. 4. Temporal evolution of the vertical component of EP flux anomalies by (a, c, e) planetary waves (wavenumber-1 to wavenumber-3) and (b, d, f) planetary wavenumber-1, over 50°–75°N, composited for La Niña events during the periods (a, b) 1951–78 and (c, d) 1979–2015, and (e, f) their difference (later minus early). Black dashes indicate the 95% confidence level.

In addition, by comparing the left-hand panels with the right-hand panels in Fig. 4, it is easy to identify that the variability of EP_z flux by planetary waves is mainly dominated by that of the wavenumber-1 component. The wavenumber-2 component is not shown for much smaller amplitude. For a DJF mean, the 30-hPa stratospheric planetary wave activities are inhibited during the period 1951–78, but close to the climatology during the period 1979–2015 (not shown), corresponding to a significantly strengthened stratospheric polar vortex but a vortex with relatively gentle variations during the period 1951–78 and 1979–2015, respectively (Figs. 2a and b).

4. Summary and discussion

We demonstrate in this paper that the impact of La Niña on the winter Arctic stratosphere features an obvious decadal variation from the late 1970s. We also prove that this is mainly due to the corresponding decadal variation of the tropospheric La Niña teleconnection. Specifically, during the period 1951–78, the La Niña teleconnection shows a typical negative PNA pattern. This strongly inhibits the propagation of planetary waves (mainly wavenumber-1) from the extratropical troposphere to the stratosphere, and leads to a significantly strengthened stratospheric polar vortex, especially during the periods from November to mid-December and from mid-February to mid-March. In contrast, during the period 1979–2015, the La Niña teleconnection shifts eastwards and is concentrated in the northeastern Pacific. The destructive interference of the La Niña teleconnection with climatological stationary waves seen in the earlier period reduces greatly, leading to a completely opposite EP flux anomaly in the extratropical stratosphere. However, the amplitude of the wintertime EP flux anomaly is less significant. Correspondingly, the stratospheric response is opposite to that during 1951–78, showing a less disturbed stratospheric polar vortex in winter.

From the analyses above, it is found that the winter polar stratospheric response to La Niña is highly sensitive to the time period from which La Niña events are selected. If the composite analysis is conducted based only on the La Niña events during the period 1951–78, a significant stratospheric response with a significantly strengthened polar vortex can be anticipated. In contrast, if one chooses La Niña events from both periods, 1951–78 and 1979–2015, and with equal sample size, a stratospheric response with smaller amplitude is found (e.g., Free and Seidel, 2009). Thus, it is not difficult to understand why Manzini et al. (2006) concluded that the stratospheric response to La Niña is negligible, because the four La Niña events they used (1984/85, 1988/89, 1995/96, 1998/99) were from the period 1979–2015. We conclude that the decadal variation since the late 1970s plainly clarifies the unsettled issue regarding La Niña's impact on the winter Arctic stratosphere.

There are many other factors that can modulate the extratropical stratospheric circulation, such as the equatorial quasi-biennial oscillation (QBO) (e.g., Holton and Tan, 1980; Garfinkel and Hartmann, 2007; Wei et al., 2007; also see Text S1 and Fig. S1), the Pacific Decadal Oscillation (e.g., Woo et al., 2015; Kren et al., 2016; also see Text S2 and Fig. S2), and Arctic sea-ice loss (e.g., Kim et al., 2014; King et al., 2016; Nakamura et al., 2016). We also consider some of these factors to examine their possible influence on the decadal variation of stratospheric La Niña signals. Taking the QBO for example (Text S1, Fig. S1), we find that a robust decadal variation of the stratospheric La Niña signals since the late 1970s appears in both the easterly and westerly phases of the QBO. In addition, the polar stratospheric response to the QBO, proposed by Holton and Tan (1980), does not change in either sub-period, in spite of the decadal variation of La Niña's impact on the Arctic stratosphere. However, we note that it is relatively difficult to eliminate the contamination of these factors with respect to the results of the present paper, based solely on reanalysis data of limited length. More attention is needed regarding these issues in future work.

Another important question that needs to be taken into account in future studies is what causes the decadal variation of the tropospheric La Niña teleconnection. Numerous model studies have examined the ENSO teleconnection in a warmer (future) climate. Some of them found an eastward shift of the well-known ENSO teleconnection pattern in the PNA region and attributed this to climate warming (Meehl and Teng, 2007; Müller and Roeckner, 2008; Bulić et al., 2012). Using a 60-year reanalysis dataset, Zhou et al. (2014) further found that the wintertime El Niño-related PNA pattern moves farther eastwards from the late 1970s, due to an eastward shift of the El Niño-induced convective center over the equatorial Pacific. However, Wittenberg (2009) and Deser et al. (2010) argued that, besides climate warming, natural variability in ENSO and the PNA pattern may also be important for the variation of the ENSO teleconnection. These issues need to be examined in further studies.

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