Pathways of influence between northern hemisphere blocking and stratospheric polar vortex variability

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Key Points:

- The pathways of influence between European and west Pacific blocking and polar vortex variability are quantified using causal inference
- Both upper tropospheric and lower stratospheric wave-activity fluxes mediate these pathways, and both are needed for a full description
- Our results suggest additional causal factors play a role in how blocking affects polar vortex variability and sudden stratospheric warmings

Supporting Information:

Supporting Information may be found in the online version of this article.

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Pathways of Influence Between Northern Hemisphere Blocking and Stratospheric Polar Vortex Variability

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Abstract We apply a causal inference-based framework to test and quantify previously suggested causal relationships between Northern Hemisphere blocking, upward wave-activity fluxes and stratospheric polar vortex (SPV) variability using reanalysis data. We show that the influence of blocking on the polar vortex is entirely mediated by upward wave-activity fluxes, as the classical view would suggest. However, the causal pathway is not completely straightforward. In contrast to the vortex-weakening effect of European blocking, the vortex-strengthening effect of west Pacific blocking on lower stratospheric wave-activity fluxes is only partially mediated by upper tropospheric wave-activity fluxes. In addition, only two-thirds of the effect of upper tropospheric wave-activity fluxes on polar vortex variability is mediated by lower stratospheric wave-activity fluxes. We also show that sudden stratospheric warmings are not entirely explainable in terms of upward wave-activity fluxes. These findings help clarify the pathways of influence between blocking and SPV variability.

Plain Language Summary Blocking has been thought to influence the wintertime stratospheric polar vortex (SPV) via its effect on upward propagating planetary waves. Yet there has been debate about the exact pathways of influence. In this study, we use reanalysis data to examine and quantify previously suggested causal relationships between Northern Hemisphere blocking, upper tropospheric wave-activity fluxes, lower stratospheric wave-activity fluxes, SPV variability, and sudden stratospheric warmings. By making the causal reasoning explicit in the statistical analysis we can quantify indirect (mediated) and direct pathways of influence. We confirm the classical view that upward wave-activity fluxes determine the influence of blocking on the polar vortex. However, we show that the pathway is not the simple causal chain described above. For example, only two-thirds of the effect of upper tropospheric wave-activity fluxes on polar vortex variability is mediated by lower stratospheric wave-activity fluxes. These non-mediated pathways suggest that additional causal factors play a role in how blocking affects polar vortex variability and sudden stratospheric warmings.

1. Introduction

The dynamical coupling between the troposphere and stratosphere has historically been explained from the established properties of stationary, planetary-scale Rossby waves and their interaction with the mean flow (Matsuno, 1970). These waves originate mainly in the troposphere and, as they propagate into the stratosphere, transfer angular momentum vertically, causing the stratospheric mean flow to decelerate (Andrews et al., 1987; Shepherd, 2002). The nonlinear interactions between these waves and the polar vortex drive wintertime Arctic stratospheric polar vortex (SPV) variability, which manifests in extreme cases as a sudden stratospheric warming (SSW)—a breakdown of the polar vortex, accompanied by rapid adiabatic heating in the polar stratosphere (Hitchcock et al., 2013).

The detailed mechanisms of SSW initiation are still not fully understood, but all studies agree on the importance of sustained absorption of stratospheric wave activity for vortex disruption (Baldwin et al., 2021). SSWs are often thought to be forced by anomalously strong wave-activity sources originating in the troposphere (e.g., Garfinkel et al., 2010; Martius et al., 2009). Some authors have argued that the stratosphere controls the upward wave propagation and determines the occurrence of SSWs, for example, through resonance and nonlinear effects responsible for the rapid amplification of wave activity in the stratosphere (Baldwin et al., 2021; Birner & Albers, 2017; de la Cámara et al., 2017). However, even if SSWs are not always dependent on tropospheric sources of variability, this does not mean that they are unaffected by these sources.

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In this respect, tropospheric blocking has often been considered a precursor to SSWs (Attard & Lang, 2019; Colucci & Kelleher, 2015; Martius et al., 2009; Nishii et al., 2011). These studies suggest a geographically dependent blocking influence on the enhancement/suppression of upward wave-activity propagation into the stratosphere through constructive/destructive interference between climatological stationary waves and the anomalous waves generated by blocking. For example, blocking over Europe and the Euro-Atlantic region tends to constructively interfere with the climatological wave pattern and enhance the upward wave-activity propagation, contributing to a warmer polar vortex and an increased probability of SSWs (Attard & Lang, 2019). In contrast, blocking over the west Pacific suppresses upward wave-activity propagation through destructive interference with the climatological pattern. As noted earlier, this focus on tropospheric wave-activity forcing does not exclude the possibility of stratospheric mechanisms playing a role in the effect of west Pacific blocking, for example, via the wave reflection mechanism (Kodera et al., 2016).

The anomalous upward wave-activity propagation signal associated with blocking is often considered to propagate from the upper troposphere around 200–300 hPa to the lower stratosphere around 100 hPa (Attard & Lang, 2019; Colucci & Kelleher, 2015; Martius et al., 2009). Recently, Weinberger et al. (2021) suggested that atmospheric variability above the tropopause, especially in the vertical gradients of buoyancy frequency, is a crucial factor controlling the extent of the upward propagation to 100 hPa. Relatedly, Attard and Lang (2019) observed that the signal associated with blocking did not depend on a single synoptic event (blocking or extratropical cyclone) alone and suggested that stratospheric conditions are precursors to the 100-hPa signal. Several questions thus remain open on what conditions are essential for anomalous wave-activity propagation between the troposphere and the stratosphere, and what is the role of blocking in this.

Various statistical analysis methods and climate modeling have been used to investigate the relationship between blocking, wave-activity propagation and SSWs (e.g., de la Cámara et al., 2017; Nishii et al., 2011). A widely applied statistical method is cross-correlation analysis, assuming a linear relationship between the different processes (e.g., Polvani & Waugh, 2004). However, the results can be highly biased by autocorrelation and indirect effects (Kretschmer et al., 2016; Runge et al., 2014). To overcome these issues, we apply a causal inference theory-based approach to examine the plausible causal connections between blocking, upward wave-activity propagation, and SPV changes and quantify the strength of the connections in reanalysis data. This relatively novel method within climate dynamics, described in Section 2.1, allows to overcome spurious correlations and identifies direct and indirect effects within the assumed causal network (Kretschmer et al., 2016, 2021; Runge et al., 2014).

Motivated by earlier results, we study the previously suggested causal relationships and ask the following questions:

1. Is the effect of blocking (either European or west Pacific) on lower stratospheric wave-activity fluxes (at 100 hPa) entirely mediated by its effect on upper tropospheric wave-activity fluxes (at 300 hPa)?
2. Is the effect of upper tropospheric wave-activity fluxes on polar vortex variability entirely mediated by its effect on lower stratospheric wave-activity fluxes?
3. Is the effect of blocking (either European or west Pacific) on polar vortex variability entirely mediated by its effect on upper tropospheric and lower stratospheric wave-activity fluxes?
4. Are SSWs explainable entirely by anomalies in upper tropospheric and lower stratospheric wave-activity fluxes?

Our choices of the different causal elements are based on previous literature to ensure continuity with that literature. The hypothesized causal model reflecting the above linkages is shown schematically in Figure 1a. In this study, we aim to quantify the strength of the causal relationships from the data and test if the above hypotheses are supported by the data, or if there appear to be other factors or pathways of influence.

2. Data and Methods

This study is based on the European Centre for Medium Range Weather Forecasts (ECMWF) ERA5 reanalysis data (Bell et al., 2021; Hersbach et al., 2020). The data is averaged daily from November to March for the period 1950–2019 and utilized on a horizontal grid resolution of $2.5° \times 2.5°$. Anomalies are computed by removing a commonly used 60-year (1950–2010) daily mean climatology, then normalized by the daily standard deviation.

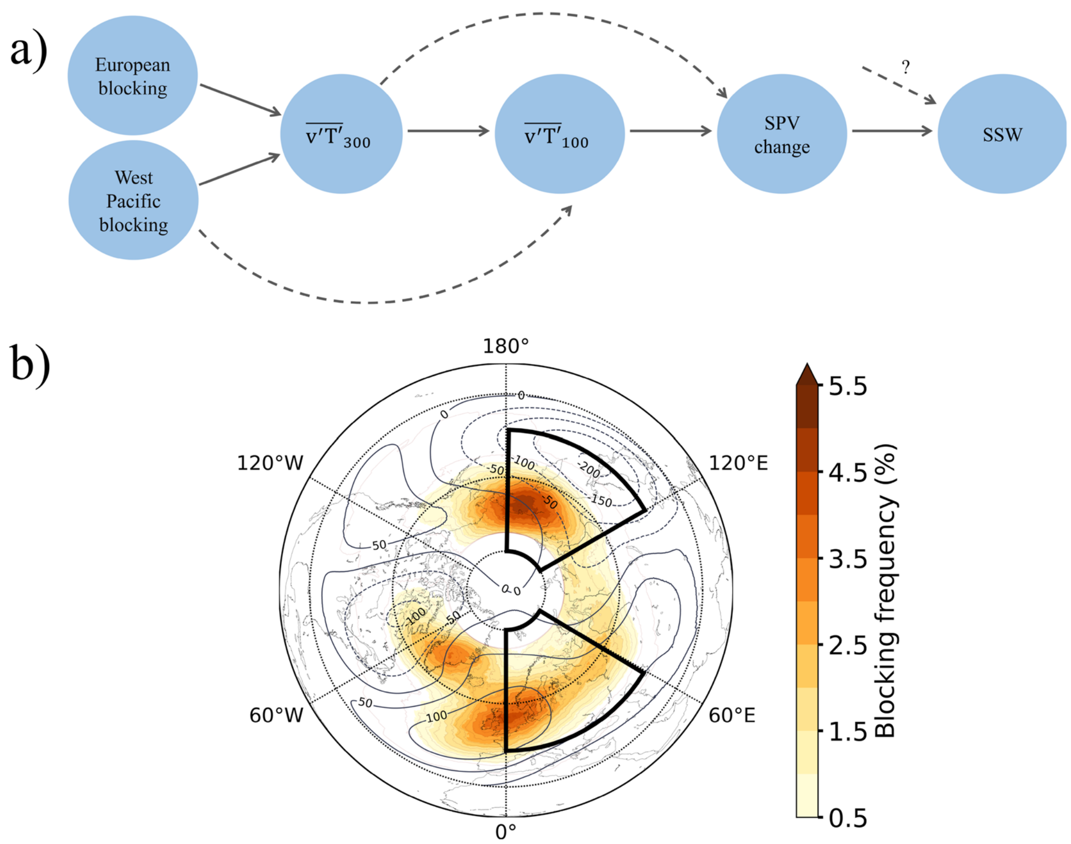

Figure 1. (a) Schematic view of the hypothesized causal model. The nodes represent the main processes: blocking either over Europe or the west Pacific, upper-tropospheric heat flux anomaly, lower-stratospheric heat flux anomaly, stratospheric polar vortex change and sudden stratospheric warming. Solid arrows represent hypothesized causal relationships between the processes and indicate the direction of influence. Dashed arrows represent the additional causal pathways identified in this analysis. (b) Shading shows the climatological blocking frequency expressed as a percentage of blocked days per grid point for the November to March season from 1950 to 2010. Contours indicate the zonally asymmetric component of the 500-hPa geopotential height climatology. Solid boxes define the European and west Pacific blocking regions.

We have re-done the analysis using a wintertime averaged climatology, and the results are essentially the same. Throughout the paper, standardised anomalies are used.

To quantify the vertical wave-activity flux, we use a 45°–75°N average of the zonal-mean meridional eddy heat flux (hereafter heat flux), which is proportional to the vertical component of the Eliassen-Palm flux vector (Edmon et al., 1980). The heat flux $\overline{v'T'}$ is calculated by zonally averaging the product of meridional wind v and temperature T deviations from their respective zonal averages (the overbar represents the zonal average and the prime deviations from the zonal averages). Following Weinberger et al. (2021), we consider the upward wave-activity propagation between the troposphere and the stratosphere using standardised heat flux anomalies at 300 and 100 hPa, which represent the lower and upper limits of the primary communication layer between the upper troposphere and the bottom of the polar vortex, respectively.

For simplicity, we use total heat fluxes for both 300 and 100 hPa. We have tested our analysis using 1–3 zonal wavenumber filtering; the results are essentially the same as for the total heat fluxes.

To determine polar vortex changes, we use the zonal-mean zonal wind, $\overline{u}$, at 10 hPa and 60°N and calculate the wind tendency, du, over 5 days, hereafter referred to as the SPV change. SSWs are detected using the commonly accepted wind reversal definition, in which the central date of an SSW is considered to be the day in which $\overline{u}$ becomes negative (Butler et al., 2017). A minimum timescale of 20 days separation is used between SSW events, and final SSW events are excluded. This leads to a total of 44 events over the time period considered. However, the sampling constraints of our time-lag analysis reduce the total number of SSW events to 37 and 30 (Figures 3a and 3b).

Following the blocking detection methodology described by Brunner and Steiner (2017) and Brunner (2018), blocking events are identified based on the reversal of 500-hPa geopotential height gradients. The three-step algorithm considers first the reversal of meridional 500-hPa gradients within the 45° to 80°N latitude band, then requires that the reversed gradients span at least 15° longitude and persist within a 10° longitude and 5° latitude extent for at least 5 consecutive days. Additionally, to identify persistent blocking events, it is required that the previous criterion is satisfied for more than 4 consecutive days.

The geographical definitions of European (0°–59°E) and west Pacific (120°–179°E) blocking are chosen following Attard and Lang (2019), who found that these two blocking regions are associated with statistically significant heat flux anomalies. Figure 1b shows the climatological blocking frequency for the winter season and highlights the two selected geographical regions. Our blocking detection methodology identifies 220 European blocks and 183 west Pacific blocks over the time period considered.

To test our hypothesis about the underlying causal mechanisms and quantify the relationships from the data, we use a causal network approach proposed by Kretchmer et al. (2021) and based on causal inference theory (Pearl, 2009a, 2009b). A causal network approach assumes a hypothetical causal model represented in graphical networks consisting of links that connect nodes, that is, conditionally dependent processes (Pearl, 2013). The graphical representation enables the identification of direct and indirect links, which is essential for generating explanations. The interest lies in quantifying the causal effects of those links, where information flows in the direction of the causal influence.

In this work, we test the hypothesis that the causal relationships have a chain structure. A causal chain network consists of a minimum of three variables, that is, $X \rightarrow Z \rightarrow Y$, where X is the independent variable, Y is the dependent variable, and Z is the mediating variable. When controlling for the mediator, the relationship between X and Y becomes nonsignificant, equivalently X and Y become independent conditional on Z, that is, $\mathrm{P}(\mathrm{X} \cap \mathrm{Y}|\mathrm{Z}) = \mathrm{P}(\mathrm{X}|\mathrm{Z})\,\mathrm{P}(\mathrm{Y}|\mathrm{Z})$, where P denotes probability density functions (Kretschmer et al., 2016; Pearl, 2009b). For example, in the chain depicted in Figure 1a, we assume that $\overline{\mathrm{v'T'}}_{300}$ affects the SPV only through $\overline{\mathrm{v'T'}}_{100}$, that is, $\overline{\mathrm{v'T'}}_{100}$ is the mediator. If the effect of $\overline{\mathrm{v'T'}}_{300}$ on SPV change becomes nonsignificant when $\overline{\mathrm{v'T'}}_{100}$ is controlled for, then full mediation would be confirmed. On the other hand, if the effect remains significant, this suggests there is another pathway from $\overline{\mathrm{v'T'}}_{300}$ to the SPV which avoids $\overline{\mathrm{v'T'}}_{100}$, at least the way it is expressed in this network.

In the case of linear relationships of continuous variables, multiple linear regression analysis (MLR) is used to estimate causal effects, and "controlling for" is achieved by including the mediator variable in the regression model. In our case, we have a mixture of continuous variables (heat fluxes and SPV change) and categorical variables (blocking and SSWs). This reflects the way these different flow elements are most commonly described in the scientific literature, to ensure a meaningful connection with that literature.

3. Results

3.1. Causal Effect of Blocking on Lower Stratospheric Heat Flux Anomalies

We first test for evidence of the statistical relationship between blocks and heat flux anomalies. We construct a composite of daily standardised heat flux anomalies 1–20 days before and after the onset of European and west Pacific blocks. We found no correlation between the occurrence of European and west Pacific blocks, so they can be considered as independent drivers. Consistent with the results of Attard and Lang (2019), European blocks are accompanied by positive heat flux anomalies, while west Pacific blocks are accompanied by negative heat flux anomalies (Figure 2a). At 300 hPa, statistically significant positive and negative heat flux anomalies, respectively, precede the blocking onset. Heat flux anomalies at 100 hPa lag those at 300 hPa, indicating their upward propagation coinciding with the blocking formation. Overall, the composite analysis supports the hypothesized causal relationships discussed in Section 1.

We then seek to establish whether the causal effect of blocking (European and west Pacific) on the heat flux in the lower stratosphere at 100 hPa is entirely mediated by its effect on the heat flux in the upper troposphere at 300 hPa. First, the time scales of the processes involved are determined. In Figure 2a, the peaks between the 300 and 100 hPa heat flux anomalies coincide within 5–7 days. The following analysis uses a 5-day average for the heat flux anomaly time series, as the sensitivity tests showed the strongest causal effect with this choice.

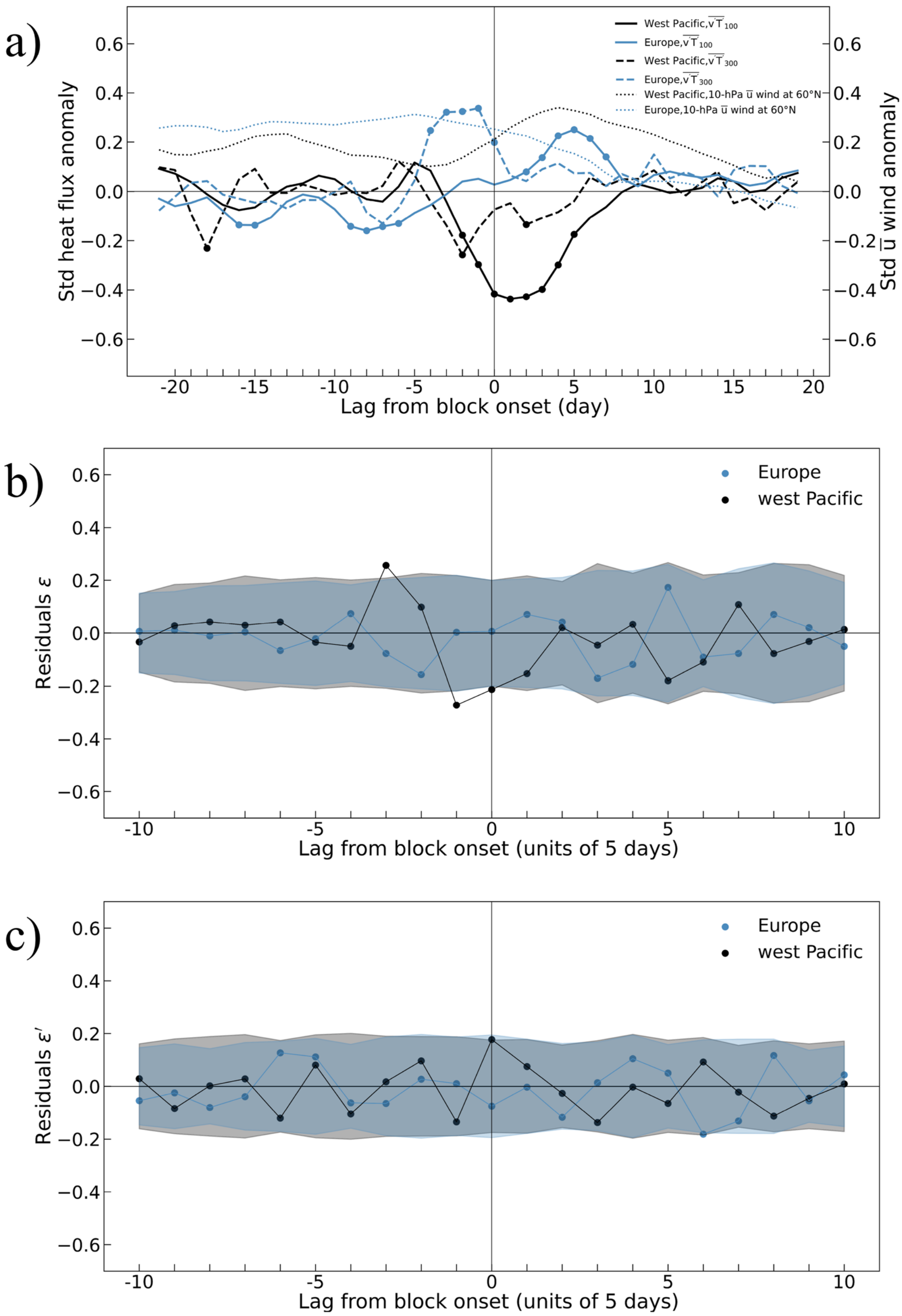

Figure 2. (a) Composite time series of the standardised 100-hPa heat flux anomaly (solid), 300-hPa heat flux anomaly (dashed), and 10-hPa zonal-mean zonal wind anomaly at 60°N (dotted) relative to the onset of European or west Pacific blocking. Dots indicate statistical significance above the 95% confidence level according to a two-tailed Student *t* test (the null hypothesis is that the composite mean at each lag is statistically indistinguishable from zero). Lag is in units of days. Composite of residuals obtained by (b) regressing the 5-day averaged 100-hPa standardised heat flux anomaly on the 5-day averaged 300-hPa standardised heat flux anomaly, and (c) regressing the 5-day averaged standardised stratospheric polar vortex change du on 5-day averaged 100-hPa and 300-hPa standardised heat flux anomalies, plotted relative to the onset of European or west Pacific blocking. Shading indicates the noise level, that is, 95% confidence range for the null hypothesis according to a two-tailed Student *t* distribution. Lag is in units of 5 days.

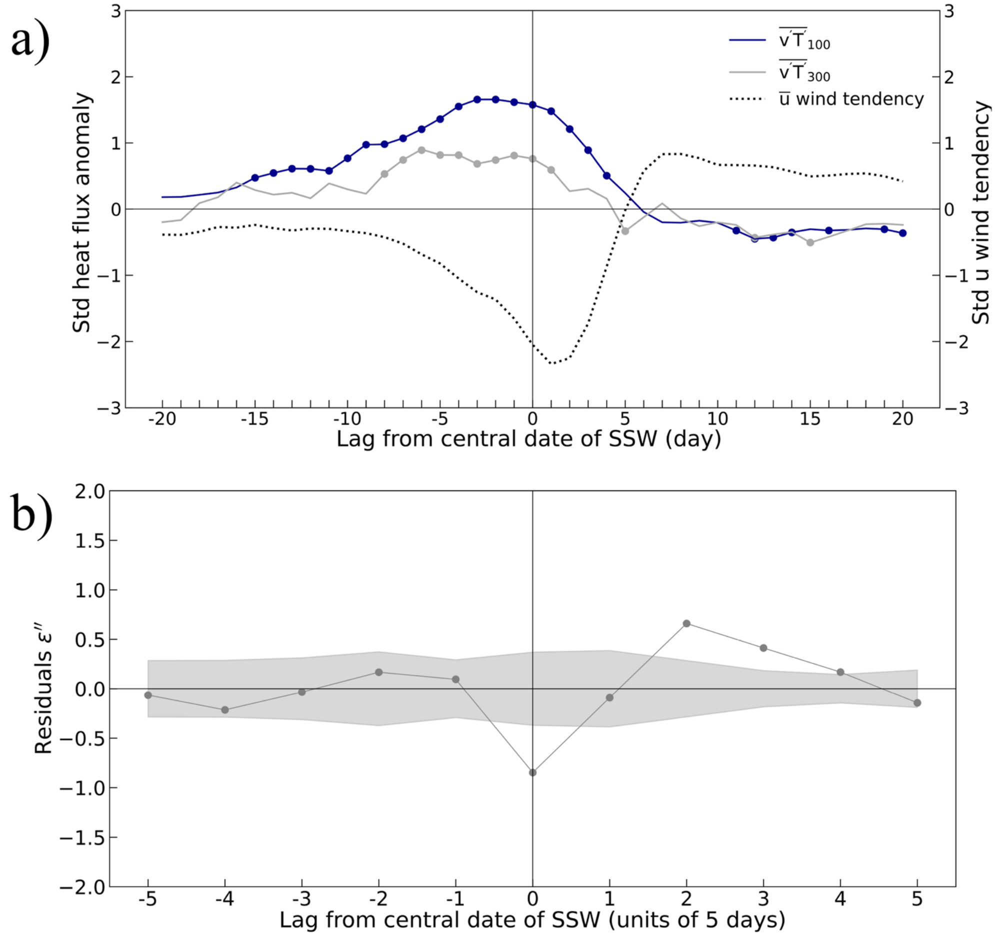

Figure 3. (a) Composite of the 100- and 300-hPa standardised heat flux anomalies, and the stratospheric polar vortex (SPV) change, relative to the onset of sudden stratospheric warming (SSW) events. Dots indicate statistical significance above the 95% confidence level according to a two-tailed Student *t* test (the null hypothesis is that the composite mean at each lag is statistically indistinguishable from zero). Lag is in units of days. (b) Composite of residuals obtained by regressing the 5-day averaged standardised SPV change du on the 5-day averaged 100- and 300-hPa standardised heat flux anomalies, plotted relative to the onset of SSW events. Shading indicates the noise level, that is, 95% confidence range for the null hypothesis according to a two-tailed Student *t* distribution. Lag is in units of 5 days.

Quantifying the causal effect in the chain can be done by regressing the 100-hPa heat flux anomaly on blocking and controlling for the mediating effect of 300-hPa heat flux by including it in the regression model. However, a technical complication is that the blocking index is a categorical variable while the other variables are continuous. Therefore, we first estimate the causal effect of the 300-hPa heat flux anomaly on the 100-hPa heat flux anomaly with time lag $\tau = +1$ (i.e., 5 days) by simply regressing the latter on the former. Choosing a lag of 5 days between variables was found to be the optimal lag choice for our analysis, after we ran sensitivity tests for lags of 1, 3, 5, and 10 days. It also makes physical sense in terms of Rossby-wave propagation timescales. A standardised causal effect is estimated as 0.33 in the regression model formulated as

$$\overline{\mathrm{v'T'}}_{100,\ t+\tau} = 0.33\,\overline{\mathrm{v'T'}}_{300,\ t} + \varepsilon, \tag{1}$$

where ε is the residual.

In the next step, we analyze the obtained residuals by plotting the lag-composite evolution of the residuals relative to the blocking onset to determine if blocking has an effect on the residuals (Figure 2b). This is effectively the same as if we regressed the residuals on the blocking index to determine the regression coefficient or causal effect, that is, performing a sequential linear regression. A random distribution of the residuals indicates that the effect of blocking on the 100-hPa heat flux anomaly is fully mediated by its effect on the 300-hPa heat flux anomaly. Figure 2b shows the residuals spread over 50 days before and after the onset of European and west Pacific blocking. Recall that lag 1 corresponds to 5 days. For European blocks the residuals appear to be randomly distributed around zero, supporting the hypothesized pathway in this case. However, for west Pacific blocks, there appears to be a negative signal immediately preceding block onset. This suggests that in this case the residuals contain a structure not accounted for in our model, meaning there may be another pathway of influence or a more complex time dependence which cannot be captured with a single time lag.

Given the limited length of the winter season, using the 50 days before and after block onset in Figure 2b, compared with only 20 days in Figure 2a, reduces the number of blocks considered to 77 European blocks and 88 west Pacific blocks. We have performed a sensitivity test, re-doing the calculation leading to Figure 2b using only the 25 days before and after block onset, which increases the number of blocks considered to 181 European blocks and 154 west Pacific blocks. The results are included in Figure S1a in Supporting Information S1, and confirm the conclusion derived from Figure 2b.

3.2. Causal Effect of Blocking and Heat Flux Anomalies on SPV Changes

We now assess the relationship between blocking, heat flux anomalies and SPV changes. We first test whether the effect of the 300-hPa heat flux anomaly on the SPV is entirely mediated by its effect on the 100-hPa heat flux, as depicted in Figure 1a. We use a MLR model to quantify the standardised causal effect of a 300-hPa heat flux anomaly on the SPV change du when controlling for the 100-hPa heat flux anomaly as a mediator. The model is formulated as

$$\mathrm{du}_{t+\tau} = -0.62\,\overline{\mathrm{v}'\mathrm{T}'}_{100,\ t+\tau} - 0.10\,\overline{\mathrm{v}'\mathrm{T}'}_{300,\ t} + \varepsilon' \tag{2}$$

where ε' is the residual, and the lag τ is in units of 5 days. Note that the 95% confidence intervals on the regression coefficients are approximately ± 0.035. This result indicates a direct pathway from $\overline{\mathrm{v}'\mathrm{T}'}_{300}$ to du which avoids $\overline{\mathrm{v}'\mathrm{T}'}_{100}$. To estimate the relative strength of the direct and indirect pathways from $\overline{\mathrm{v}'\mathrm{T}'}_{300}$ to du, we employ the path tracing rule. The direct pathway has a standardised strength of -0.10. The strength of the indirect pathway is the regression coefficient of du on $\overline{\mathrm{v}'\mathrm{T}'}_{100}$, -0.62, multiplied by the correlation between $\overline{\mathrm{v}'\mathrm{T}'}_{300}$ and $\overline{\mathrm{v}'\mathrm{T}'}_{100}$, 0.32, which gives -0.20. The correlation between $\overline{\mathrm{v}'\mathrm{T}'}_{300}$ and du is the sum of the strength of the direct and indirect pathways, namely -0.30. Thus, one-third of the influence of $\overline{\mathrm{v}'\mathrm{T}'}_{300}$ on du occurs via the direct pathway, and two-thirds is mediated by $\overline{\mathrm{v}'\mathrm{T}'}_{100}$.

To test if the effect of blocking on SPV changes is mediated via its effect on the 300- and 100-hPa heat flux anomalies, we repeat the residual analysis as in Section 3.1. Figure 2c shows the composite of residuals ε' relative to blocking onset. It is observed that the residuals are distributed relatively evenly around zero for both European and west Pacific blocking. The same sensitivity test used for Figure 2b is applied here to increase the number of blocking events considered. The results are included in Figure S1b in Supporting Information S1, and confirm the conclusion derived from Figure 2c. This suggests that once we consider the complete causal chain from blocking to SPV and condition on the upper tropospheric and lower stratospheric heat fluxes, their effect controls away the effect of blocking on the SPV. This confirms the classical view that the influence of blocking on the SPV is entirely mediated by upward wave-activity fluxes represented by the standard metrics. However, using only the upper tropospheric or lower stratospheric wave-activity fluxes alone does not fully capture the pathway.

We finally try to understand the contribution of the heat fluxes to the occurrence of SSWs. Figure 3a summarizes the results of the composite heat flux anomalies and wind tendency 1–20 days before and after the SSW central date.

Significant positive standardized heat flux anomalies (about 2 standard deviations) appear first around lag −15, preceding the central date. This enhanced peak in heat flux is accompanied by an increased negative wind tendency, indicating preconditioning of the SPV followed by a breakdown. This suggests as expected that anomalous upward wave-activity propagation precedes SSWs, consistent with the existing literature (Baldwin et al., 2021).

We now ask whether the SSW occurrence is fully explainable by the heat fluxes. To this end, we perform the same residual analysis as in Figures 2b and 2c, but now composited relative to the SSW central dates (Figure 3b). This is an inverse regression, as we condition on the target variable. We see that the strong features in du at and just after the SSW central date in Figure 3a are weakened, but are still there. Using the same logic as for the analysis in Section 3.1, we can conclude that SSWs are not fully explainable from the heat fluxes. This could suggest an alternative causal factor, which would certainly not be inconsistent with the literature. However, it could also reflect a confounding factor. Monnin et al. (2022) showed that the seasonal dependence of the climatological strength of the SPV induces a seasonal dependence of the relationship between SSWs and other variables, which can be considered a statistical artifact. (In causal statistics, this is known as a "collider bias.") However, it is not possible to determine whether that effect might be playing a role here, due to the small sample size of SSWs in the reanalysis record. Note that the lag relations evident in Figure 3a suggest that there might be a time lag of about 5 days between the upper stratospheric heat flux and the SPV change associated with SSWs. We have performed a sensitivity test, re-doing the calculation leading to Figure 3b using a regression analysis with a 5-day time lag between these two quantities. The results are included in Figure S2 in Supporting Information S1, and confirm the conclusion derived from Figure 3b.

4. Discussion and Conclusions

In the present study, we apply a causal inference-based framework to examine the effect of blocking on Northern Hemisphere polar stratospheric variability through upward propagating wave activity. We test a hypothesized causal chain for blocking in Europe and the west Pacific using causal reasoning. The paper considers two main aspects: first, we test the evidence for a causal relationship between blocking and lower-stratospheric heat flux, and then, whether this is linked to changes in SPV and the occurrence of SSWs.

Our findings are generally consistent with the proposed hypotheses, but not entirely so. Our first analysis supports the assumption that the influence of European blocking on the lower stratospheric heat flux is fully mediated (within our sampling uncertainties) by its influence on the upper tropospheric heat flux. This does not hold for west Pacific blocking, however, meaning there is another pathway (or pathways) of influence on the lower stratospheric heat flux. This may indicate that the mechanisms of vertical influence differ for European and west Pacific blocking. West Pacific blocking has been linked to regional wave reflection, where upward propagating waves are reflected downward due to conditions in the stratosphere (Kodera et al., 2016; Matthias & Kretschmer, 2020). Wave reflection has also been addressed by Weinberger et al. (2021). They suggest that near-reflecting conditions above the tropopause are crucial for determining the upward wave propagation from 300 to 100 hPa. A possible causal variable accounting for the factor determining the upward wave propagation would be the refractive index (Matsuno, 1970; Weinberger et al., 2021). The inclusion of the refractive index in the causal network may potentially explain the difference in results for the two types of blocking. Therefore, wave reflection should be considered in the causal network of the stratosphere-troposphere coupling mechanism, which should be undertaken in future studies.

Our further results suggest that the influence of blocking on the SPV is fully mediated by its effect on the heat fluxes. This is true for both types of blocking. However, neither the upper tropospheric nor the lower stratospheric heat fluxes are sufficient on their own to fully capture this pathway. In particular, only two-thirds of the influence of the upper tropospheric heat fluxes on the SPV is mediated by the lower stratospheric heat fluxes. Answering the question about the effect of blocking and heat fluxes on the occurrence of SSWs is more challenging, partly because of the small number of SSWs in the observed record, and partly because of the potentially confounding factor of the seasonal cycle on any relationship between atmospheric variables and SSWs (Monnin et al., 2022). It is possible that this question could be addressed using hindcasts from seasonal prediction models, which can provide a much larger sample size for statistical analysis.

Overall, we have analyzed the pathways of influence between European and west Pacific blocking and polar vortex variability in line with the previously proposed hypotheses that blocking is an important source of anomalous wave activity flux which disturbs the polar vortex. Our findings, which are summarized in Figure 1a, help clarify the pathways of influence between blocking and SPV variability. The broader purpose of this paper was to demonstrate how the causal inference approach can be applied to identify and quantify these kinds of causal relationships. This approach can overcome the ambiguity of correlation analysis and provide a complementary method for hypothesis testing. More generally, our study adds to the large body of literature addressing the connection between blocking and SSWs and the mechanisms of troposphere-stratosphere coupling.

Data Availability Statement

ECMWF's ERA5 reanalysis data are freely available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5.

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