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Исследование влияния внезапного стратосферного потепления на стратосферно-тропосферный обмен и образование волн холода

A study of the impact of sudden stratospheric warming on stratosphere-troposphere exchange and the formation of cold waves

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Introduction

- Recently, due to growing demands on long-term forecasting and climate models, there has been interest in studying stratosphere-troposphere interactions and, in particular, the influence of stratospheric processes on the troposphere.

- At the same time, circulation, spatial and temporal scales in the troposphere and stratosphere are known to differ, as is the effectiveness of the mutual influence of the layers.

- Stratosphere-troposphere interactions are most pronounced during sudden stratospheric warmings (SSWs).

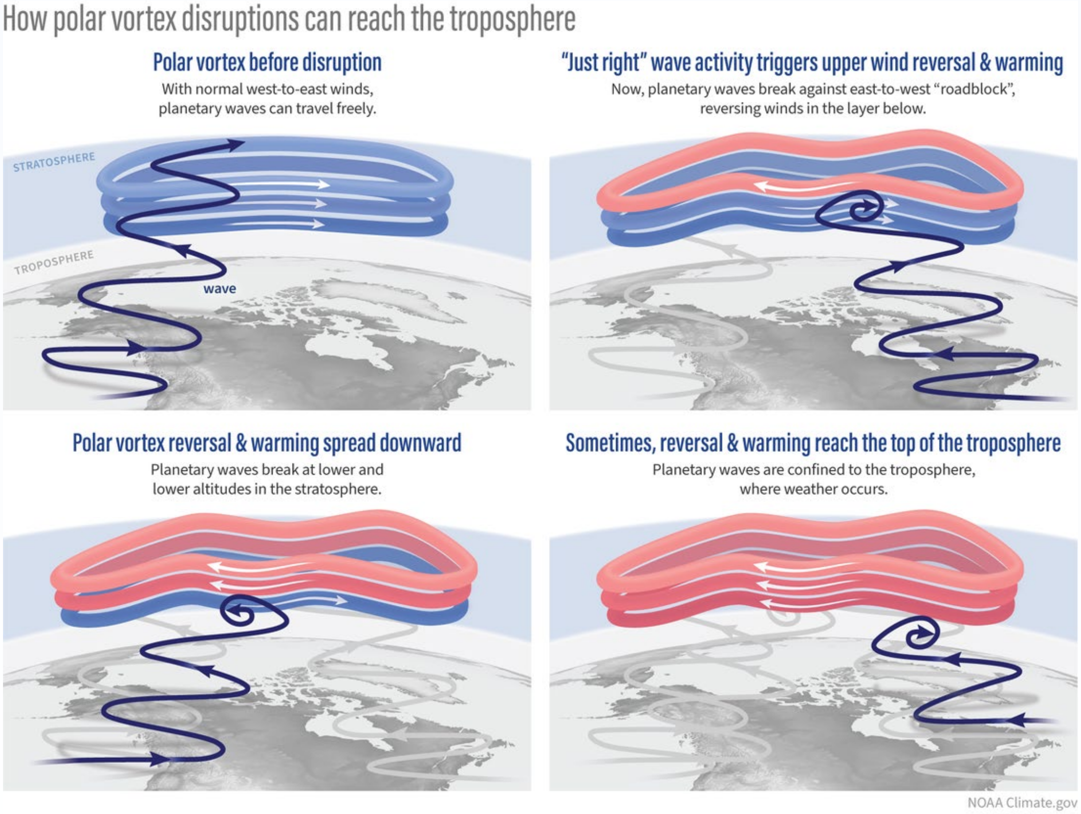
- Planetary waves (PWs), generated in the troposphere by orography, differences in heating between continents and oceans, and baroclinic/barotropic instability, propagate into the stratosphere, interacting with the stratospheric polar vortex, contributing to the formation of SSWs during the winter months.

- Changes in the stratospheric vortex affect the variability of the troposphere, including through the downward propagation of stratospheric anomalies arising from the reflection of PWs

Goals/objectives

- To study the influence of stratospheric polar vortex dynamics on changes in tropospheric circulation during a major SSW event, using the 2018–2019 and 2020–2021 winter seasons as examples.
- To analyze the relationship between surface temperature anomalies (cold waves) that occurred after the SSW event.
- To analyze the relationship between tropospheric processes and changes in stratospheric polar wave activity.

Studying the relationship between the stratosphere and the troposphere in this way may be important both for long-term and seasonal forecasting of anomalies and for more realistic climate change modeling.



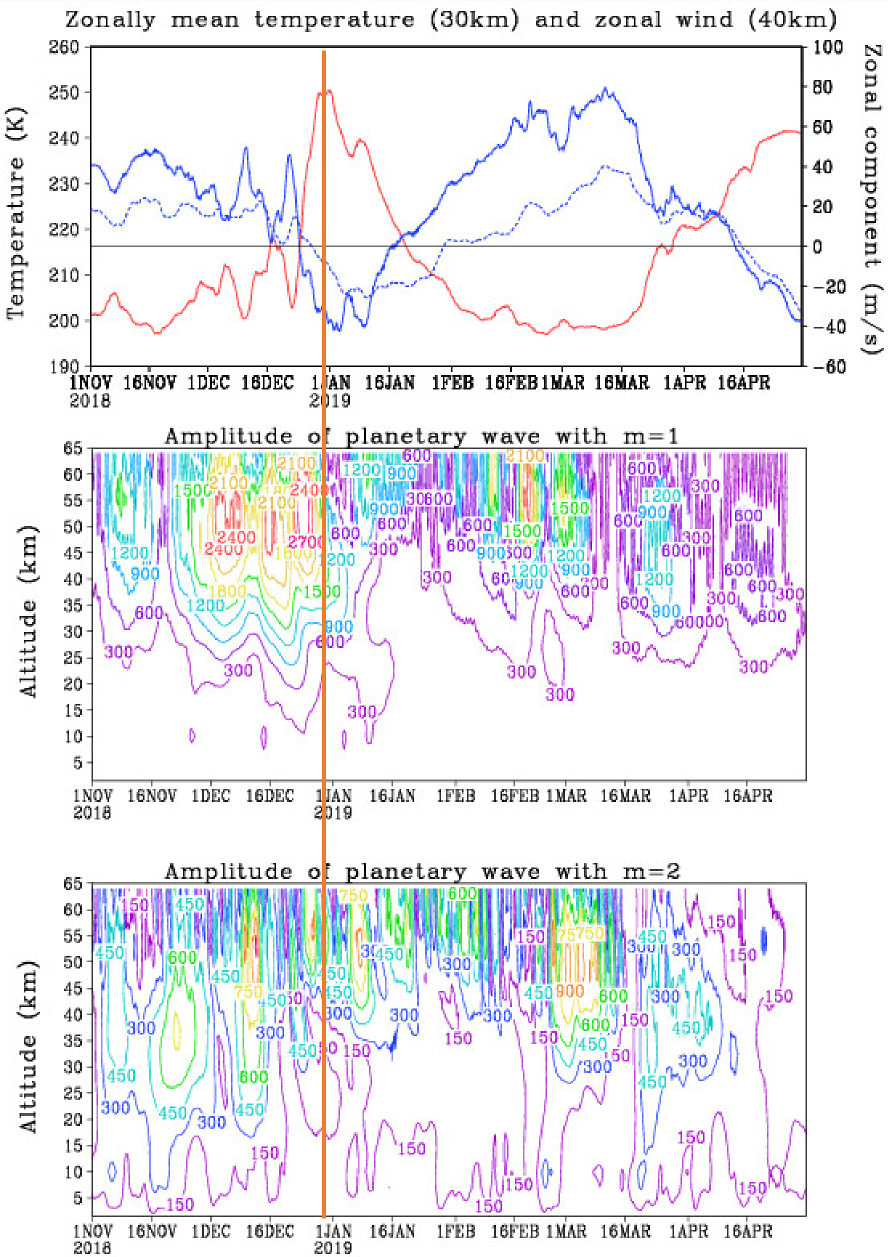
Data and research methods

- **MERRA2** reanalysis was used to study dynamic atmospheric processes in this study.

- **Calculations include**:
  - ✓ pressure and temperature anomalies/amplitudes of the PWs
  - ✓ position of the upper-level frontal zone (UFZ)
  - ✓ 3-dimensional wave activity flux (Plumb)
  - ✓ 2-dimensional wave activity flux (Eliassen-Palm)
  - ✓ Ertel potential vortex -> dynamic tropopause
  - ✓ Cold Air Mass (CAM) and Negative Heat Content (NHC) characteristics

- **Studies include**:
  - ✓ Correlation analysis of geopotential height anomalies with time lag
  - ✓ Isentropic analysis
  - ✓ Analysis of the interaction of planetary waves with the mean flow

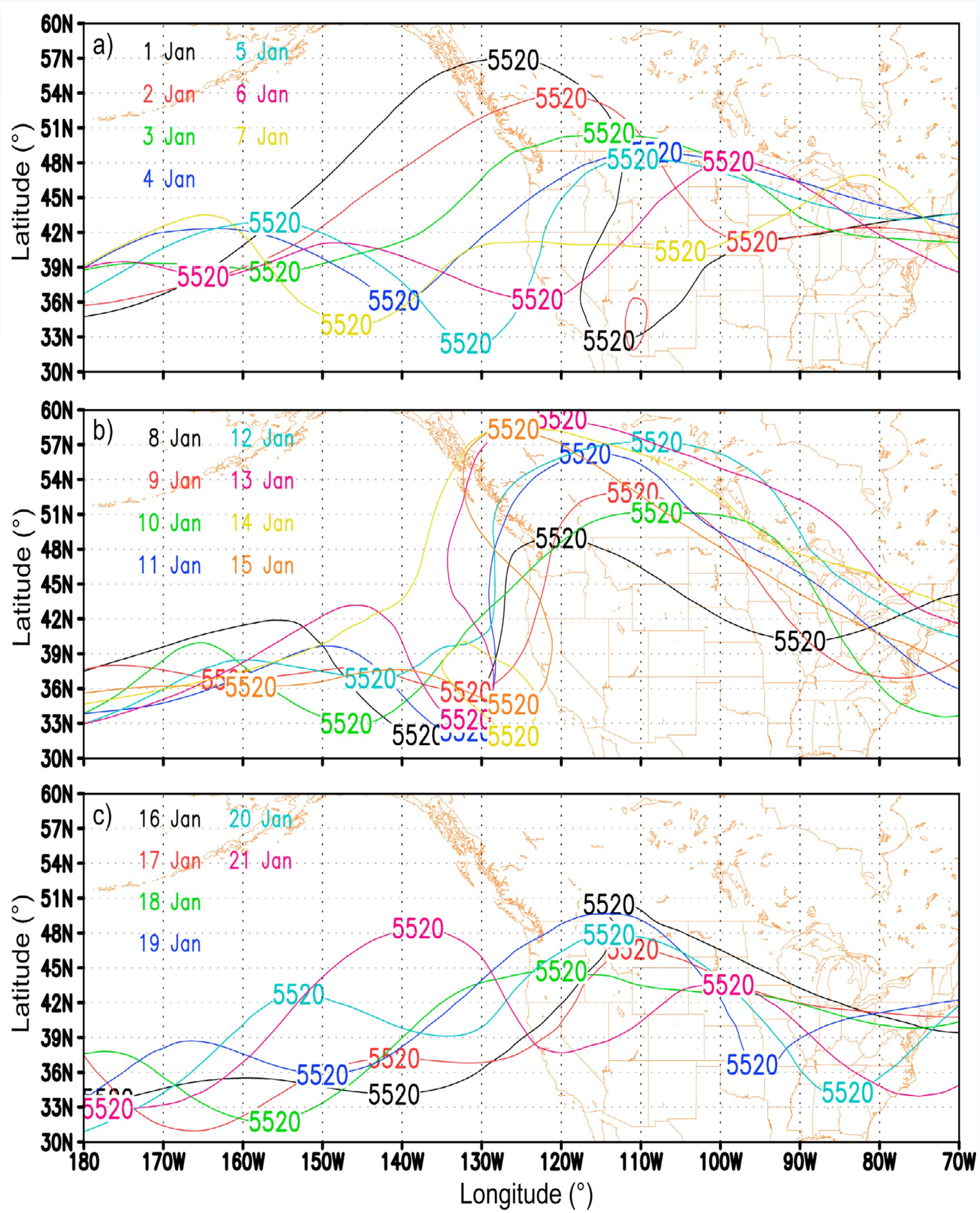
New Year SSW 2019



The SSW event began to develop in late December 2018 and peaked around January 1, 2019.
This event was preceded by an intensification of the PW1.

a) Zonal-mean temperature at an altitude of 30 km, 77°-87° N (red line) and zonal-mean zonal wind component at an altitudes of 30 and 40 km, 62.5° N (blue line);
b) PW1 amplitude in the geopotential height field;
c) PW2 amplitude in the geopotential height field.

Upper-level frontal zone *

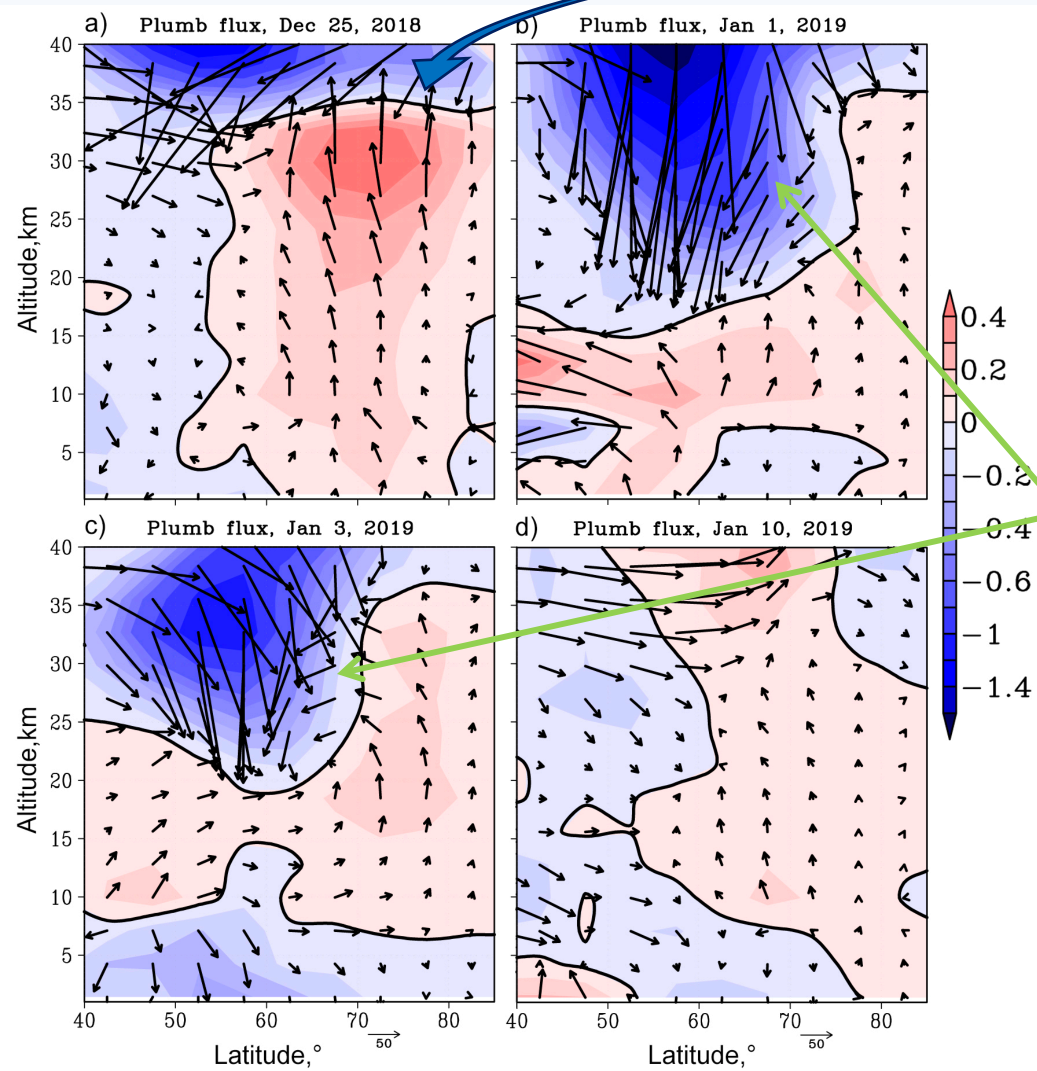


Over Canada, the UFZ undergoes significant distortion, with oscillations weakening toward the end of the period. The transport zonality characteristic of the first period gradually breaks down, the trough over eastern Canada deepens, and the ridge over the west coast intensifies. This UFZ position facilitates the penetration of colder air masses from the pole into central and eastern Canada.

** An upper-level frontal zone (UFZ) is an atmospheric formation in the middle or upper troposphere, characterized by sharp horizontal changes in temperature and pressure, as well as dense contour lines on weather maps. These zones concentrate large amounts of energy, actively transport air, and generate intense vertical motion, leading to cyclo- and anti-cyclogenesis.*

The position of the upper frontal zone (500 hPa level) determined during the natural synoptic period in January: a) 1–7 January; b) 8–15 January; c) 16–21 January.

Wave activity fluxes after SSW



- On December 25, positive anomalies in the vertical component of the VA flux predominate, indicating increased propagation of wave activity from the troposphere to the stratosphere poleward from 50° N, amid a general increase in wave activity during the first phase of the SSW.

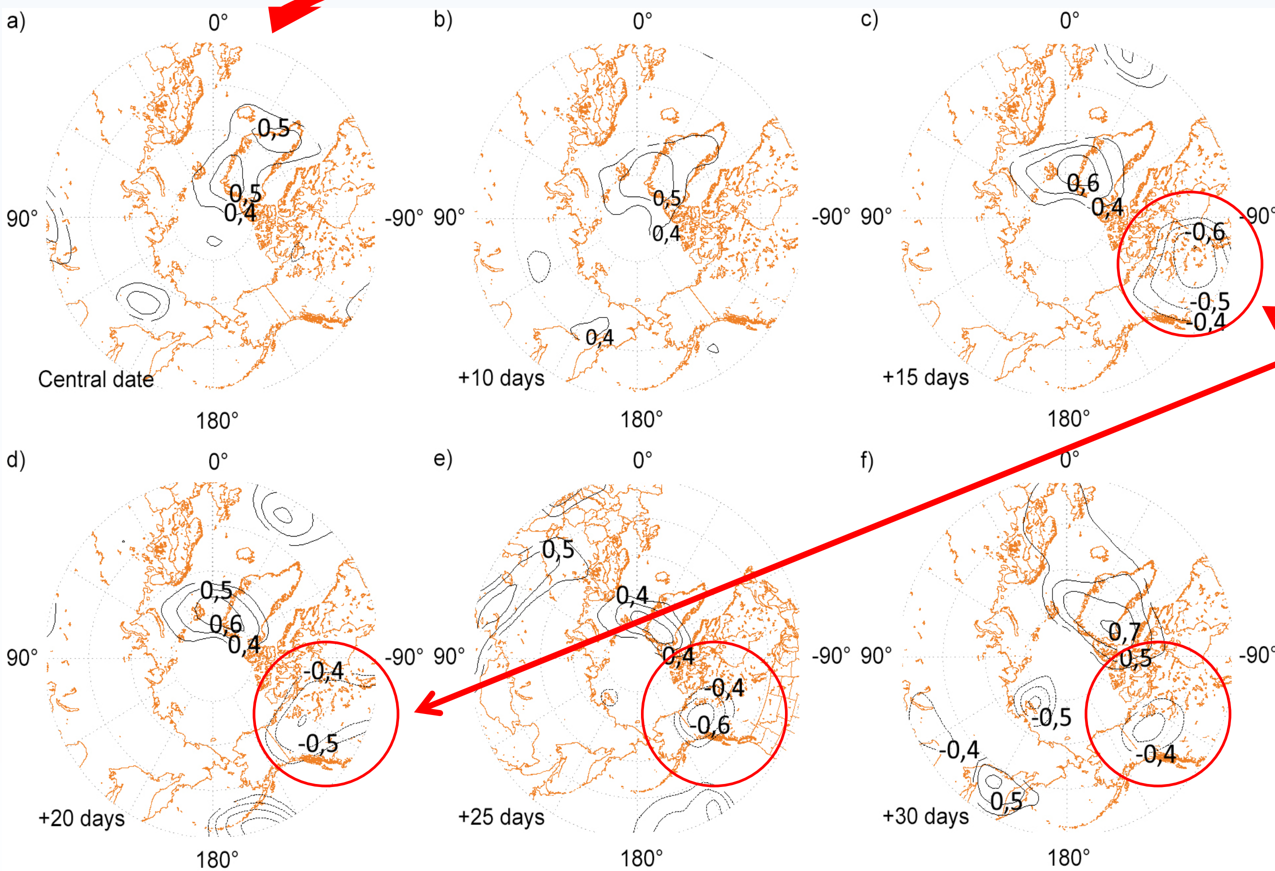
- During the SSW peak, from January 1 to 3, a strong planetary wave reflection is observed, facilitating a direct dynamic impact from the upper atmosphere to the lower atmosphere.

- After the SSW, wave activity anomalies decrease, bringing the distribution closer to the climate norm. However, the process of momentum transfer by reflected waves near the SSW peak has already contributed to the deformation of the UFZ and the onset of a cold air intrusion into the troposphere in the Canadian sector.

*Latitude - altitude distributions of Plumb wave activity flux anomalies (arrows, m2/s2) relative to climate values (2010–2019), averaged over longitudes 60° W–170° W (**Canada**) for December 25 (2018), January 1, 3, 10 (a–d, respectively).*

Correlation analysis of geopotential anomalies

In order to show that the change in the UFZ occurred **not after** the SSW event, **but as a result** of this event, a correlation analysis of the geopotential anomaly fields with a time lag was performed.



During a SSW event, the stratosphere and troposphere interact weakly, with no signal between the stratosphere and troposphere.

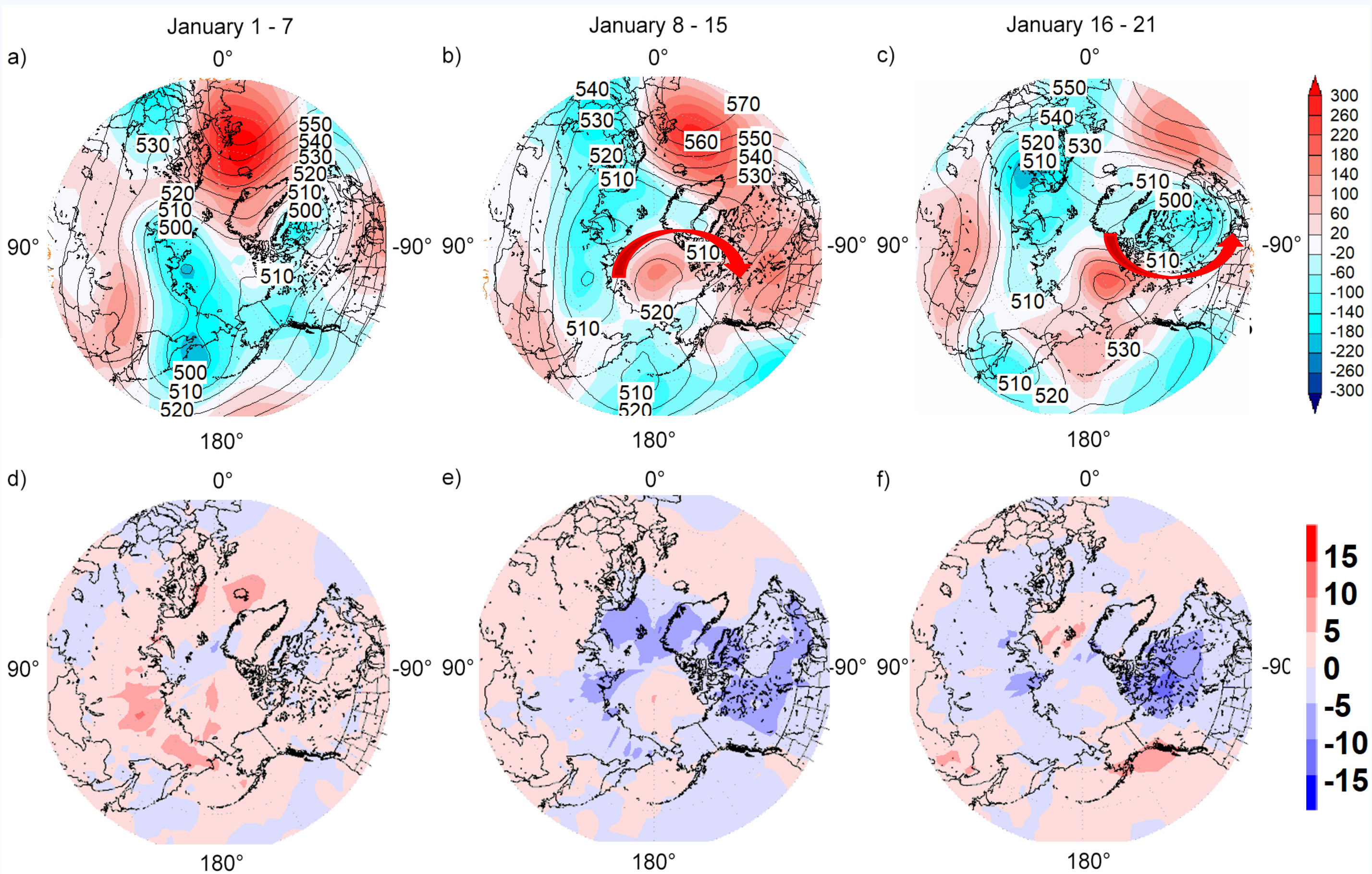
After two weeks, the signal from the stratosphere penetrates, and the correlation coefficient increases. **This coefficient is greatest in the region where the UFZ changed.**

The shift of the stratospheric vortex leads to an increase in the upper-air ridge in the region of Canada at 500 hPa, as indicated by negative correlation coefficients.

The stratosphere influences the shift in surface pressure changes through the change in the UFZ. The SSW event disrupted zonal circulation.

Significant correlation coefficients between the anomalies of the geopotential of 7 hPa and 500 hPa a) on the central date; b) with a shift of 10, 15, 20, 25 and 30 days (b-e, respectively).

Formation of a cold air outbreak



500 hPa geopotential anomalies (colored fill) and absolute geopotential values at 500 hPa (contours).

Corresponding surface temperature anomalies for the same time intervals.

- ❖ The SSW resulted in a strengthening ridge over Alaska and western Canada from January 8 to 15, which is **atypical** for this period.
- ❖ Along the periphery of anticyclonic and cyclonic formations, cold Arctic air masses rush to lower latitudes on the continent (shown by arrows).
- ❖ Cold waves form over Canada in the second half of January.

Isentropic analysis

- **An isentropic surface is a surface with a uniform potential temperature.**
- Potential temperature is the temperature a particle would assume if brought adiabatically to a pressure of 1000 hPa.
- From the definition of potential temperature, it follows that on surfaces with uniform potential temperature, **isobars can be considered isotherms**.

- From the ideal gas equation of state and the definition of potential temperature, it follows that on isentropic surfaces, lines of uniform pressure can also be considered lines of uniform density.

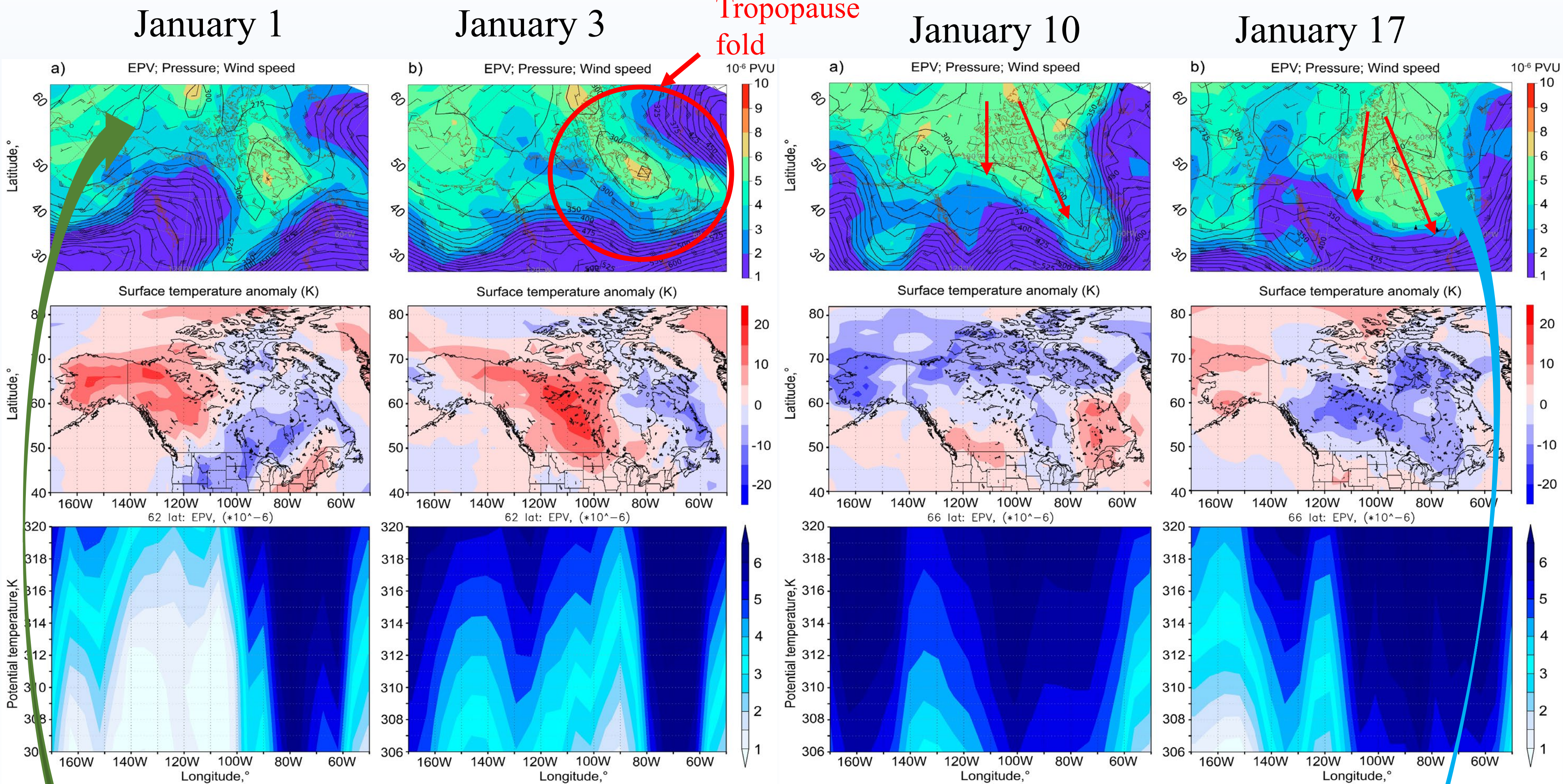
- Thus, on isentropic surfaces, pressure advection can be considered temperature advection.

  - That is, if on an isentropic surface the wind blows from a high-pressure region to a low-pressure region, the air rises, creating **heat** advection.

  - If on an isentropic surface the wind blows from a low-pressure region to a high-pressure region, the air sinks, creating **cold** advection.

Moore, J.T., 1993. Isentropic Analysis and Interpretation: Operational Applications to Synoptic and Mesoscale Forecast Problems. National Weather Service Training Center, Kansas City, Missouri, p. 99.

Isentropic analysis

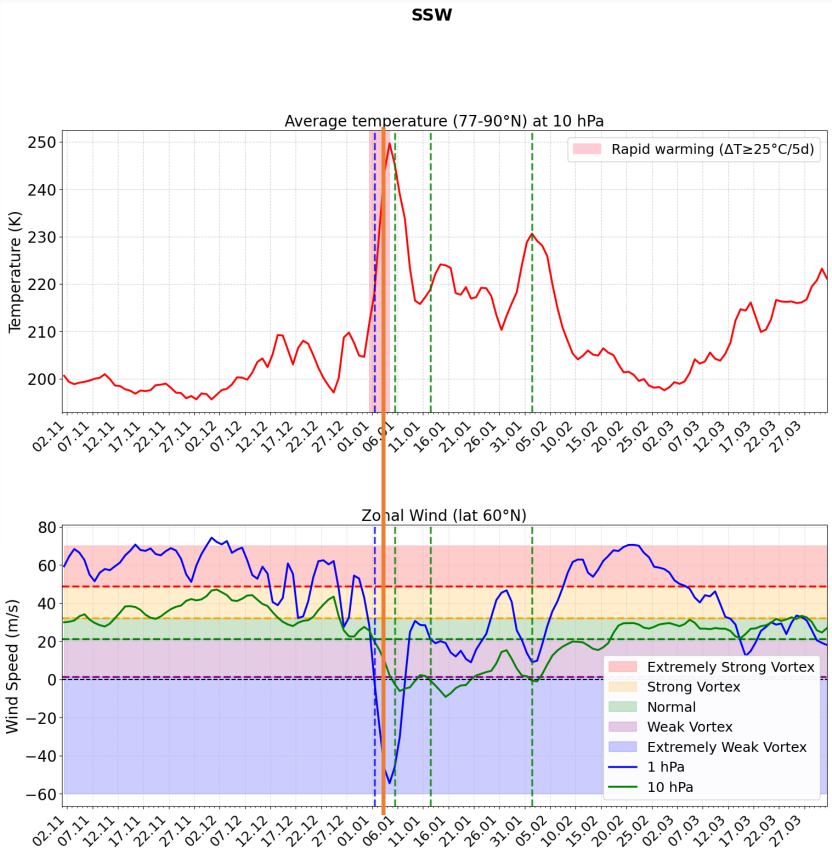


Ertel's potential vortex, pressure and wind at the isentropic surface 310 K (top row); surface temperature anomaly (middle row), both for the region 60°W-170°W and 40°N-90°N (Canadian sector); vertical cross-section of potential vorticity *in the same sector (latitude 62°N - bottom) on January 1, 3, 10 and 17.*

High PV values indicate a low tropopause and a cold air mass.

On January 10 and 17, winds blow from an area of low pressure (temperatures) to an area of high pressure over the center of the continent. Temperatures drop here.

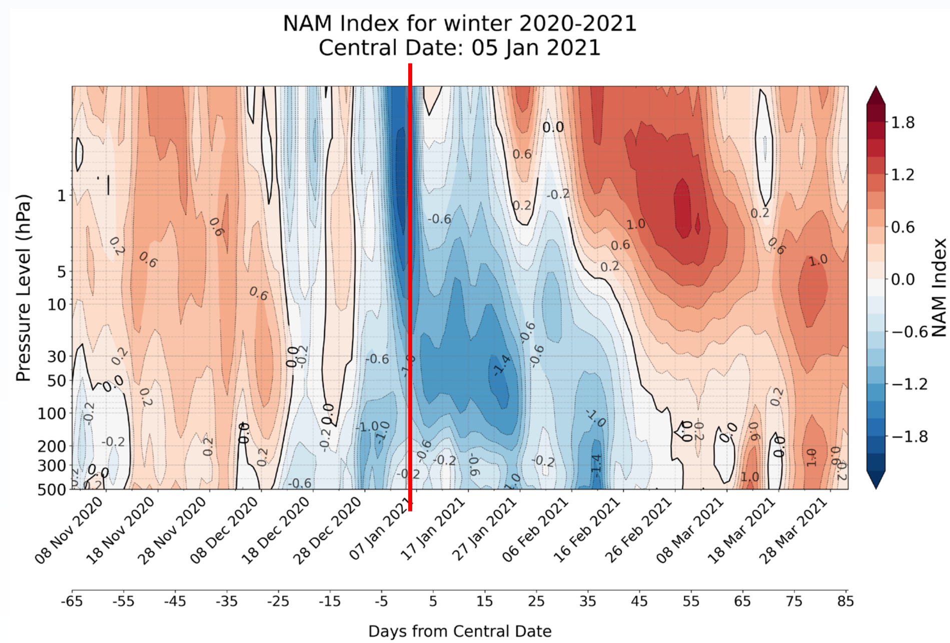
SSW in January 2021



Zonal mean temperature (at 10 hPa level for latitudes 77–90° N) (top panel); zonal wind speed at 10 hPa level (green curve) and at 1 hPa level (blue) at latitude 60° N (bottom).

- The NAM index, which characterizes the polar vortex's intensity, demonstrates a weak and unstable vortex state beginning in the second ten-day period of December.
- This state persisted in the stratosphere until the second half of February.
- In the lower stratosphere-troposphere, the NAM index remained negative until early March, two months after the first SSW, indicating that the SSW had a long-lasting and strong influence on tropospheric dynamics.

Northern annular mode (NAM) index. The red line marks the SSW date.

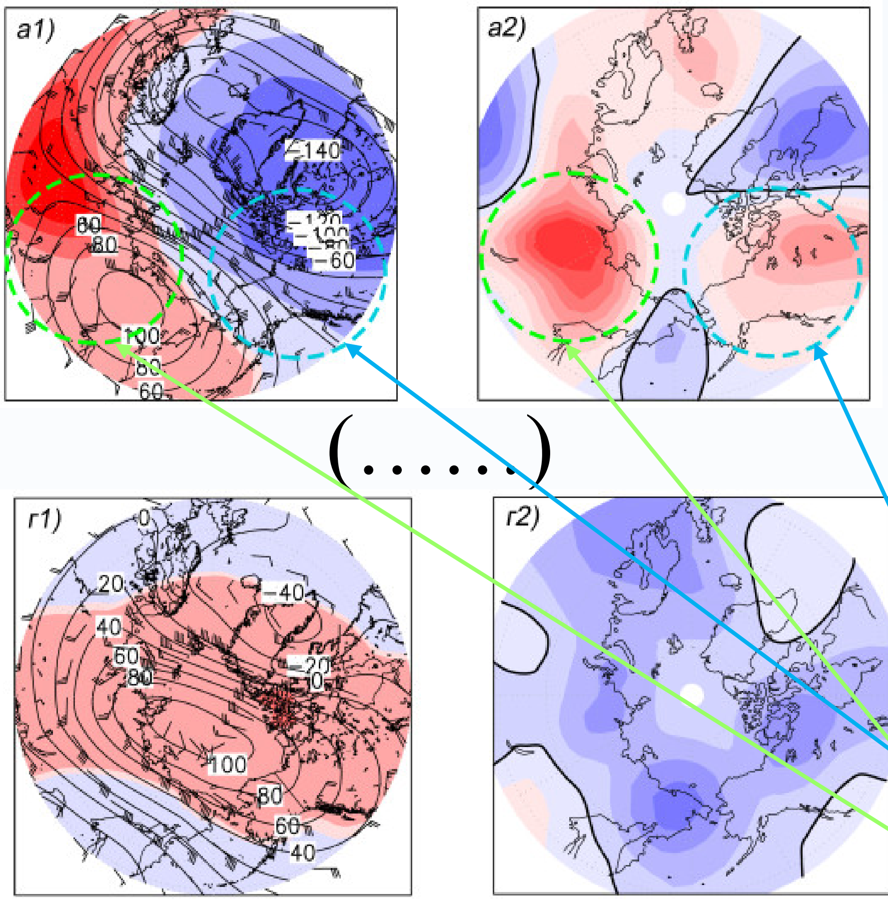


The stratosphere before the SSW

Polar vortex structure at 10 hPa:
December 30 and January 5.

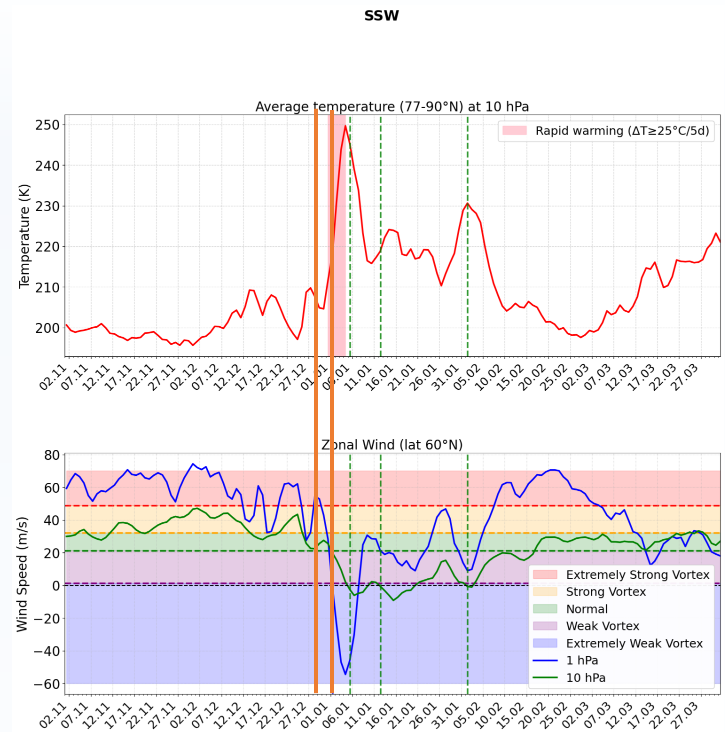
December 30

January 5



Anomalies of geopotential height (contours) and temperature (filling), as well as horizontal wind

Plumb's vertical flux anomalies.



The vertical Plumb flux is proportional to the meridional heat flux **v'T'**.

Product of negative v'T'

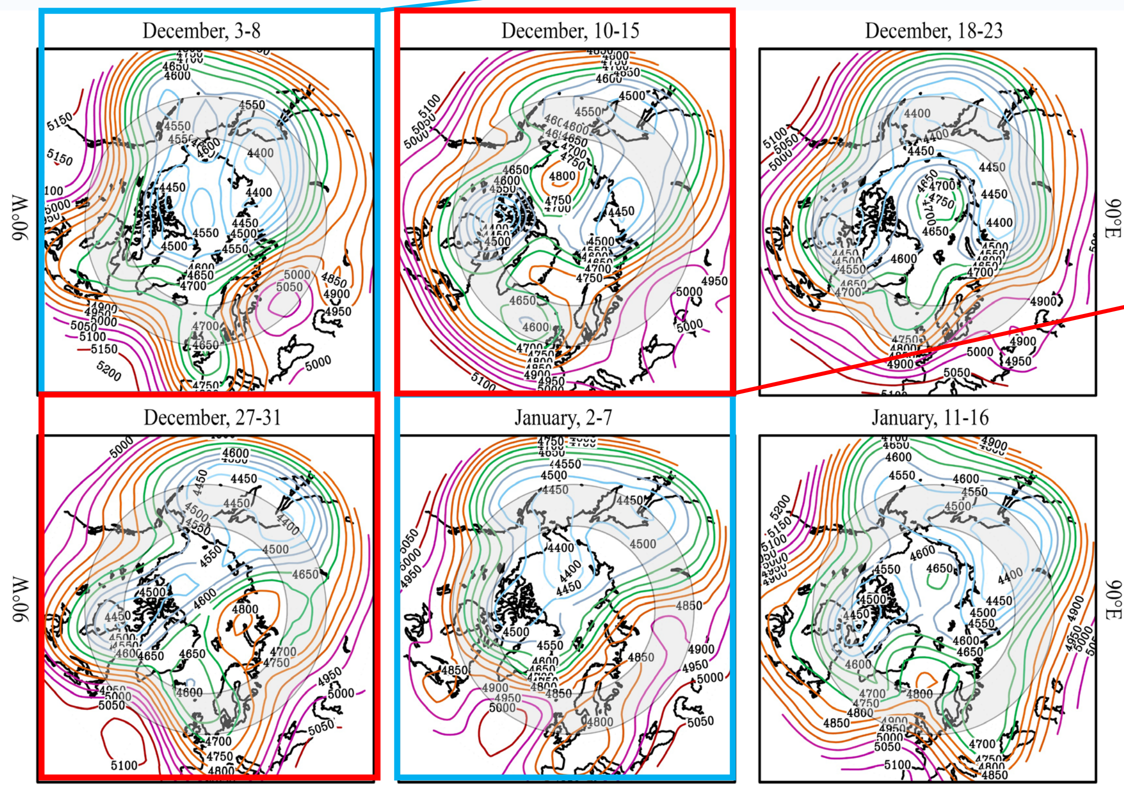
Product of positive v'T'

=> **Increased wave activity.**

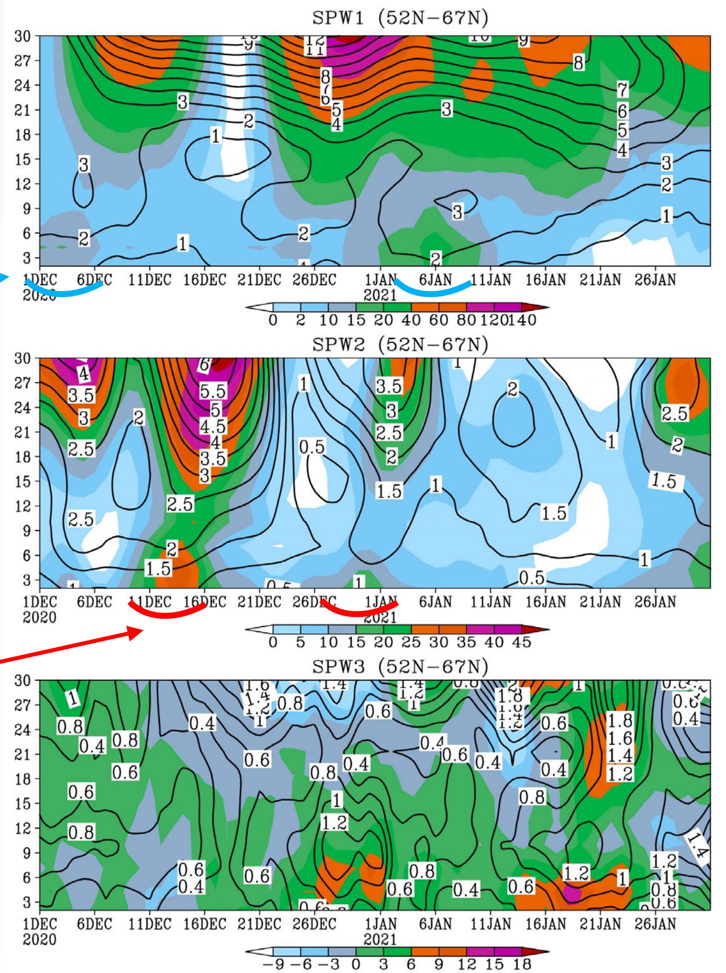
Troposphere -> Stratosphere

Signal from bottom to top before SSW

The relationship between the longitudinal configuration of quasi-stationary pressure disturbances in the troposphere and the generation of stationary PWs with zonal numbers 1-3



Geopotential height (gpm) of the 500 hPa surface in the latitude range 30°-90° N.



Altitude-temporal distribution of EP fluxes (filling $m^2/s^2 * 10^{-2}$) and amplitudes (contours, gpm $* 10^2$) of SPV1-3 (a-c) in December-January in the latitudinal belt 52°-67° N.

Stratosphere -> Troposphere

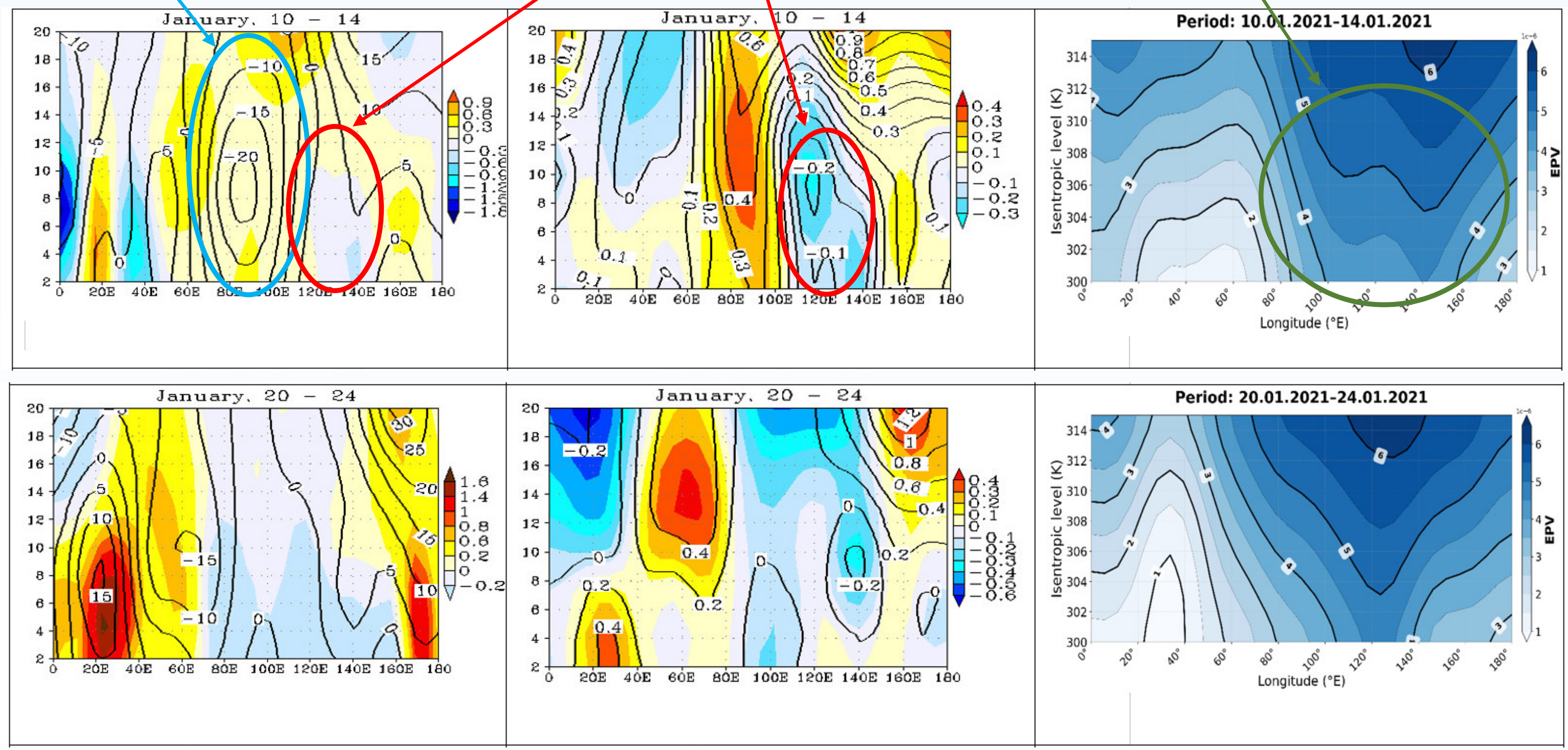
Signal from top to bottom after SSW

Eastern Hemisphere, 62° N, mid to late January.

Arctic air influx.

Downward mass flows and WA (rare in the eastern hemisphere).

Lowering of the tropopause



Vertical (fill, cm/s) and meridional (contours m/s) wind components.

The vertical component of the Plumb flux (contours, m^2/s^2) and its anomalies relative to climate (filling)

Potential vorticity in an isentropic coordinate system

Formation of a cold air outbreak in Eurasia after the SSW

To diagnose cold waves caused by stratospheric processes, a method was used to calculate the characteristics obtained on an isentropic vertical grid: Cold Air Mass (CAM), Negative Heat Content (NHC), and their fluxes, which are calculated using the following formulas:

CAM shows the size of the air column in hPa from the surface to the isentropic level θT and characterizes the "quantity" of cold air.

$$\mathrm{CAM} = \mathrm{p}_0 - \mathrm{p}(\theta_T) \quad (1)$$

$$\mathrm{NHC} = \int_{\mathrm{p}(\theta_T)}^{\mathrm{p}_0} (\theta_T - \theta)\mathrm{dp} \quad (2)$$

$$F_{CAM} = \int_{\mathrm{p}(\theta_T)}^{\mathrm{p}_0} \mathrm{vdp} \quad (3)$$

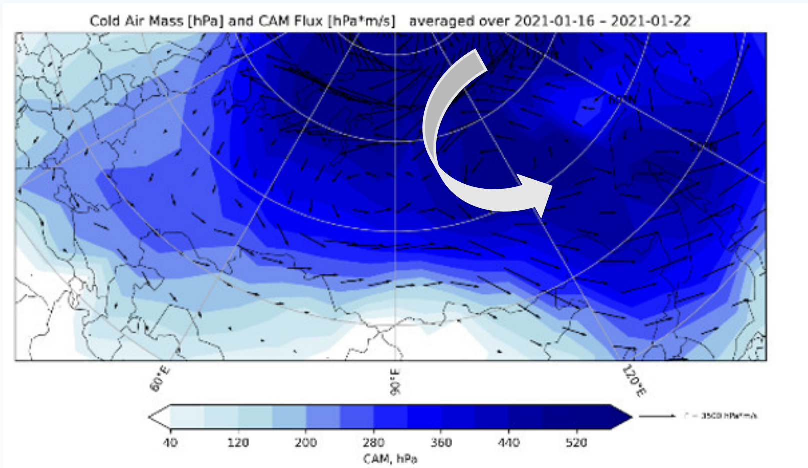
$$F_{NHC} = \int_{\mathrm{p}(\theta_T)}^{\mathrm{p}_0} (\theta_T - \theta)\mathrm{vdp} \quad (4)$$

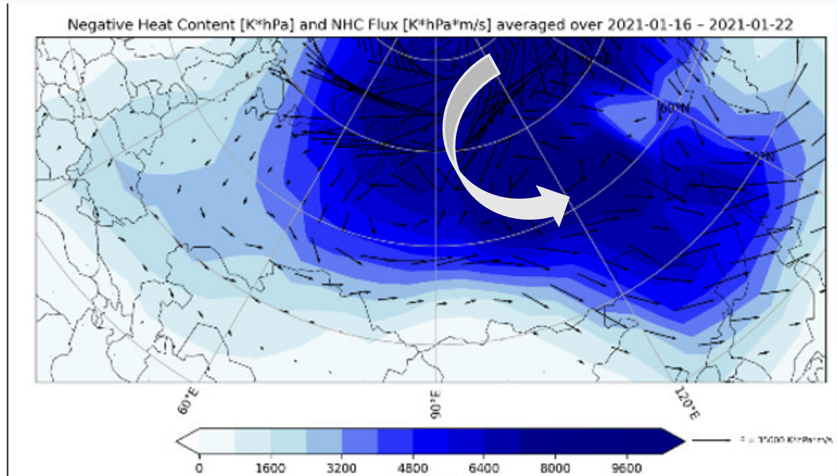
NHC takes into account the temperature profile in a given column and characterizes the potential temperature deficit relative to some threshold value, or the "intensity" of cold air

where P0 is the surface pressure; P(θT) is the pressure at the isentropic level θT; **v** is the wind speed vector; θT is the threshold temperature, the isentropic level at which the zonal-average air mass flow in extratropical latitudes in the winter hemisphere changes direction from downward to equatorial. This level is usually taken to be 280 K.

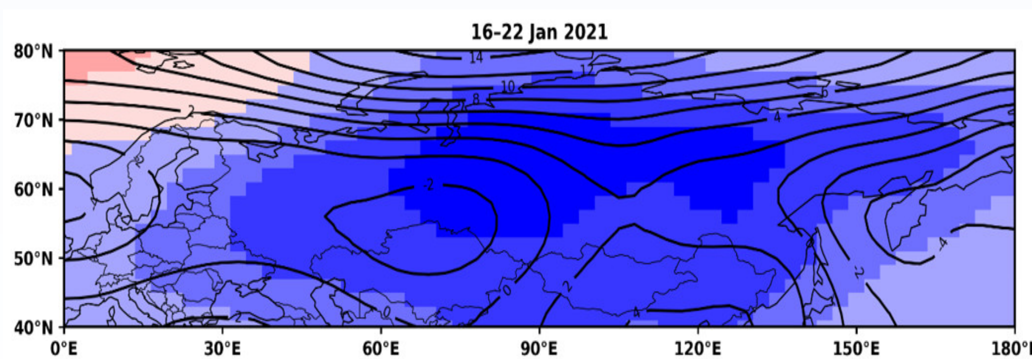
Formation of a cold air outbreak in Eurasia after the SSW

Cold wave peak: January 16-22, 2021





CAM (left) and NHC (right) indices (fill) and corresponding fluxes



Temperature (fill) and geopotential height (contours) anomalies at the 1000 hPa level on January 16-22.

Conclusion

SSW in the winter of 2018-2019

- The SSW resulted in a change in the shape of the UFZ, followed by a shift in the direction of the steering flows over Canada. The UFZ deformation occurred approximately 15-20 days after the central date of the SSW. This change in the steering flows led to the formation of a cold air outbreak over Canada.
- Isentropic analysis showed that, in addition to changing mid-tropospheric flows, the SSW caused an intrusion of stratospheric air into the troposphere, which, in turn, further intensified the onset of the cold wave. This intrusion of high-vorticity stratospheric air contributed to an overall decrease in the tropopause height and the formation of tropopause folds.
- To study the influence of the stratosphere on the troposphere, a time-shifted correlation analysis was used. Starting with a time lag of 2 weeks, a correlation between geopotential variations is observed, with the maximum correlation coefficient corresponding to the region with UFZ deformation.
- An analysis of 3-dimensional wave activity fluxes revealed an intensification of the downdraft during the SSW over the Canadian sector, confirming an increase in the dynamic influence of the stratosphere on the troposphere.

SSW in the winter of 2020-2021

- The coincidence of the intensification of SPW1 and SPW2 in the stratosphere played a significant role in the formation of the SSW, with tropospheric wave generation sources clearly visible throughout December before the SSW.
- In the Eastern Hemisphere, the stratosphere's influence on the troposphere intensified after the SSW in January, and it was in this sector that a surface cold wave was observed in the second half of January.
- The CAM and NHC fluxes demonstrate the maximum volume and intensity of the cold intrusion from January 16 to 22. Stratospheric intrusion also served as an important additional driver of cold air outbreak.

A new set of methods for studying dynamic processes has been developed, integrating synoptic analysis and calculating global dynamic interactions between the middle and lower atmosphere.

This methodology will be further scaled up.

For more details, see the publication:
Toptunova, O.N., Motsakov, M.A. , Koval, A.V., Ermakova, T.S., Didenko, K.A. (2025) Impact of sudden stratospheric warming on tropospheric circulation and a cold wave formation: The case of the January 2019 event. Atmospheric Research 318 (2025) 107998. DOI: 10.1016/j.atmosres.2025.107998

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