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A critical role of the North Pacific bomb cyclones in the onset of the 2021 Sudden Stratospheric Warming

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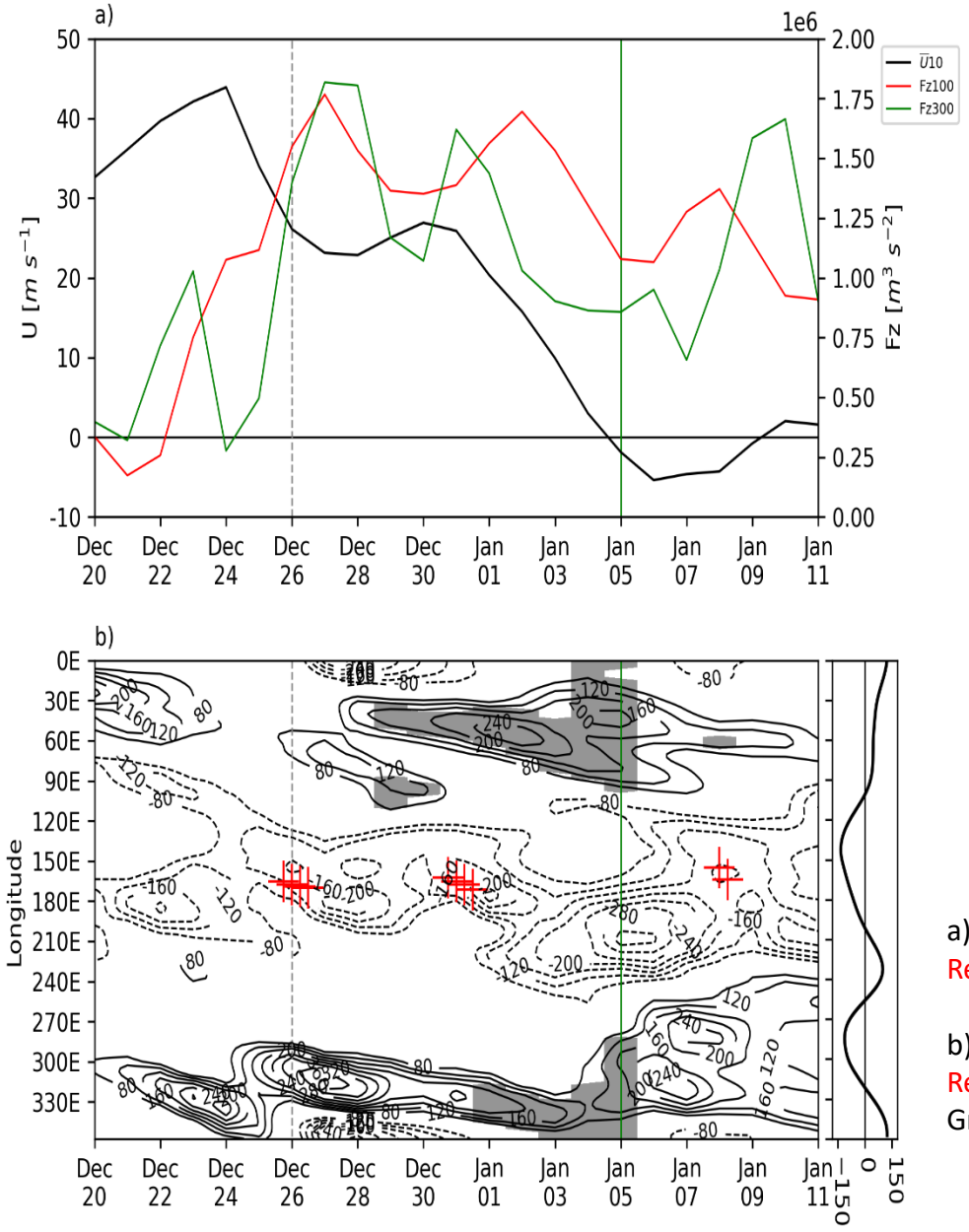
The 2021 SSW & tropospheric precursors



- 2021 SSW onset: **January 5, 2021**.
- There are **two peaks of upward wave propagation** from the upper troposphere to the lower stratosphere.
- Before the SSW onset, successive **bomb cyclones** are developed over the North Pacific where the climatological Aleutian low exists.

a) Black solid: $\bar{U}10$ at 60°N
Red/Green solid: planetary-scale Fz (normalized) at 100/300 hPa

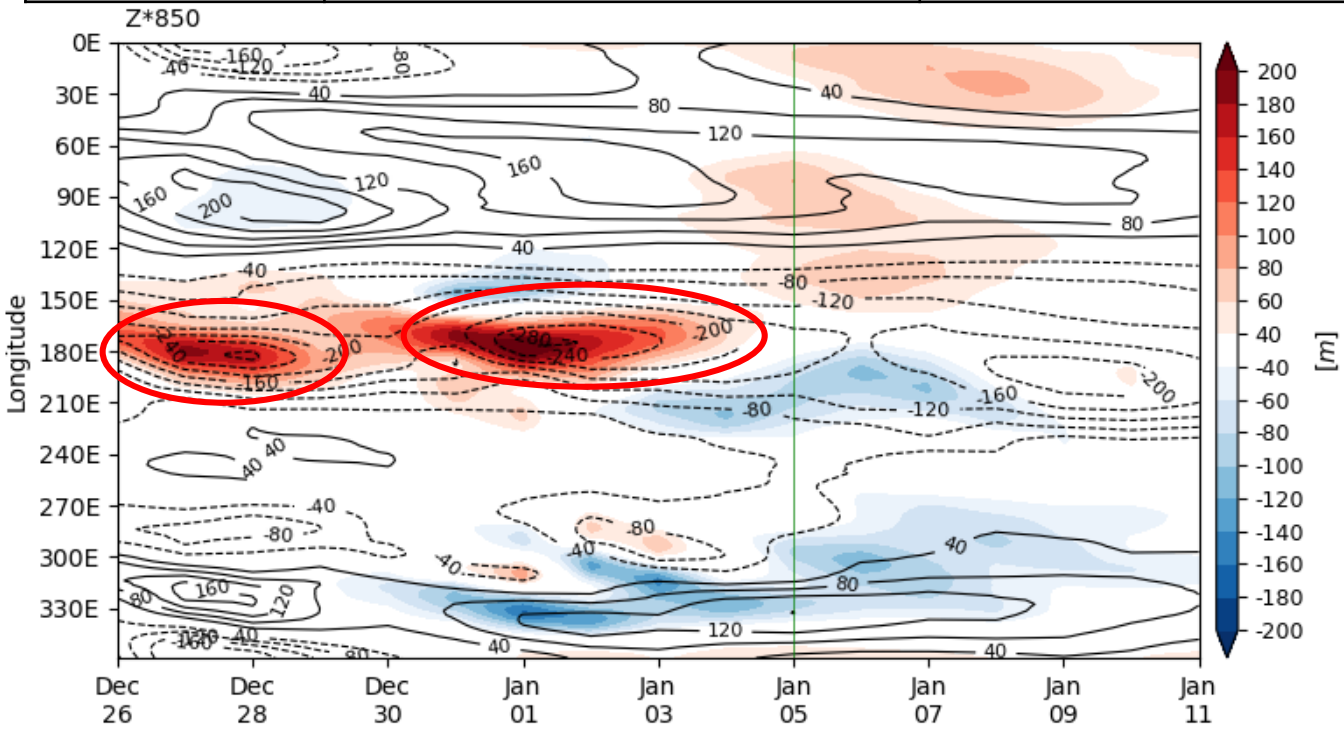
b) Contour: Z^*850 over 45°–75°N, their climatology (right)
Red cross: Rapidly deepening position of bomb cyclones
Gray shading: blocking at 60°N.

Experimental designs

Numerical Model: Global/Regional Integrated Model system (GRIMs)

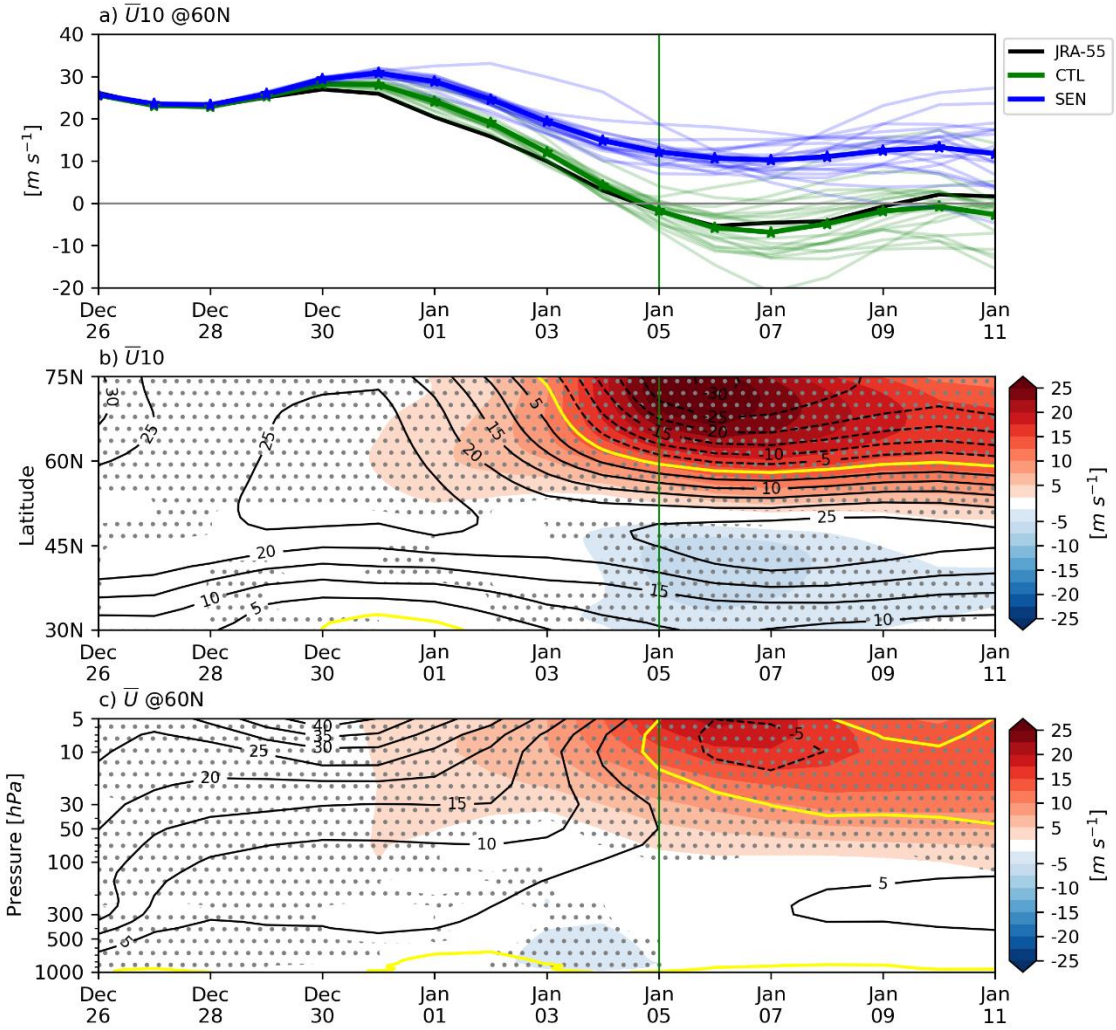
Initialization: 00 UTC December 26, 2020
Ensemble: 20 perturbed ensemble
In SEN, the bomb cyclone is removed using Potential Vorticity (PV) inversion

	Control (CTL)	**Sensitivity (SEN)**
Initial condition	U, V, T, Z, Q from JRA-55	Same with CTL, but **anomalous cyclonic fields** (U, V, T, Z) are removed
PV inversion domain	Not used	Pacific: 20°–80°N, 110°E–160°W Levels: 1000–150 hPa



Z^*850 over 45°–75°N
Contour: CTL
Shading: SEN minus CTL

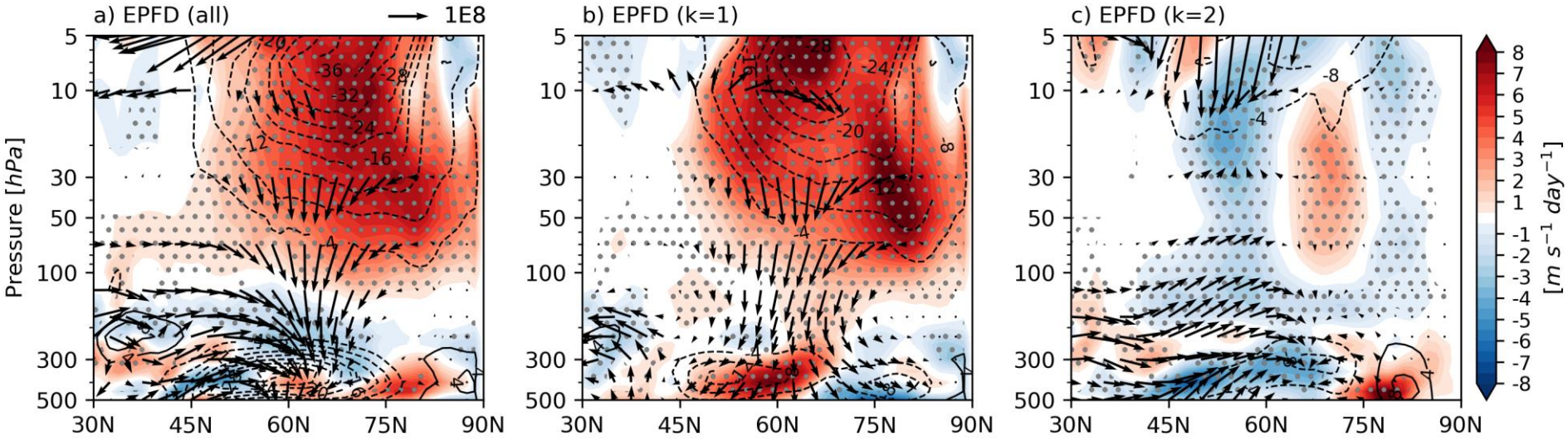
Impact of bomb cyclones on 2021 SSW



- **CTL: reproduces the 2021 SSW (T+10 day lead)**
- **SEN:** much weaker wind deceleration, **not recorded SSW onset**.
- The weaker deceleration in SEN: evident in the polar stratosphere

a) $\overline{U}10$ at 60°N
Green: CTL, Blue: SEN
b) $\overline{U}10$, and c) $\overline{U}$ at 60°N
Contour: CTL
Shading: and SEN minus CTL

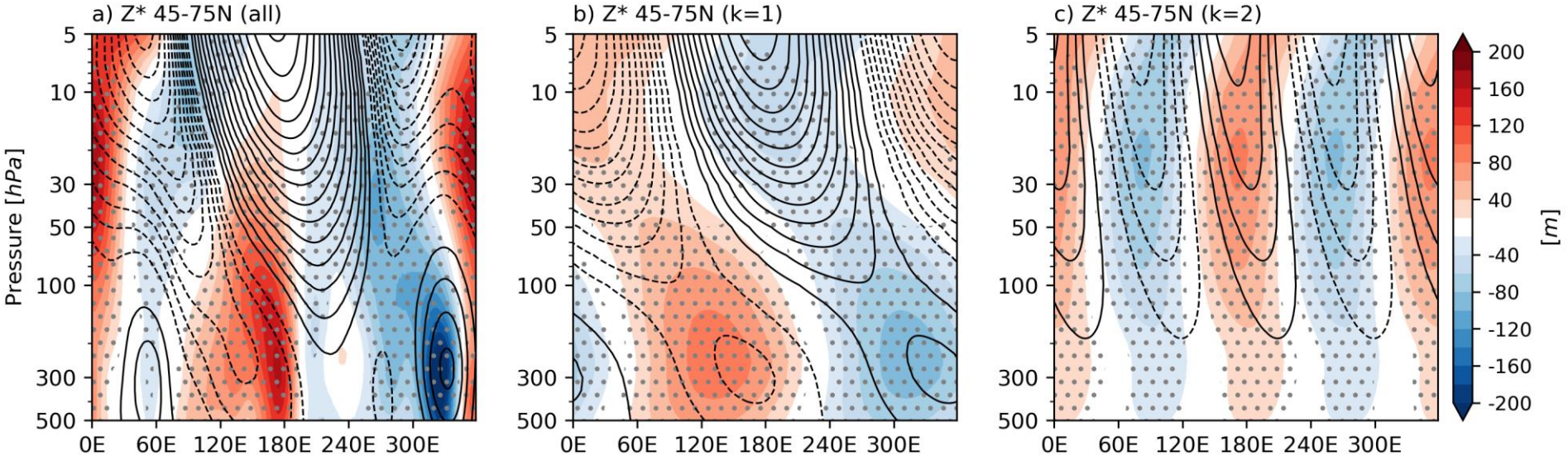
Dynamical explanation: EP flux analysis



Contour: CTL
Shading: SEN minus CTL
Arrows: normalized EP flux vector difference ($p<0.01$)

- Before the 2021 SSW onset, **strong negative EPFD** is found in CTL, which explains polar vortex weakening.
- Compared to CTL, **EPFD magnitude in SEN is significantly small** due to reduced wave propagation in the vertical direction.
- The differences are mainly attributable to the difference in **upward propagation of the k=1 wave**.

Wave interference



Contour: CTL
Shading: SEN minus CTL

- The k=1 components in SEN are **out of phase** with the k=1 pattern in CTL, which is a dominant pattern from the upper troposphere to the lower stratosphere.
- The k=2 component in SEN is in phase with the k=2 pattern in CTL, but recessive than the k=1 component.
- These results imply that **k=1 wave** interference by bomb cyclone plays an important role in the onset of the 2021 SSW.

Conclusions

- The 2021 SSW is successfully reproduced by a model initialized 10 days before the SSW.
- The model initialized without the North Pacific bomb cyclone does not simulate the 2021 SSW.
- Removing the North Pacific bomb cyclone reduces the k=1 wave propagation into the stratosphere, reducing wave breaking in the stratosphere.

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