Influence of energetic particle precipitation on polar vortex mediated by planetary wave activity

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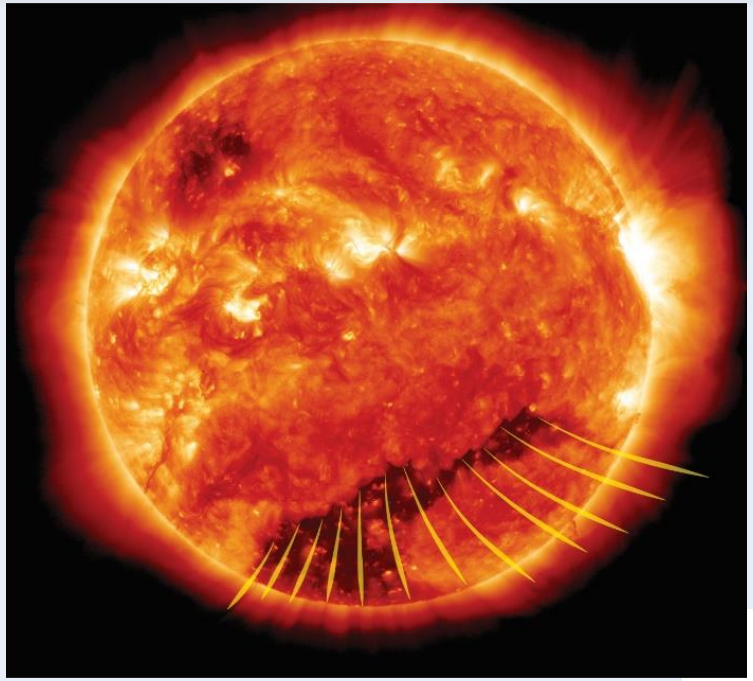
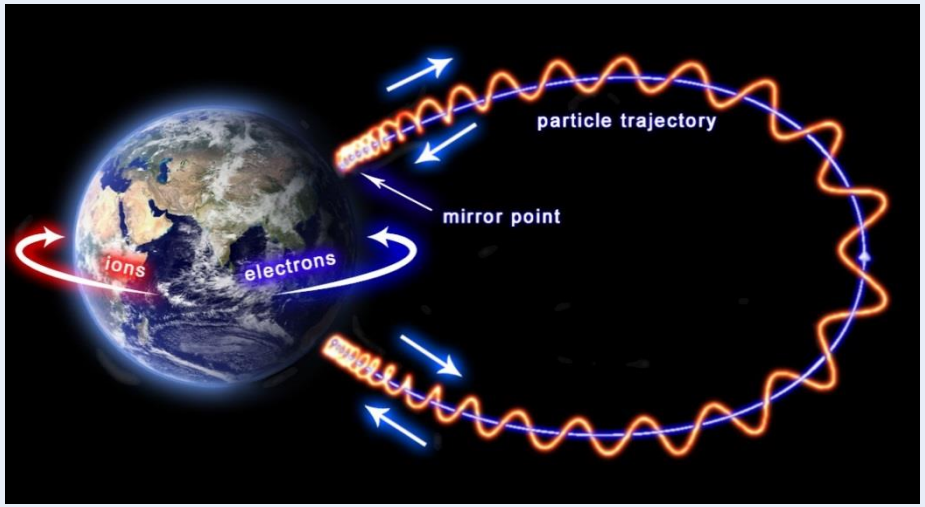
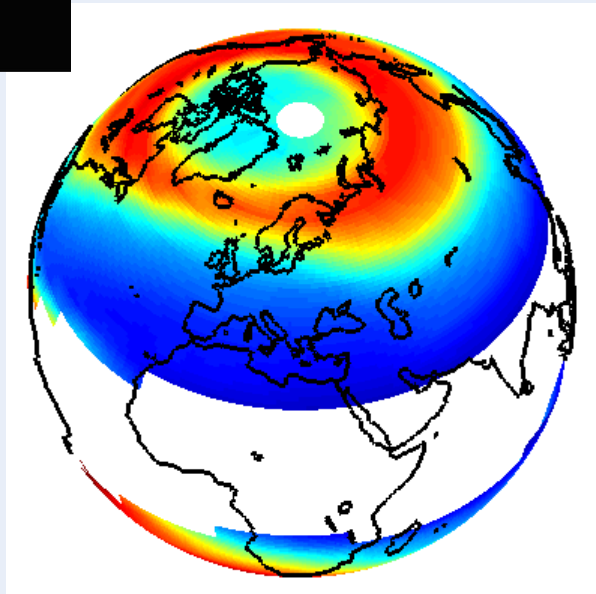
Background: solar wind and energetic particle precipitation

- Sun emits fast solar wind from coronal holes, which are open magnetic field regions in solar corona.
- Solar wind accelerates charged particles in near-Earth space…



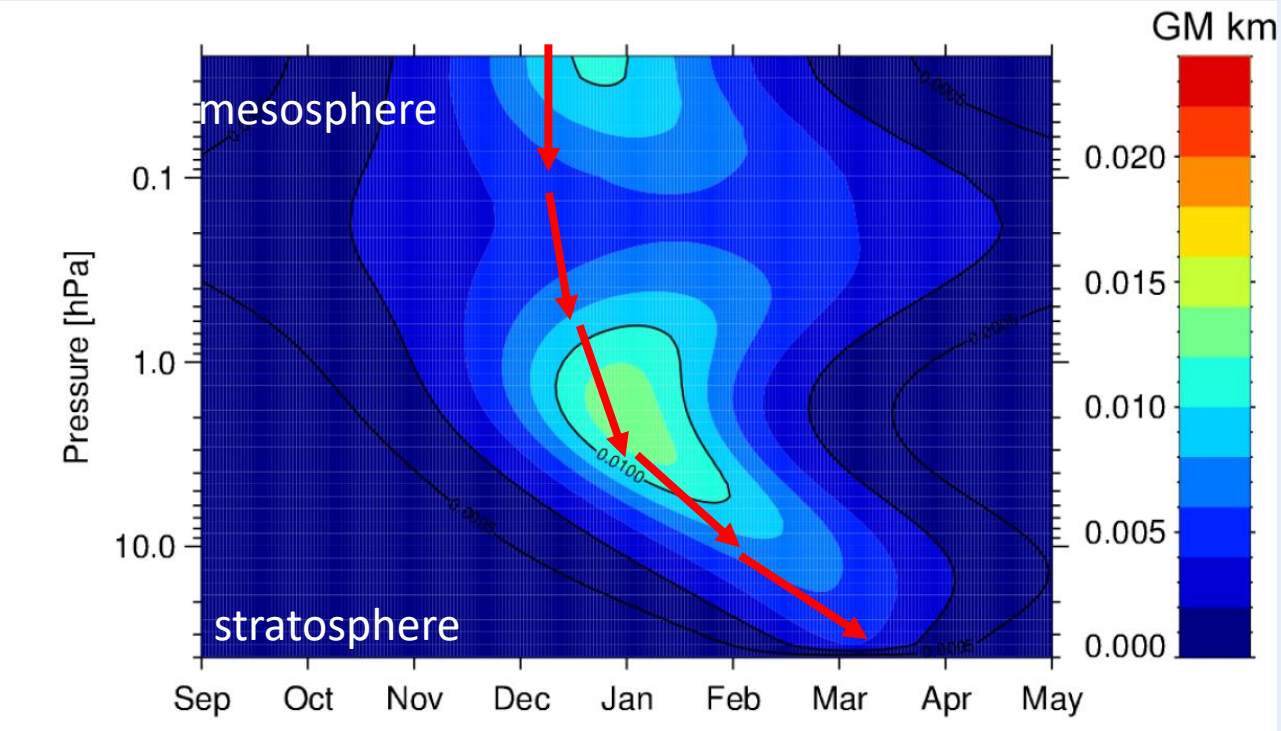


… and causes them to precipitate into the polar atmosphere



Background: Energetic particle influence on winter stratosphere

- Past research has demonstrated that energetic particle precipitation (EPP) leads to formation of ozone-depleting molecules (e.g., HOx and NOx).
- Especially long-lived NOx is transported from mesosphere/thermosphere down to the stratosphere during winter
- ➔ EPP causes ozone loss in mesosphere and stratosphere during winter

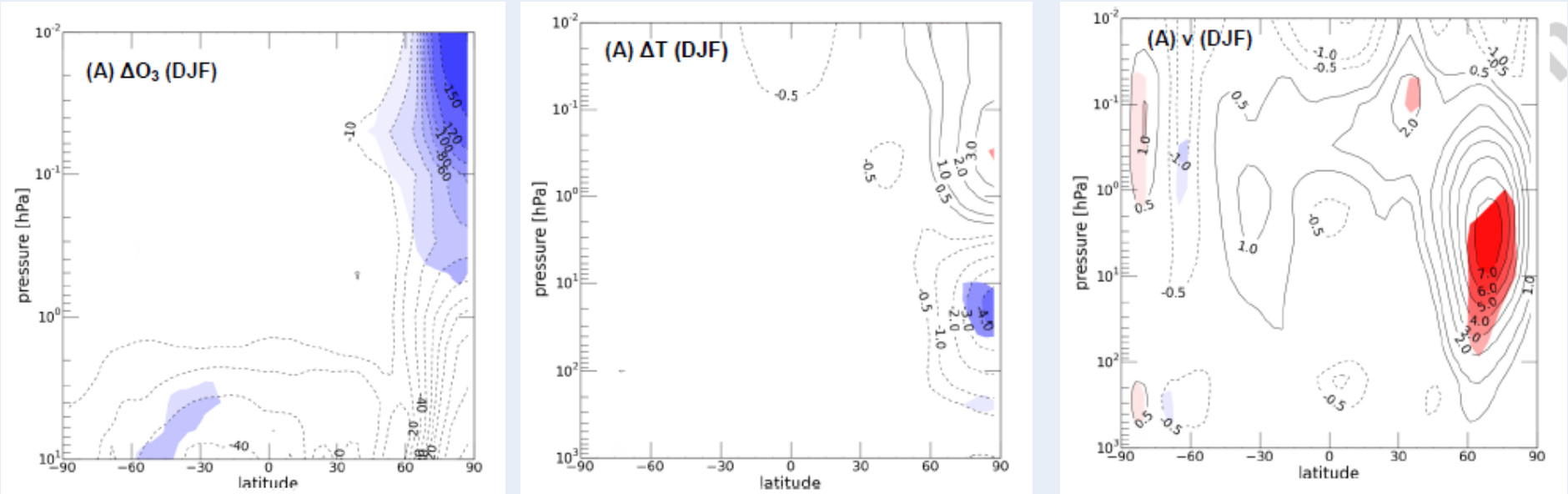


Average descend of EPP-created NOx/NOy from mesosphere to stratosphere during northern hemisphere winter.
Figure adapted from Funke et al., (2016)

Background: EPP leads to enhancement of polar vortex

- Observations and modelling results indicate that ozone loss is associated with warming in mesosphere and upper stratosphere and cooling in the lower stratosphere. These changes are accompanied by enhanced westerly wind in the polar vortex (e.g., Arsenovic et al., 2016; Salminen et al., 2019).
- The polar vortex variations also propagate to ground level, where they affect the NAO/NAM modes of climate variability (e.g. Baldwin and Dunkerton, 2001).

Ozone | Temperature | Zonal wind



Ozone, temperature and zonal wind responses to increase in EPP in a chemistry climate model. Figure from Arsenovic et al. (2016)

Background: Response to EPP is modulated by QBO

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- Recent observations indicate that the response of polar vortex to EPP is strongly modulated by phase of the equatorial Quasi-Biennial Oscillation (QBO)
- E.g., Salminen et al. (2019) showed that the **response is much stronger in QBO-E** phase than in QBO-W phase
- The cause of this modulation is unknown, but it has been suggested it may be related to meridional circulation and/or planetary waves in the stratosphere, which are strongly modulated by QBO.
- The largest changes of meridional circulation and planetary wave activity in the polar stratosphere are associated to Sudden Stratospheric Warmings (SSW)

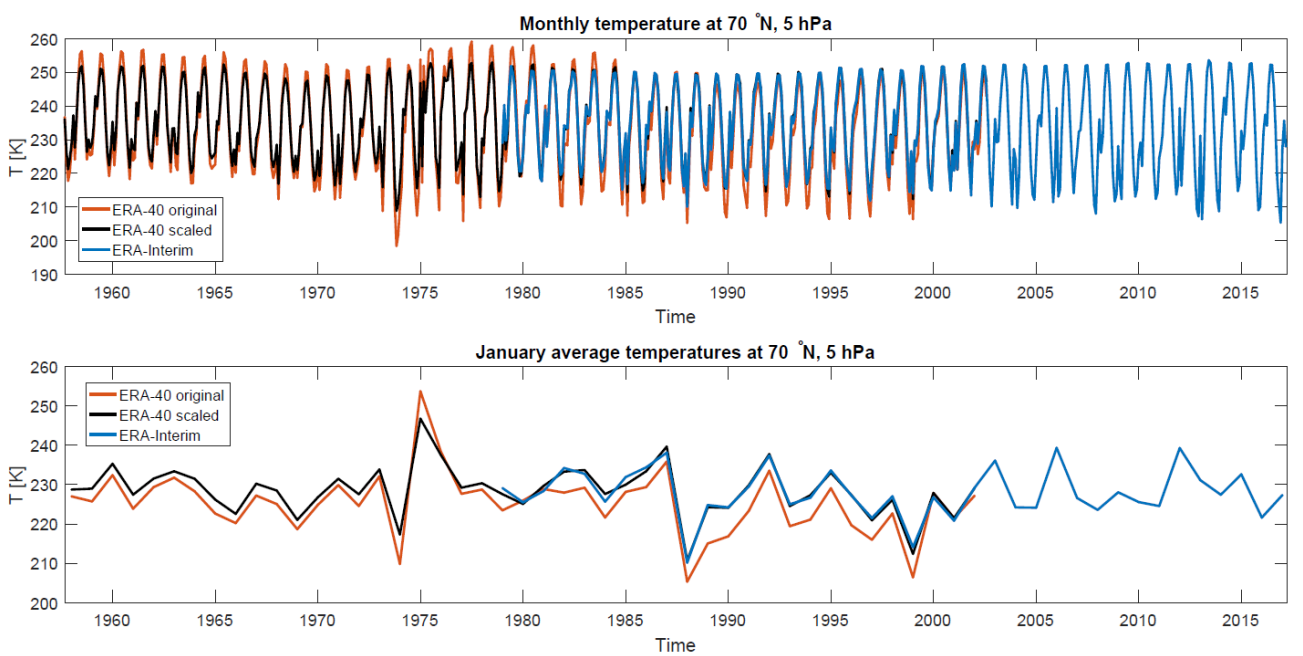
- **To understand the modulation of the response here we study how the enhanced planetary wave conditions best associated to SSWs influence the EPP-related response.**

Datasets

- We use ERA-40 and ERA-Interim reanalysis datasets
- ERA-40 covers Sep 1957 to Aug 2002
- ERA-Interim covers Jan 1979 to Mar 2017

- We computed the following zonally averaged quantities at 23 pressure levels between 1000 hPa (surface) and 1 hPa (stratopause):
  - Zonal wind
  - Temperature
  - Eliassen-Palm flux and its divergence for describing planetary wave activity
  - Components of residual circulation and corresponding rate of adiabatic heating, which is related to vertical residual velocity

- **The daily ERA-40 dataset is scaled to daily ERA-Interim level** using methodology based on principal components and canonical correlation analysis (Asikainen 2019; Asikainen et al., 2020)
- The scaling greatly reduces the differences between the two datasets especially in the polar stratosphere, where the differences between the two are largest (see the Figure of the right)



- Scaled ERA-40 and ERA-Interim are composited together (ERA-40 until 1979 and ERA-Interim after that)
- Monthly averages calculated from daily composite.

- As a proxy for the energetic electron precipitation (EEP) we use geomagnetic Ap index

Methods

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Linear regression:

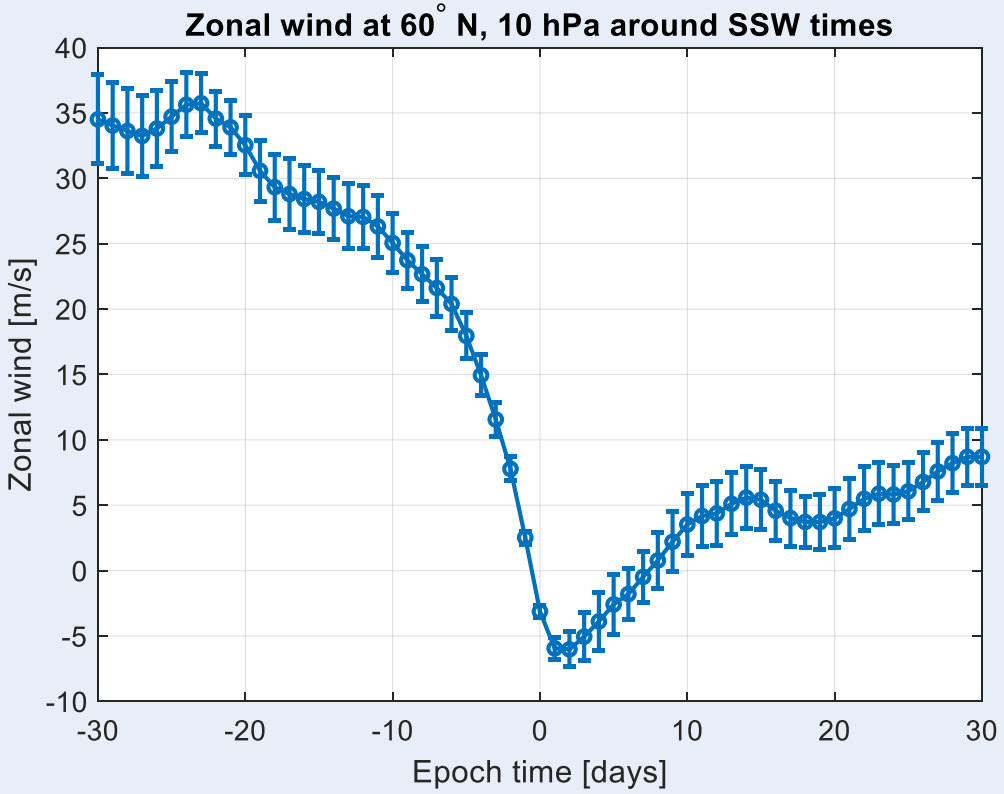
- We estimate the response of atmospheric variable Y to Ap index separately in each latitude-pressure level grid box
- We use a linear regression model with an autoregressive AR(1) residual

$$Y_t = \alpha + \beta \times Ap_t + \varepsilon_t$$
$$\varepsilon_t = \rho\varepsilon_{t-1} + e_t, \text{where } e_t \text{ is gaussian white noise}$$

- Before regression we remove smooth trend from all variables estimated with LOWESS method using 31-year window
- The regression coefficient β is scaled then by the standard deviation of Ap index (same for all regressions)
- All years potentially contaminated by volcanic eruptions are discarded
- Regression is done for Dec, Jan, Feb and Mar months employing the following lags for Ap in different months:
  - No lag in Dec and Jan
  - 1 month lag in Feb
  - 3 month lag in Mar

Identification of Sudden Stratospheric Warmings:

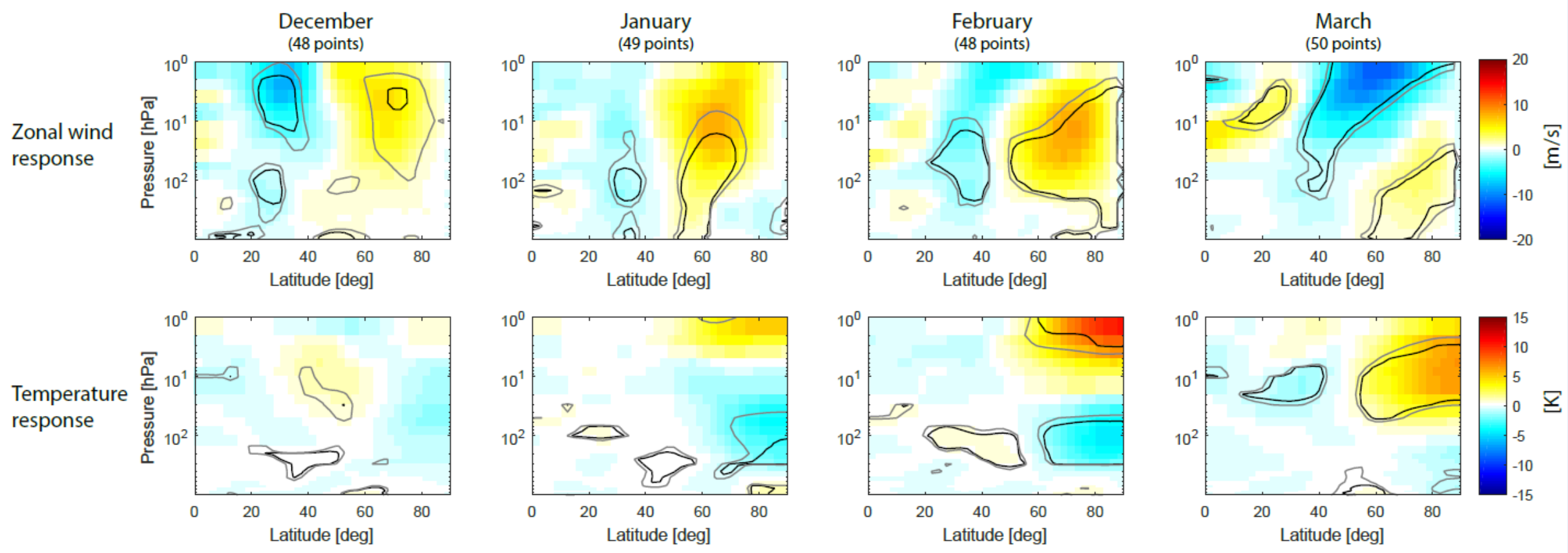
- SSWs identified when zonal wind U at 60°N, 10 hPa turns easterly (see the Figure on the right for average behaviour of U around SSW times based on all the identified SSW events)
- Wind must be westerly for 10 days before SSW and 5 days after recovering from SSW
- Those months, where U remains easterly longest after SSW are flagged as SSW-months.
- Altogether 39 SSW events in our analysis



Wind and temperature response to EEP

- Increase in EEP enhances polar vortex in all winter months.
- Warming in upper stratosphere and cooling in lower stratosphere

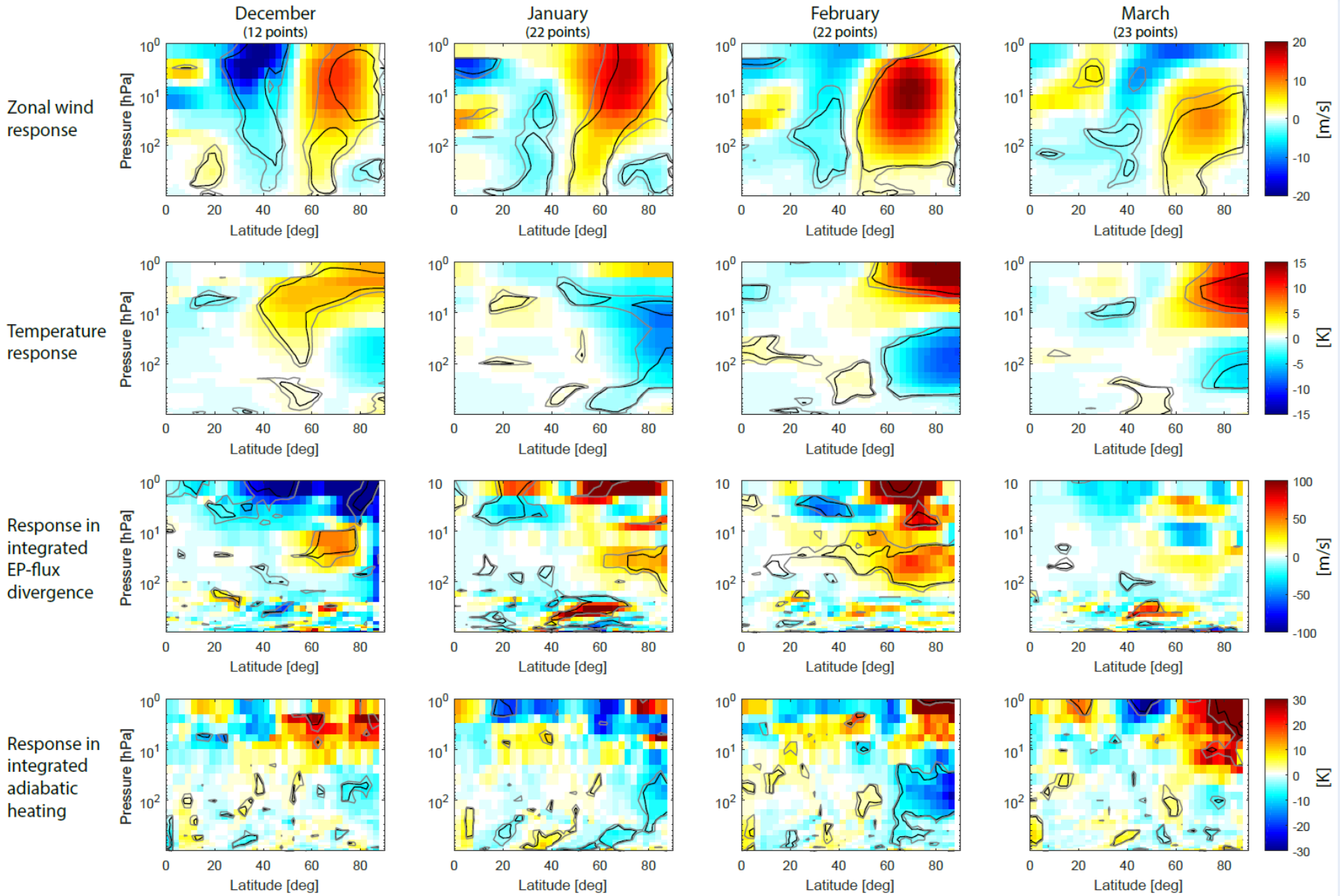
- (We have excluded from these analyses Jan-Feb 2004, which was influenced by an exceptionally strong and long-lasting SSW. Including this year here significantly decreases the obtained response because the SSW breaks the vortex for entire Jan-Feb while EEP during that time is very high).



Response in SSW winters

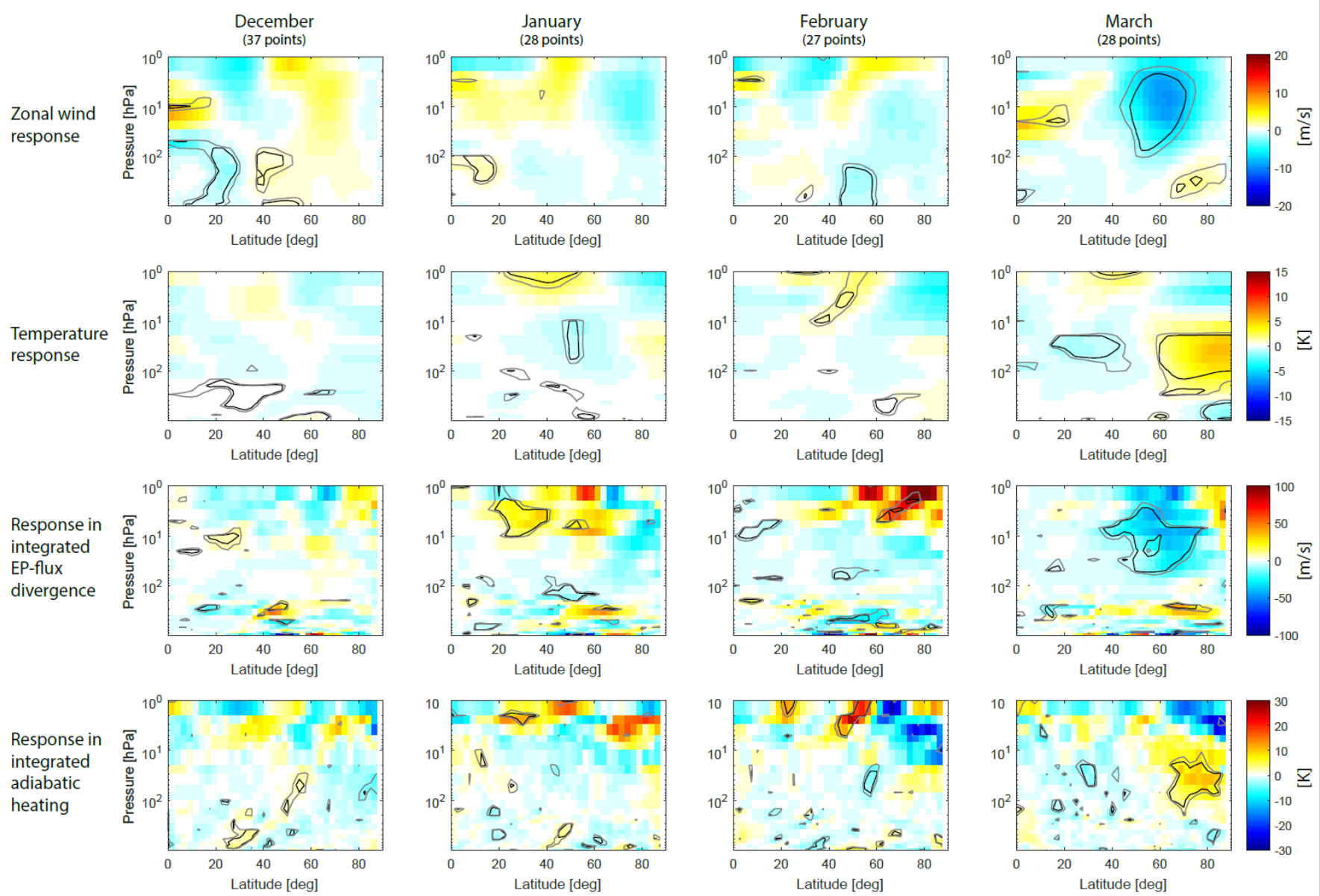
- Regression is here done for those Decembers when SSW occurs in Dec-Jan and for those January-March months when the SSW occurs in Feb-March
- I.e., SSW occurs mostly AFTER the corresponding months
- EEP enhances polar vortex
- Enhancement is associated with
  - Anomalous warming (cooling) in upper (lower) stratosphere
  - Anomalous divergence of planetary waves in the middle stratosphere
  - Reduction of downwelling, i.e., adiabatic cooling of lower stratosphere

- **The signal in all winter months is strong and significant, and stronger than when considering all years**



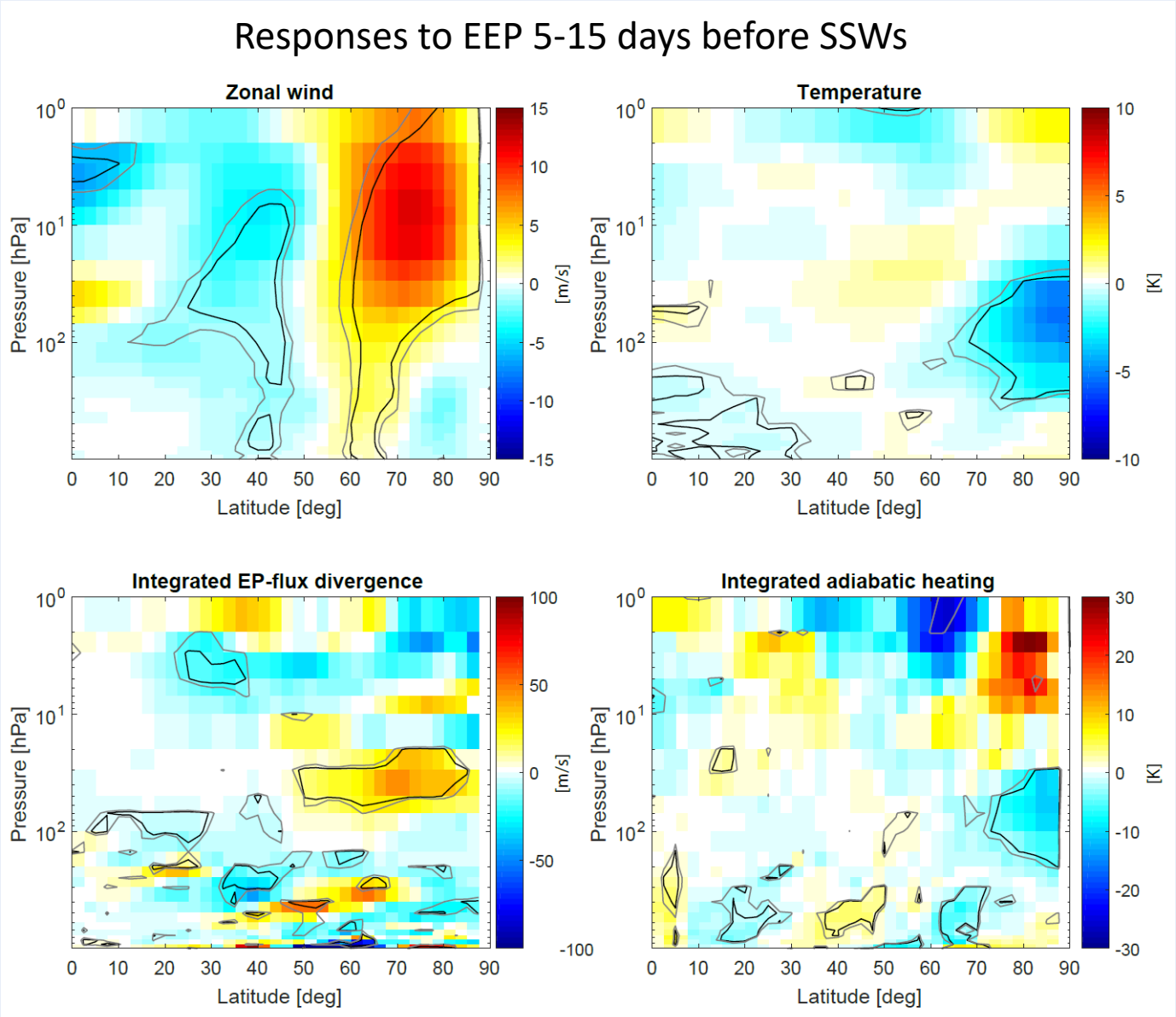
Response in remaining winters

- The figure shows the results for those Decembers where an SSW did not occur in December or January, and for those January-March months where an SSW did not occur in February or March.
- **In these conditions there are no significant systematic EEP-related responses**



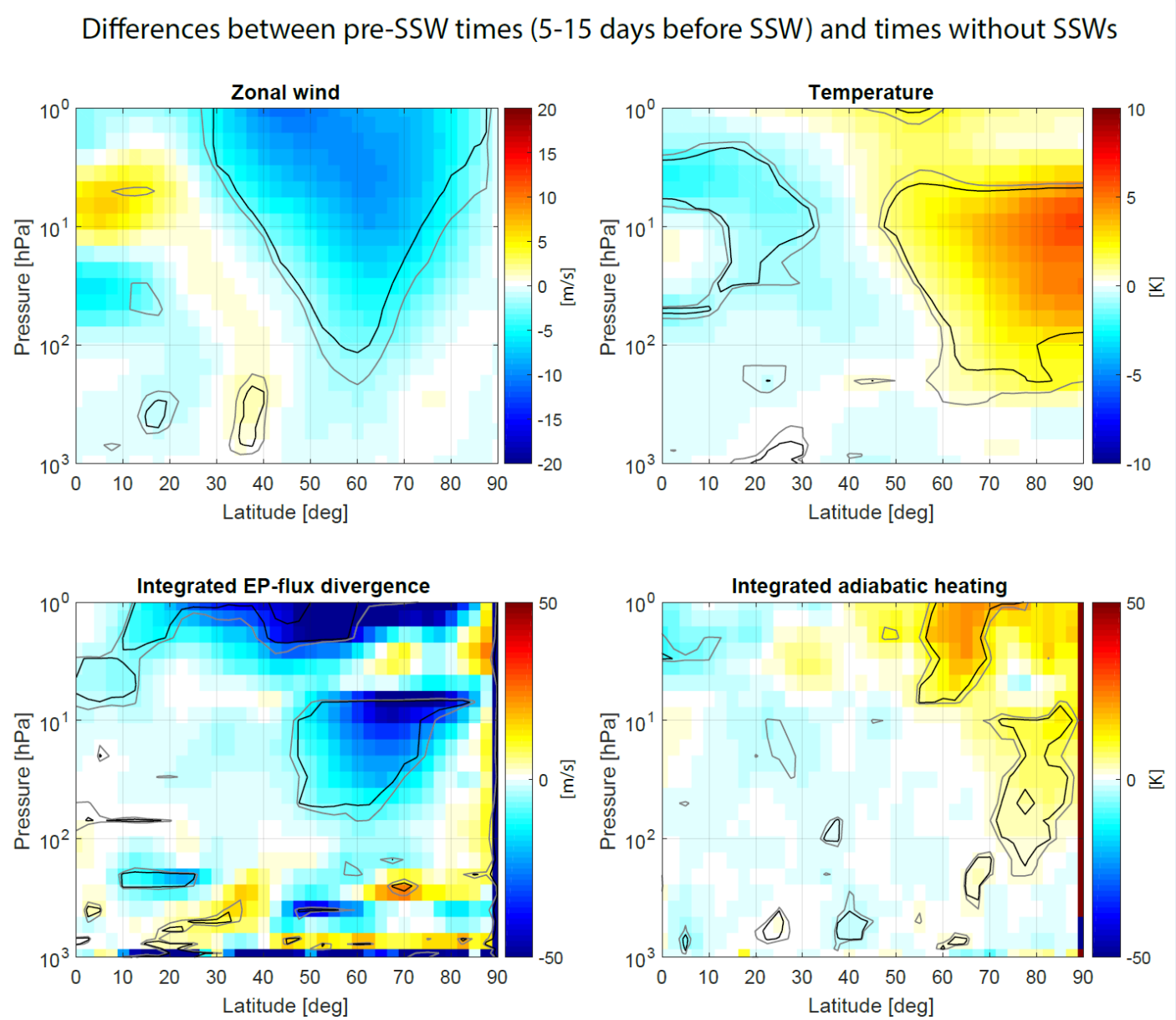
Response to EEP before SSW times

- We computed the response to EEP within 5-15 day window before SSW times in daily resolution using the regression method
- We find a strong polar vortex enhancement associated with
  - Anomalous planetary wave divergence
  - Reduction of downwelling and resulting adiabatic cooling of lower stratosphere
- These responses are statistically significantly different than at other times (see p-value contours for 5%, black and 10% gray) significance.



Stratospheric conditions before SSW

- The average stratospheric conditions before 5-15 days before SSWs are characterized by:
  - Weaker than average zonal wind
  - Warmer than average polar stratosphere
  - Convergence of planetary waves in the polar vortex
  - Stronger downwelling and adiabatic warming
- **These conditions allow the EEP-related signal to arise.**

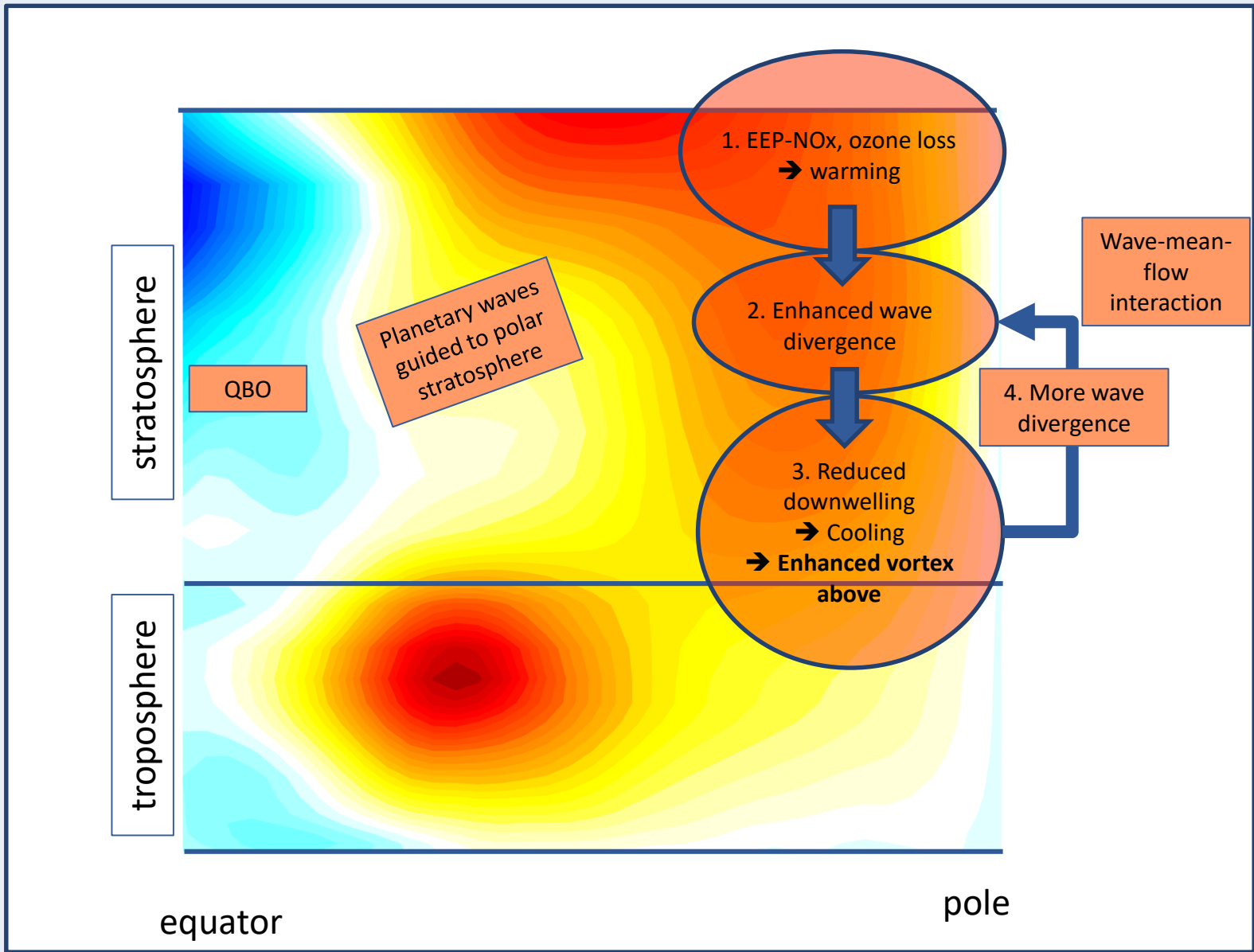


Conclusion: Schematic of EEP-influence

- The schematic here shows the suggested mechanism for amplification of the EEP response by planetary waves (the background color shows wintertime zonal wind climatology)

1. initial EEP-related ozone loss warms mesosphere/upper stratosphere
2. This changes wave propagation and enhances wave divergence in the stratosphere
3. Wave divergence reduces downwelling, cools lower stratosphere and enhances polar vortex above the cooled region
4. Enhanced vortex further refracts planetary waves, which creates a positive feedback-loop.

- The above mechanism works most efficiently when sufficient planetary wave activity is present. Eventually such activity also causes an SSW.
- Since SSWs are more common in QBO-E the suggested mechanism also explains why QBO modulates the EEP response.



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- The study presented here has been published:
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