Dynamics of Sudden Stratospheric Warmings

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ECMWF w/s "Stratospheric Predictability & Impact on Troposphere" (Nov 2019), Reading, UK

Background

- Sudden Stratospheric Warmings (SSWs) are a manifestation of strong (planetary) wave-mean flow interactions.
- source of planetary waves: troposphere (mostly...)
- likelihood of SSWs ~ strength of upward flux of planetary wave activity from the troposphere (e.g., SH versus NH)

→ Does this mean that SSWs occur more likely following bursts of planetary wave activity from the troposphere?

→ Is a burst of tropospheric planetary wave activity needed to force a sudden warming?
(given sufficient climatological forcing)

Quasi-linear Theory – Matsuno (1971)

- Linear wave propagation on the sphere, combined with (non-linear) wave-mean flow interaction
- switch-on wave forcing prescribed at lower boundary
- Initial value problem for non-linear transient wave-mean flow evolution

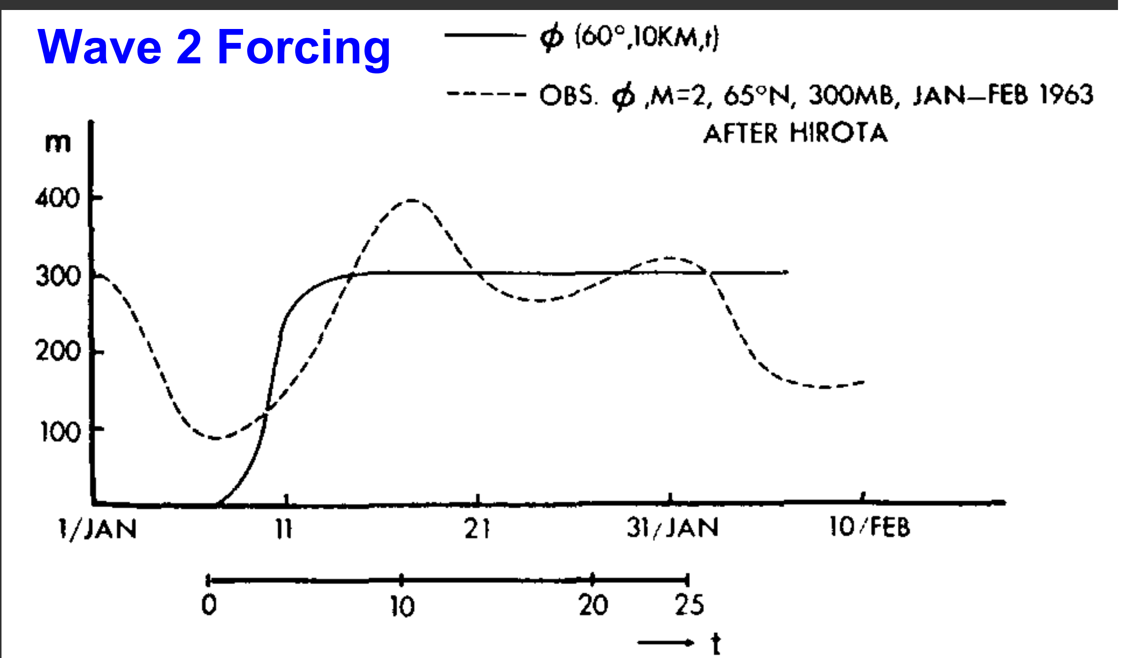
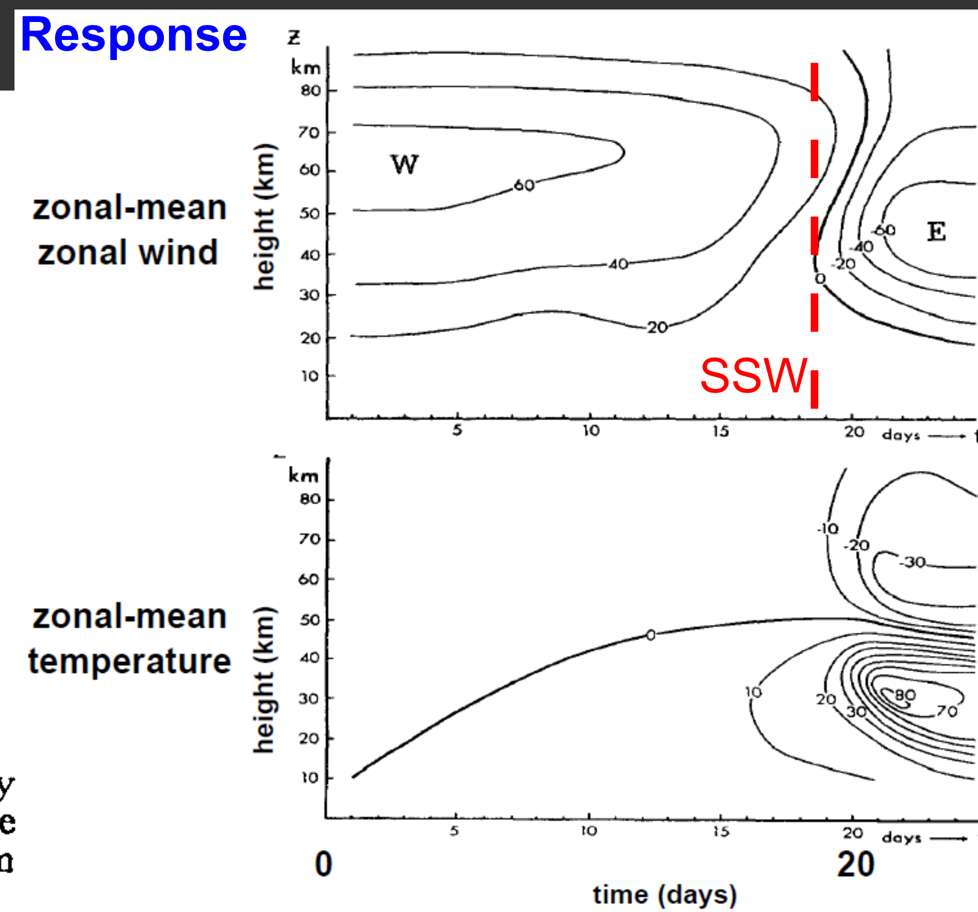


FIG. 3. The amplitude of the waves forced at the lower boundary (solid line). The dashed line shows the observed amplitude of the $m=2$ wave at 300 mb in January–February 1963, (data from Dr. Hirota).



Quasi-linear Theory – Holton-Mass (1976) Stratospheric Vacillations

Quasigeostrophic, β–channel, 60ºN±30º, 10km ≤ z ≤ 80km,
Coupled equations for linearized PV and zonal mean flow:

$$
\begin{aligned}
\left(\partial_t + \overline{u}\partial_x\right) q' + \beta' \partial_x \psi' \quad &+ \quad \frac{f_0^2}{\rho}\partial_z \left(\frac{\alpha\rho}{N^2}\partial_z \psi'\right) = 0 \\
\partial_t \left[\partial_{yy}\overline{u} + \frac{f_0^2}{N^2\rho}\partial_z\left(\rho\partial_z\overline{u}\right)\right] = \quad &- \quad \frac{f_0^2}{N^2\rho}\partial_z\left[\alpha\rho\partial_z\left(\overline{u} - U_R\right)\right] \\
&+ \quad \frac{f_0^2}{N^2}\partial_{yy}\left[\rho^{-1}\partial_z\left(\rho\overline{\partial_x\psi'\partial_z\psi'}\right)\right]
\end{aligned}
$$

Prescribed wave forcing via bottom boundary (~tropopause) condition for *Ψ′* (~geopotential height perturbation)

U(z=25km,t)

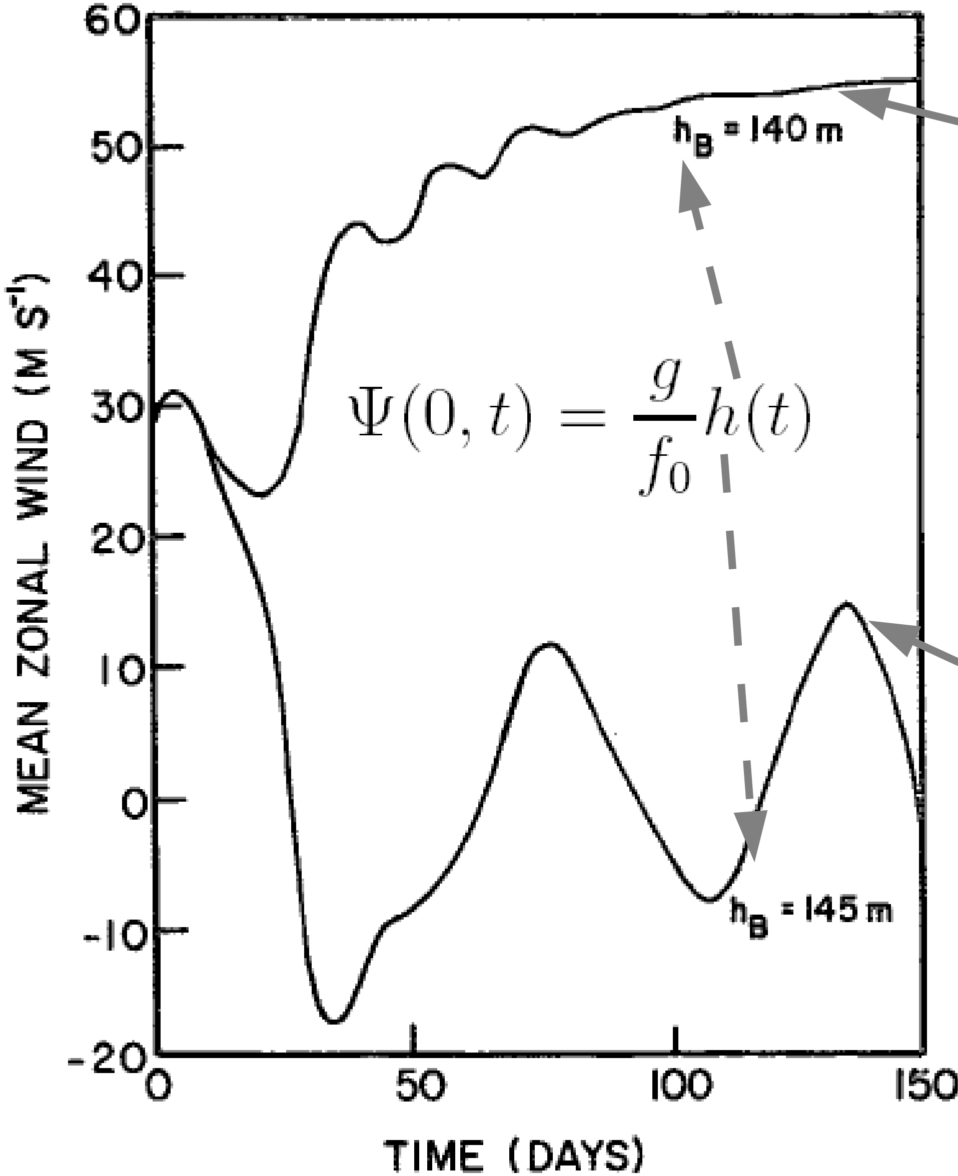


FIG. 2. Time evolutions of the mean zonal wind at 25 km and midchannel for the steady regime ($h_B = 140$ m)and the vacillating regime ($h_B = 145$ m) for zonal wavenumber 2 forcing.

Radiative Solution
($h < h_{crit}$)

Standing wave caused by reflection in strong upper westerlies, virtually no eddy heat flux.

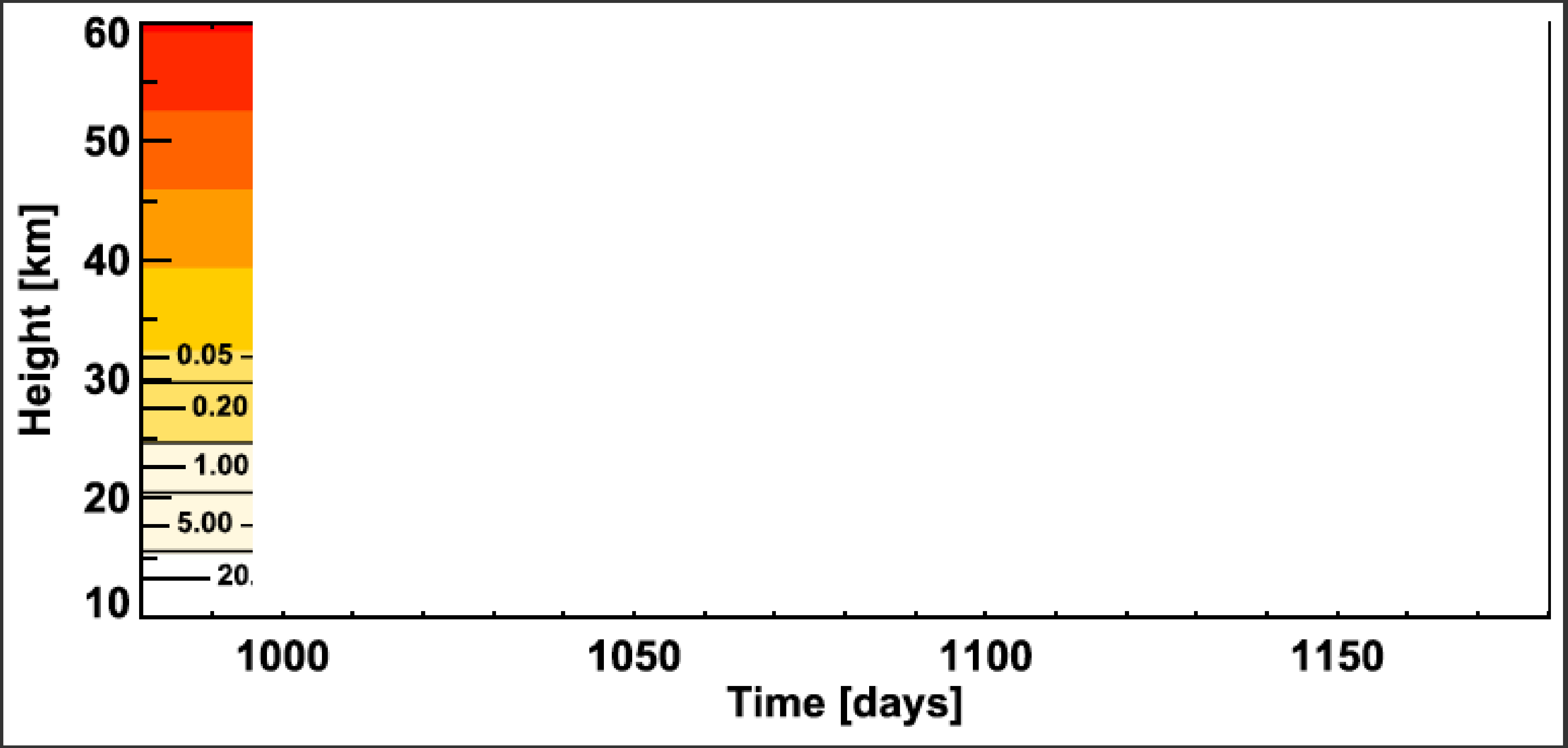
Vacillation ~ SSWs
($h > h_{crit}$)

Strongly oscillating eddy heat flux & mean flow

Holton & Mass (1976)

Is a burst of wave activity flux from the troposphere needed to trigger a SSW?

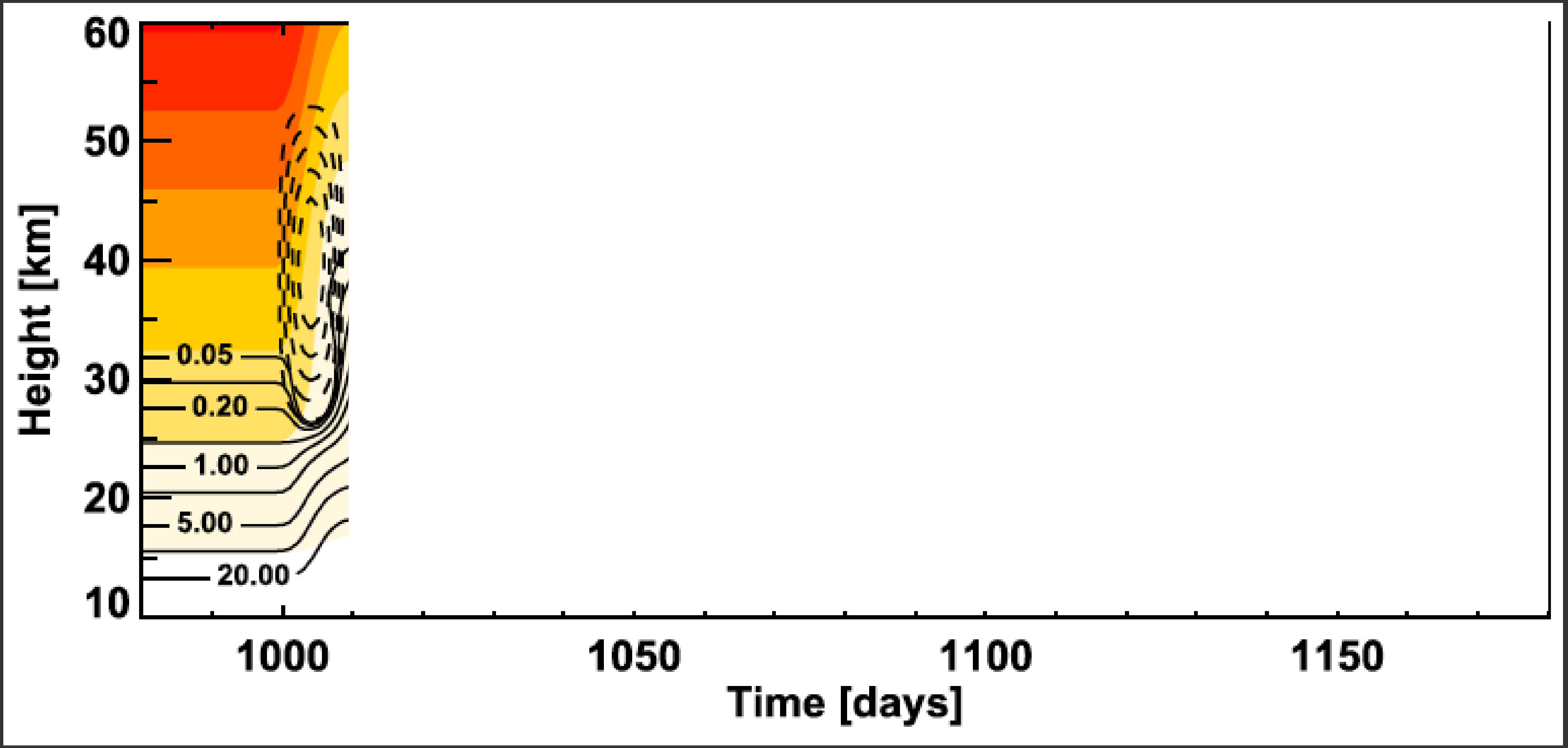
Sjoberg & Birner (2014): modified Holton-Mass model with *prescribed bottom boundary upward wave activity flux*



- Constant incoming wave forcing at lower boundary

Sjoberg & Birner (2014): modified Holton-Mass model with prescribed bottom boundary upward wave activity flux

→ response to stratospheric zonal wind perturbation:



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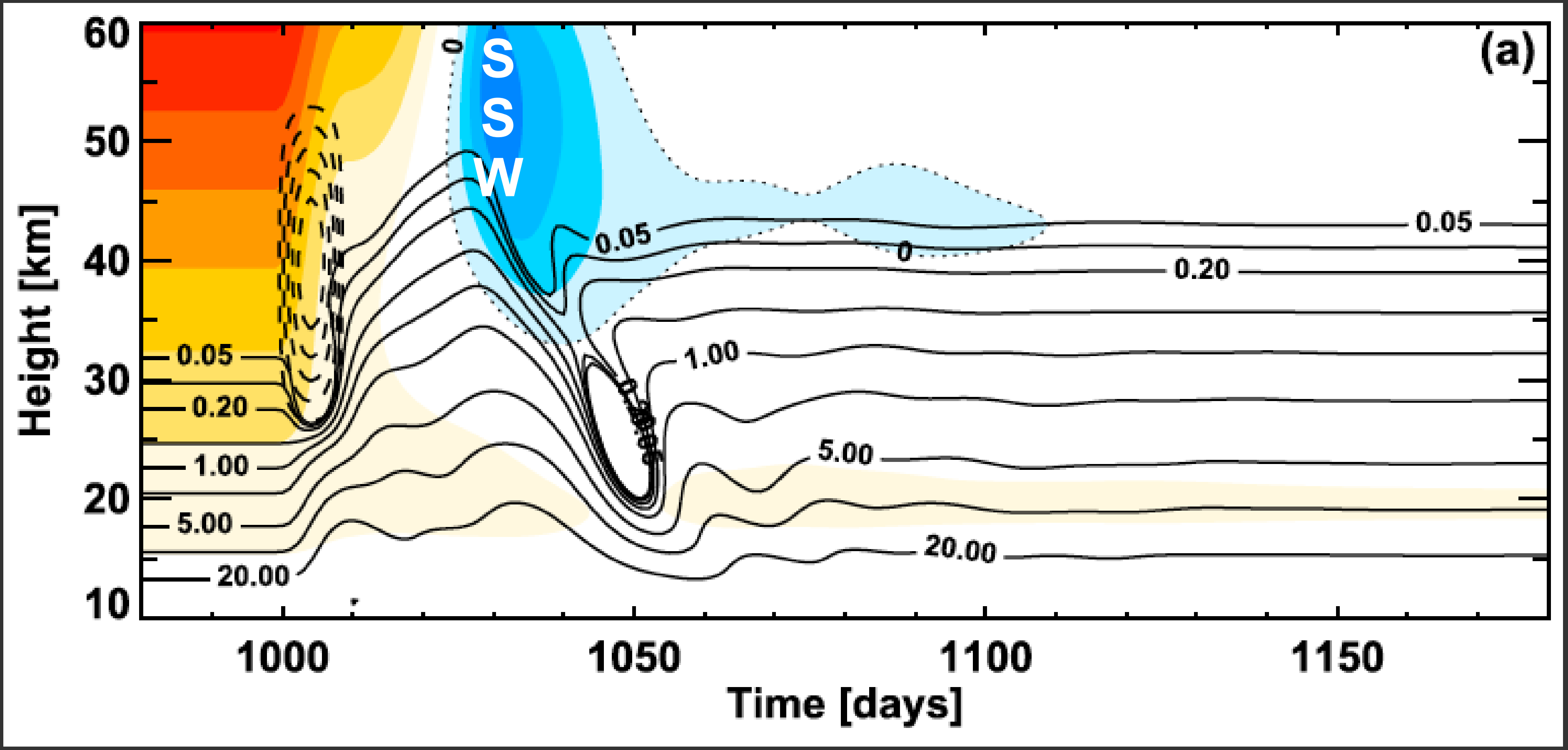
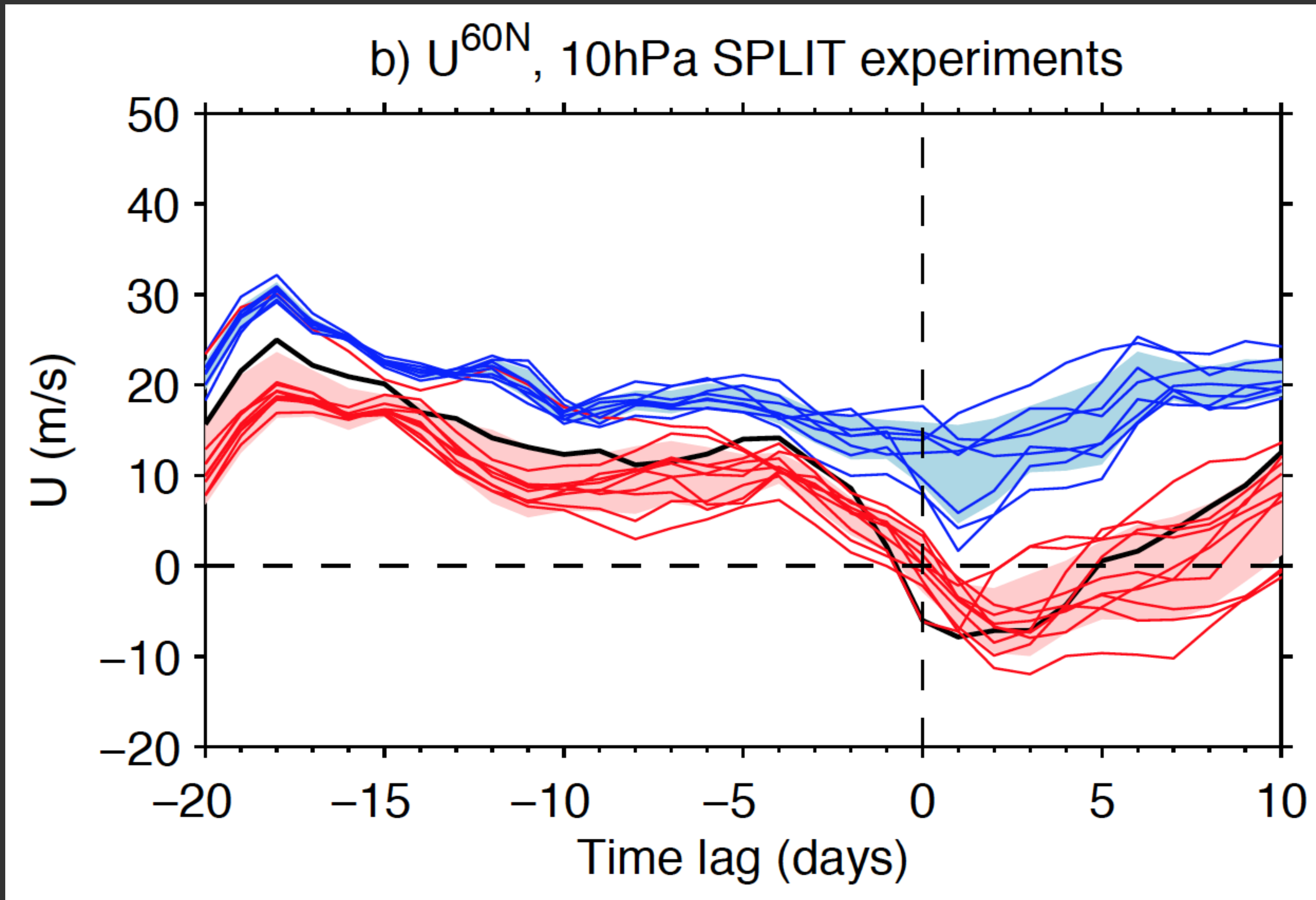


- Constant incoming wave forcing at lower boundary
- Imposed initial stratospheric deceleration → SSW

Sensitivity of Sudden Stratospheric Warmings to stratospheric initial conditions:



de la Cámara et al., 2017

Tropospheric evolution is nudged to control run, i.e., all differences due to stratospheric initial conditions

Sudden Stratospheric Warmings (SSWs) triggered by internal stratospheric dynamics:

- Clark (1974): 'tuning' vortex geometry to support resonance (cf. Albers & Birner, 2014)
- Plumb (1981): self-tuned resonance; also, e.g., Esler & Scott (2005); Matthewman & Esler (2011)
- Scott & Polvani (2004, 2006): SSWs can arise due to internal stratospheric dynamics in idealized GCM simulations

Are sudden stratospheric warmings preceded by anomalous tropospheric wave activity?

Birner & Albers (2017)

de la Cámara, Birner, Albers (2019)

Upward Wave Activity Flux Events

- Based on upward Eliassen-Palm flux of a given (planetary) wave number and at a given level, averaged over 45º–75ºN
- Wave Event = 10-day averaged upward EP-flux exceeds two standard deviations (during November – March, 1979 – 2016, from ERA-interim data)
- Here: lower tropospheric wave events (at ~700 hPa = LTWEs), 21 wave 1 events, 32 wave 2 events

Birner & Albers (2017)

Sudden Stratospheric Deceleration Events

= SSDs

- Based on zonal mean zonal wind (U) at 10 hPa, averaged over 45–75 N
- Deceleration Event = 10-day change in U falls below –20 m/s (during November – March)
- 32 events between 1979 – 2016 (ERA-Interim)
- Most SSWs included
- Similar event definition used by Martineau & Son (2013, 2015)

Birner & Albers (2017)

2018/19 SSW: strongest warming and deceleration (SSD) happened ~7-10 days before wind reversal!

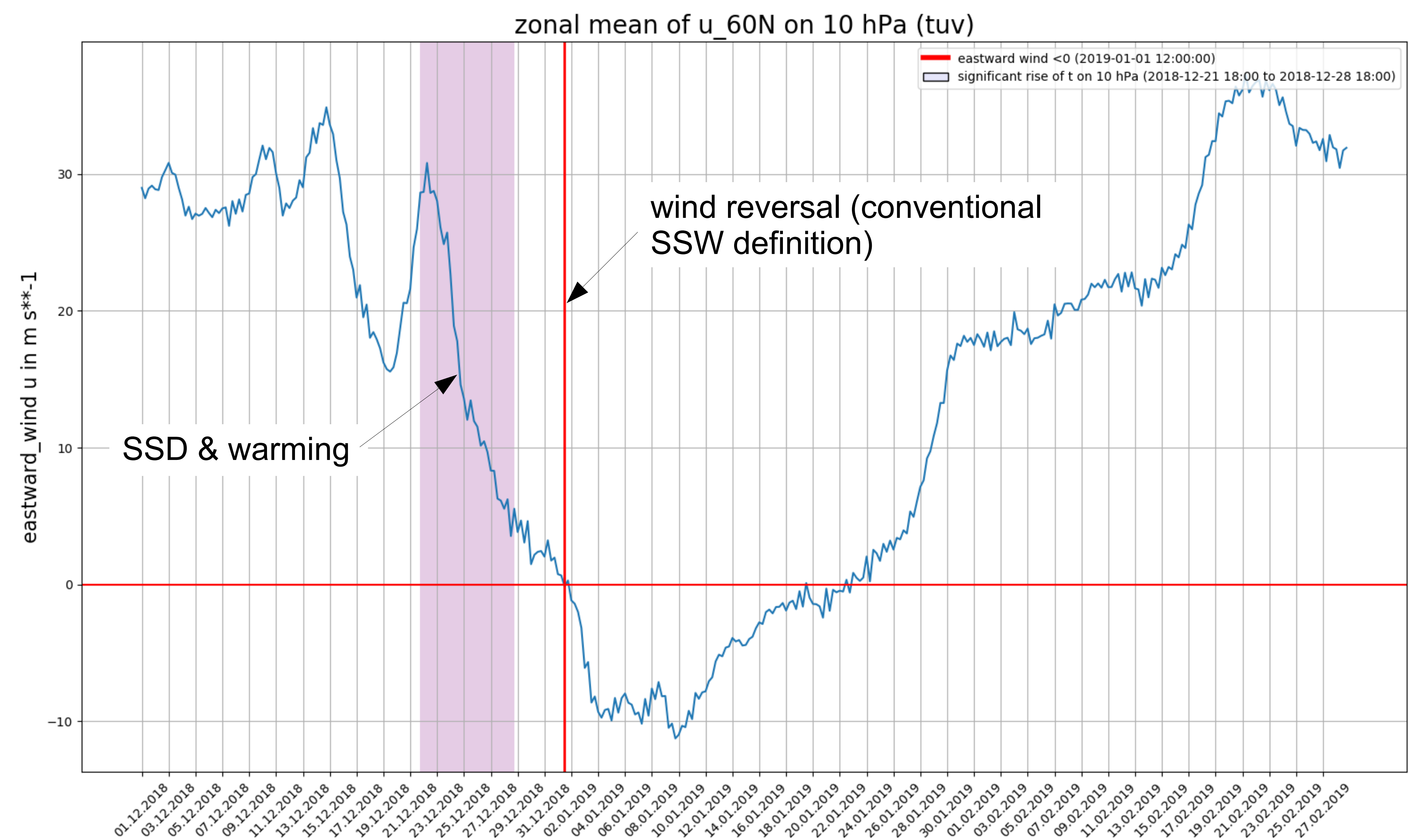
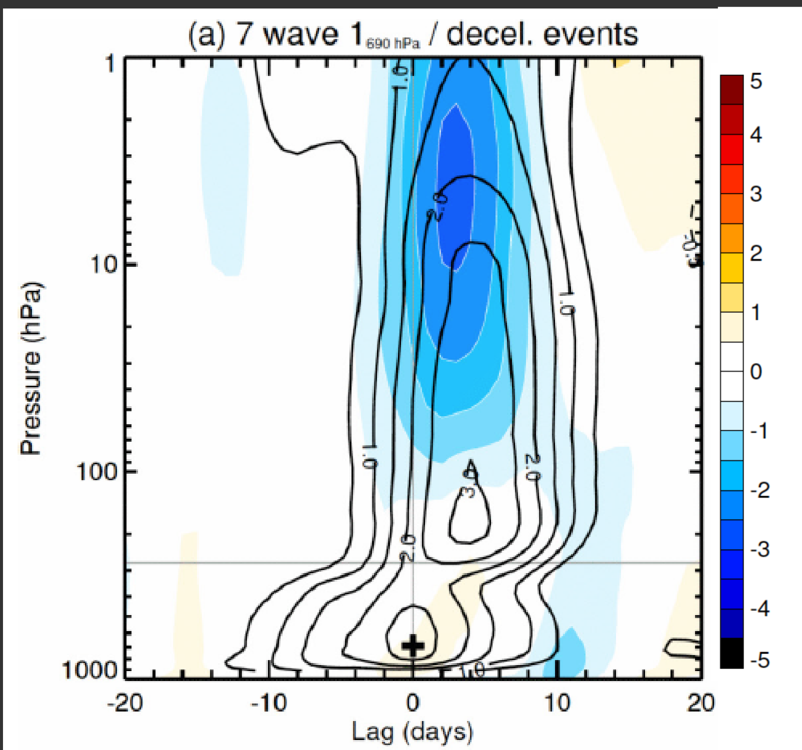


Fig. courtesy Julia Kolb (LMU)

Events in lower tropospheric upward wave activity flux

21 Wave 1 Events

wave 1 & deceleration event



Colors: wind tendency, normalized by std dev

Contours: upward wave activity flux (wave 1), normalized by std dev

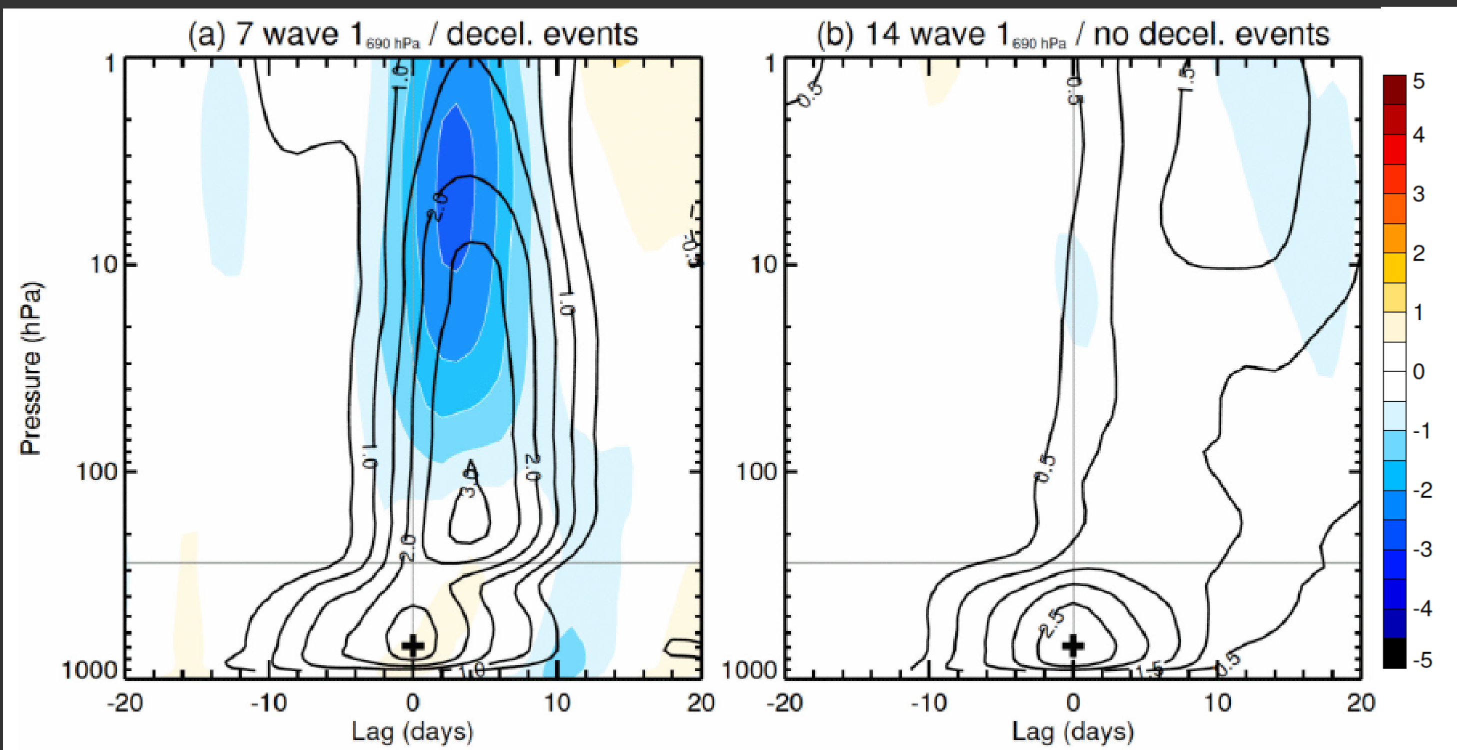
(averages between 45-75 N)

Birner & Albers (2017)

Events in lower tropospheric upward wave activity flux

21 Wave 1 Events

wave 1 & no deceleration event



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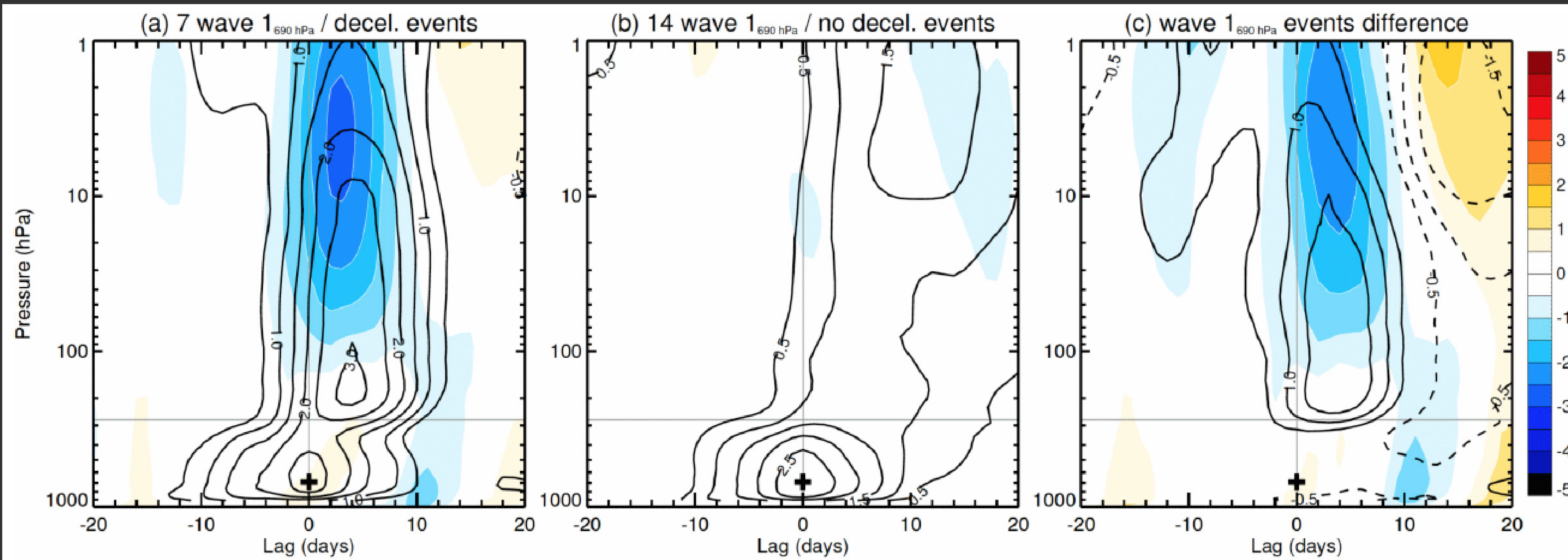
Birner & Albers (2017)

Events in lower tropospheric upward wave activity flux

21 Wave 1 Events

difference



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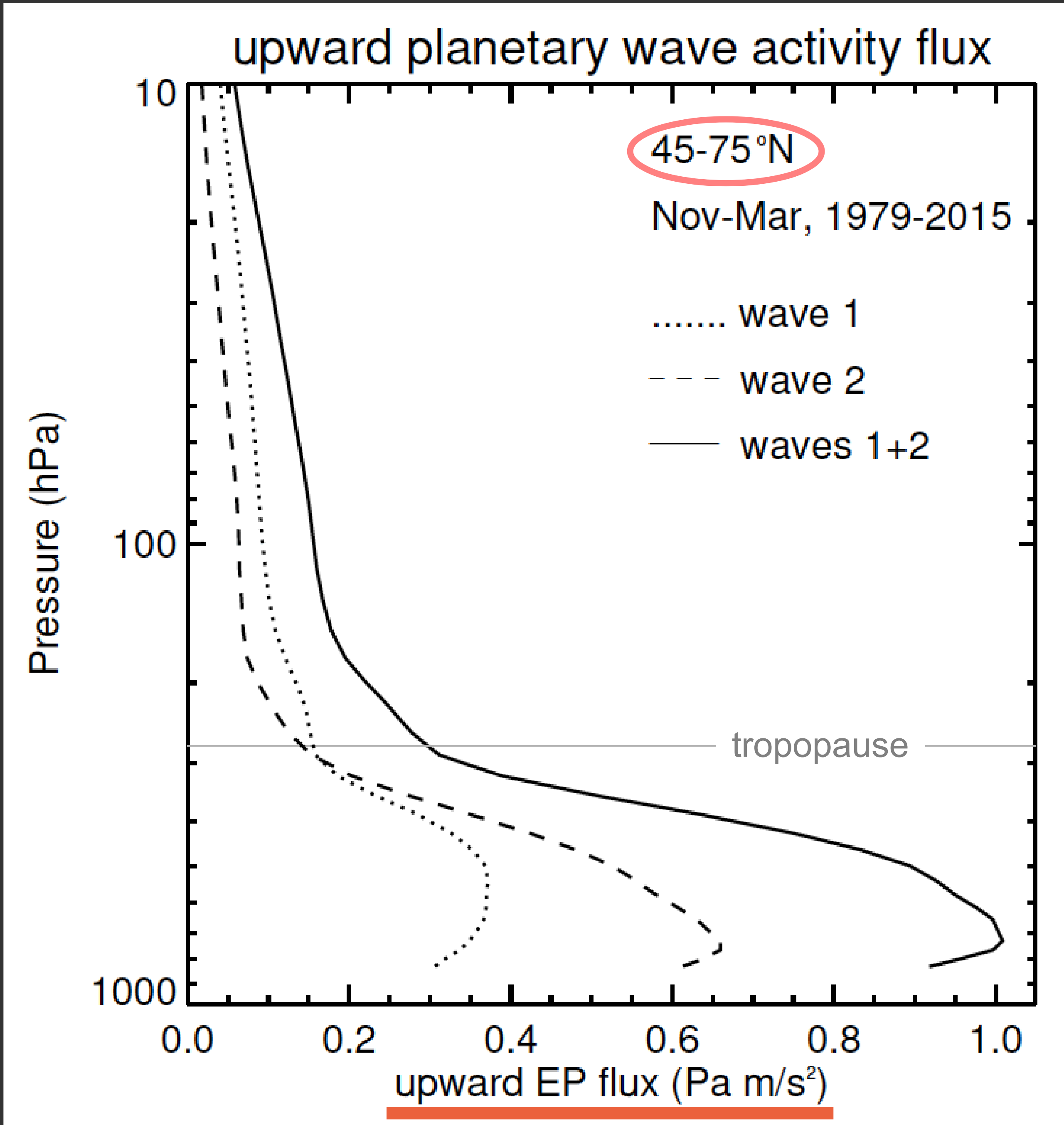
Birner & Albers (2017)



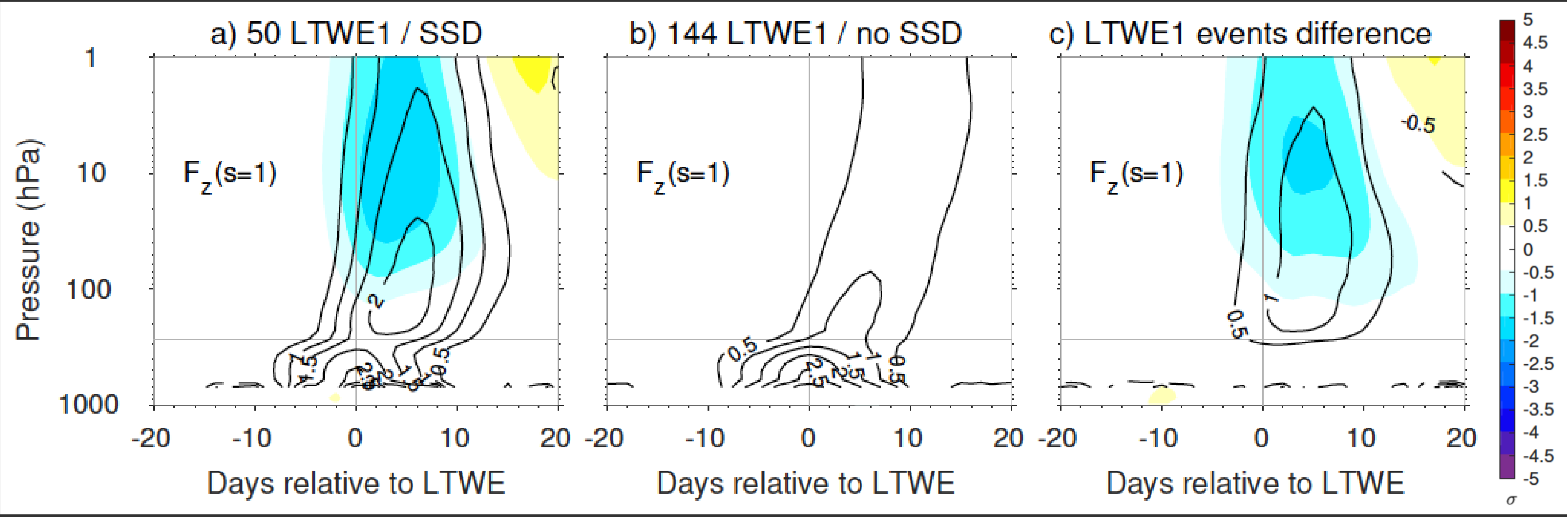
Birner & Albers (2017)

→ ~25% of maximum wave 1 upward wave activity flux past 100 hPa (~10% for wave 2)

→ Improved statistics from climate model simulation (de la Cámara, Birner, Albers, J. Climate, 2019):

- Whole Atmosphere Community Climate Model (WACCM) forced with observed SSTs 1955-2014
- 4 members: total of 240 years of data
- LTWEs versus SSDs, each split into wave 1 & 2
- Very similar results for ERA-20C (“Reanalysis” using only surface observations, 1900-2010)
- Results consistent with White et al. (2019)

194 lower tropospheric wave 1 events from WACCM



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de la Cámara, Birner, Albers (2019)

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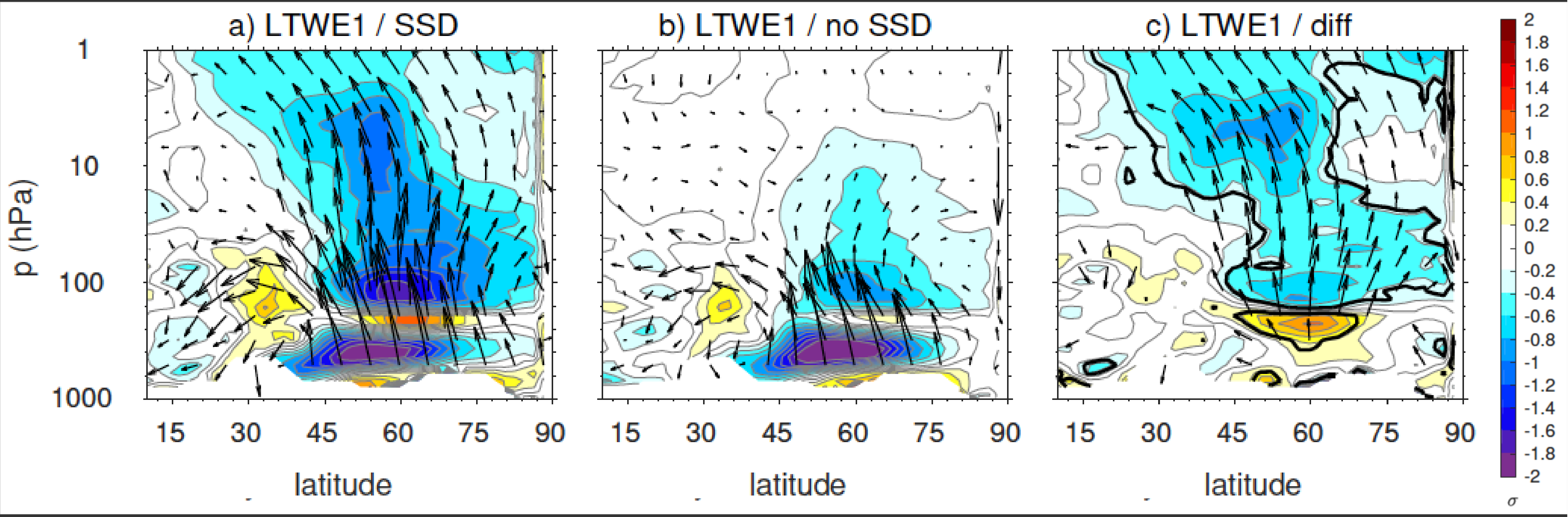


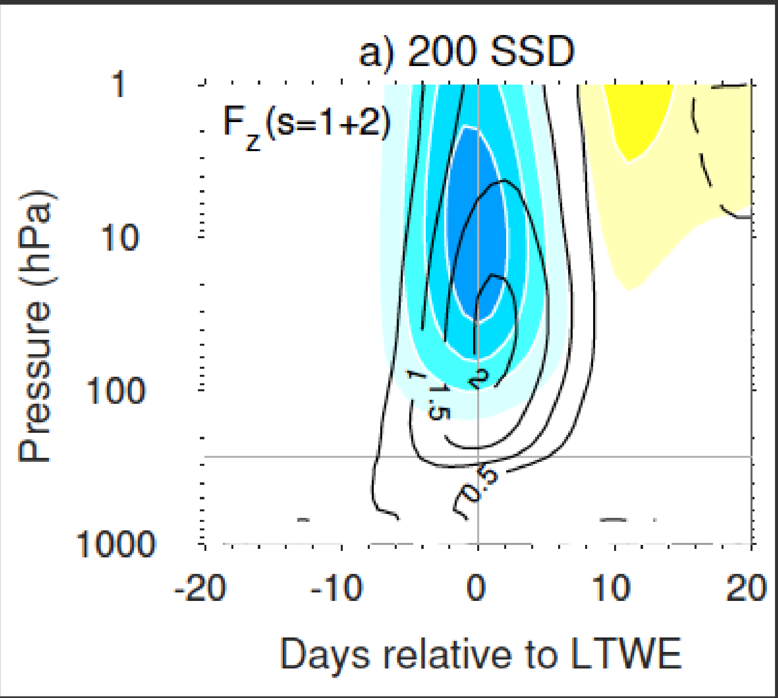
Colors: wind tendency, normalized by std dev

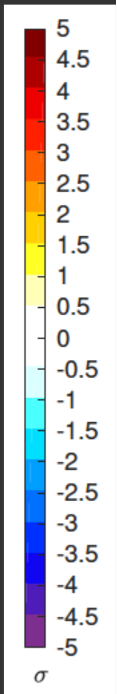
Arrows: normalized wave activity (EP) flux (wave 1)

de la Cámara, Birner, Albers (2019)

Sudden Deceleration Events (SSDs)

200 sudden deceleration (SSD) events from WACCM





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de la Cámara, Birner, Albers (2019)

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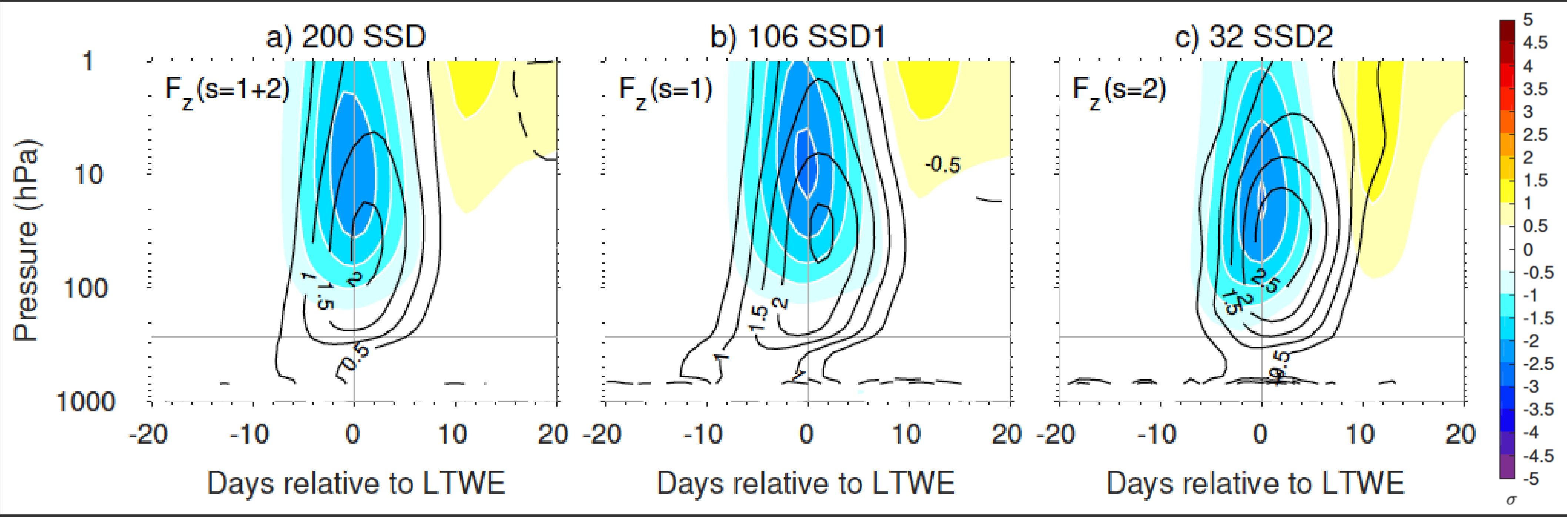

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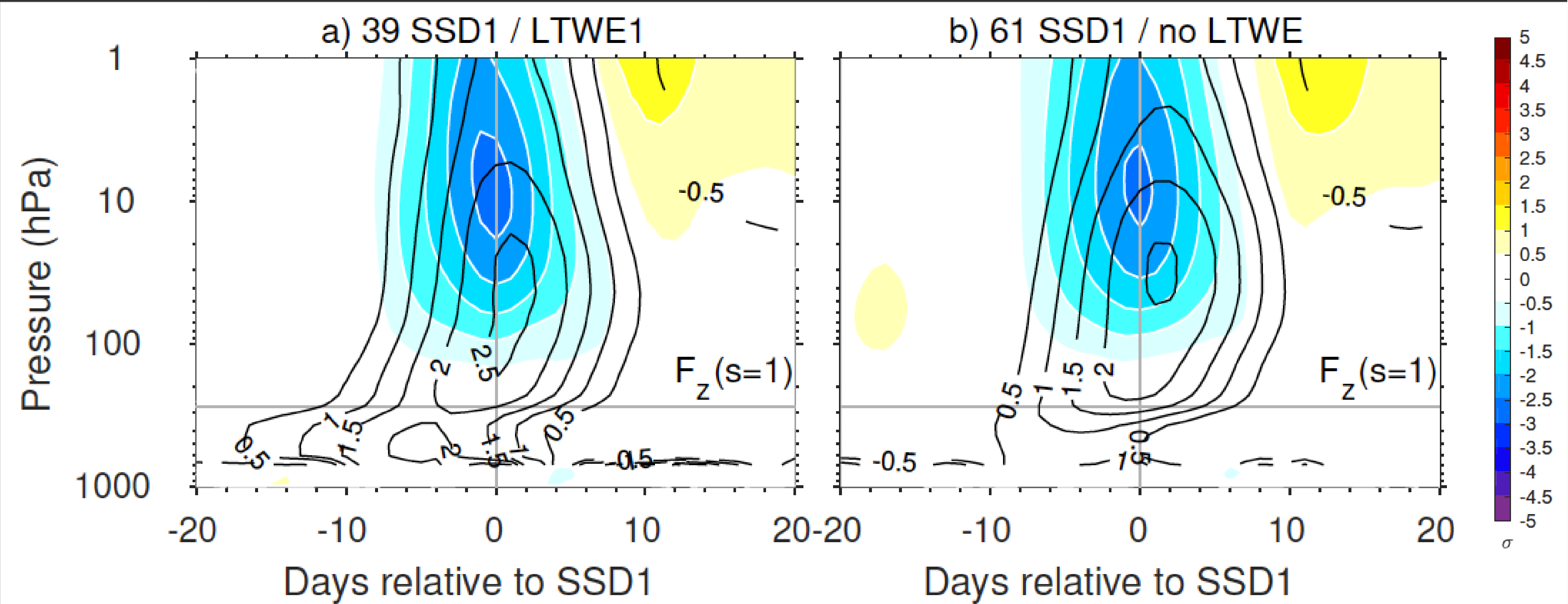
(averages between 45-75 N)

de la Cámara, Birner, Albers (2019)

Wave 1 SSD's (~displacement SSWs): role of preceding lower tropospheric wave 1 event?



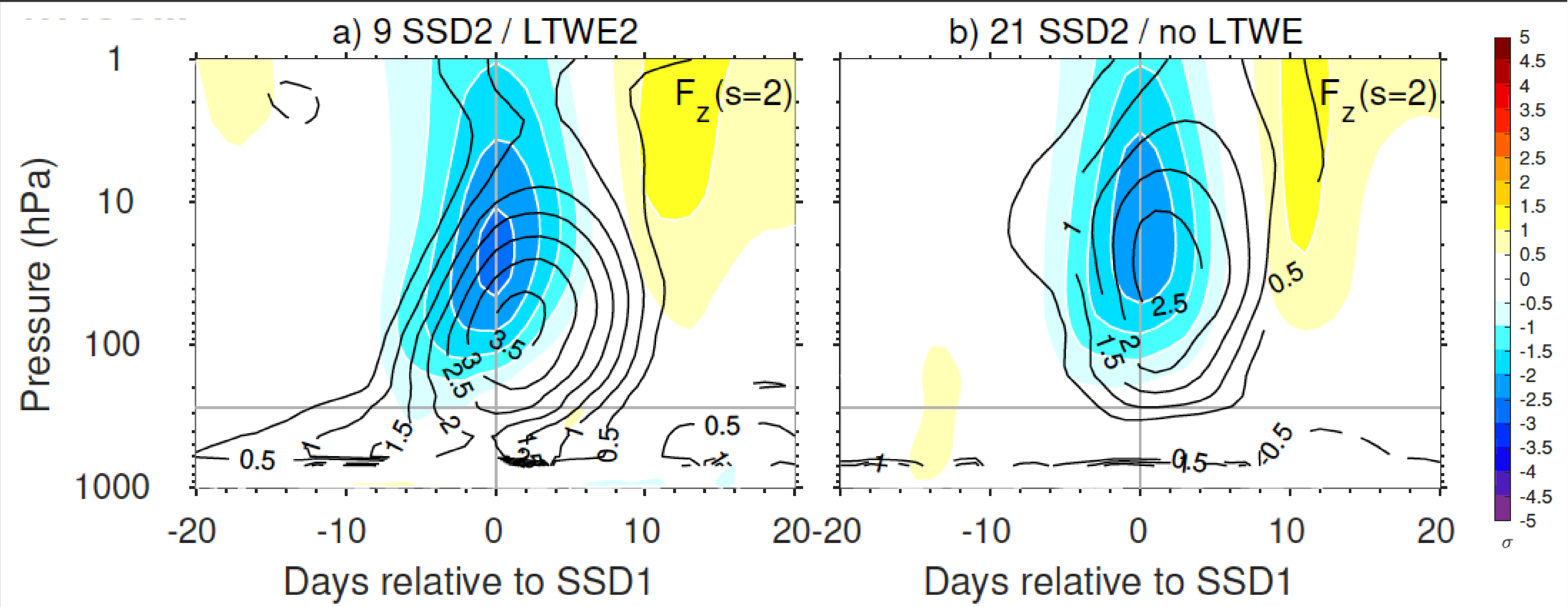
Colors: wind tendency, normalized by std dev

Contours: upward wave activity flux (wave 1), normalized by std dev

(averages between 45-75 N)

de la Cámara, Birner, Albers (2019)

Wave 2 SSD's (~split SSWs): role of preceding lower tropospheric wave 2 event?



Colors: wind tendency, normalized by std dev

Contours: upward wave activity flux (wave 2), normalized by std dev

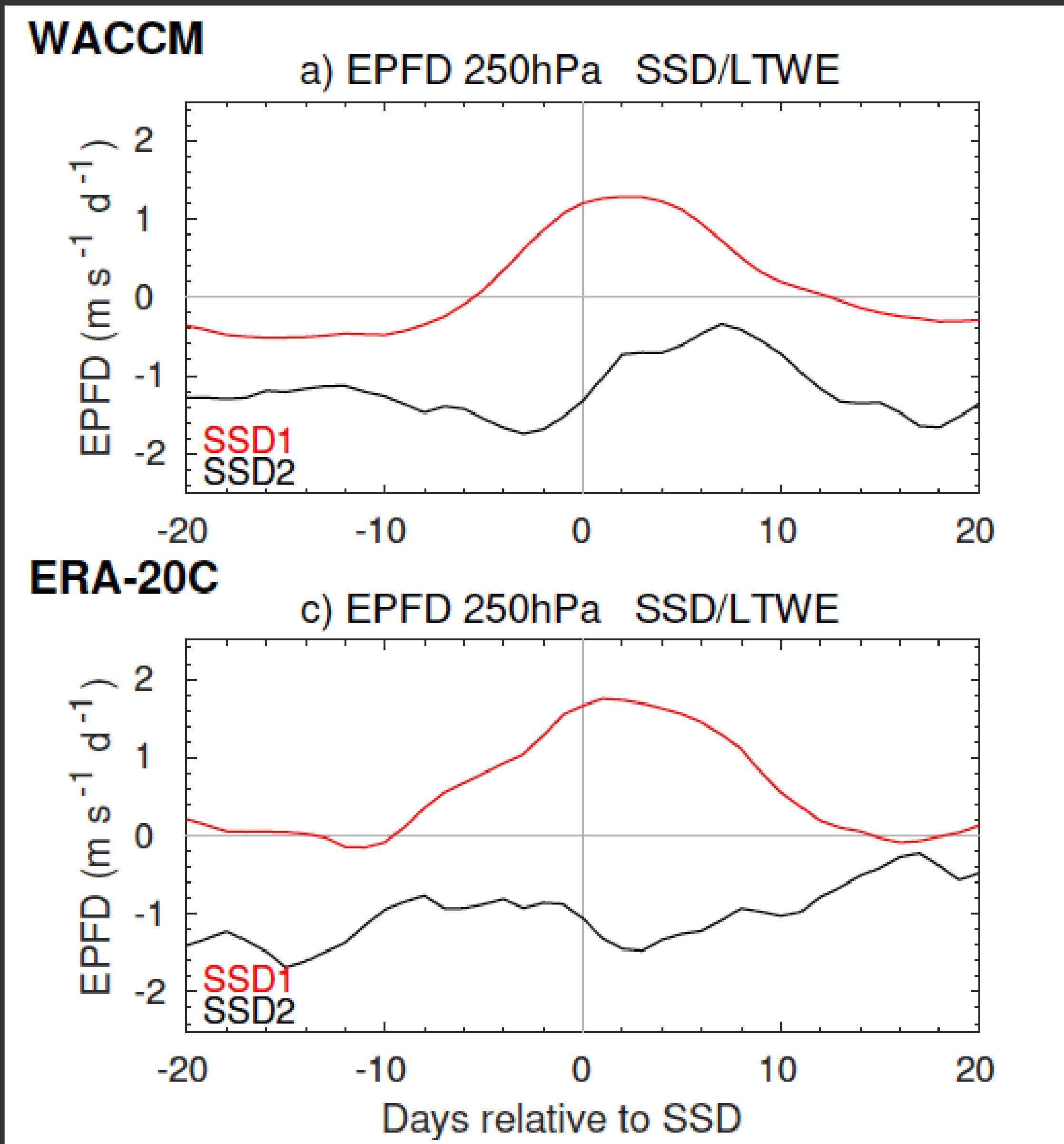
(averages between 45-75 N)

de la Cámara, Birner, Albers (2019)

Tropopause-Level Wave Source

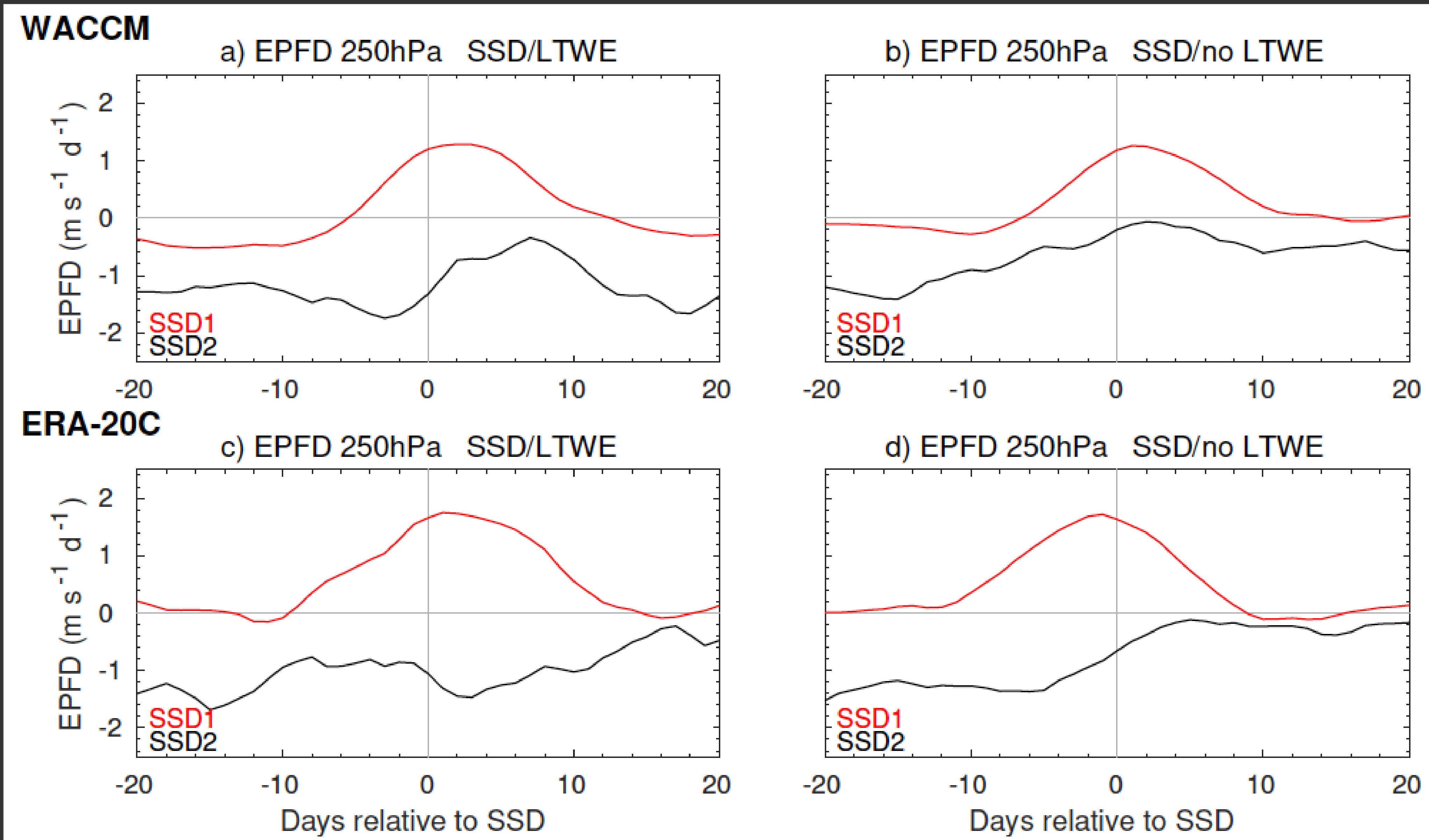
Net wave-induced forcing (anomaly+climatology)

→ source of wave 1 just above tropopause



de la Cámara, Birner, Albers (2019)

Net wave-induced forcing (anomaly+climatology)
→ source of wave 1 just above tropopause



de la Cámara, Birner, Albers (2019)

Conclusions

- most SSWs/SSDs appear to be caused by redistribution and/or generation of wave activity flux in the “tropopause communication layer” (~300-200 hPa)

  → interpreting upward wave activity flux at 100 hPa as “input from the troposphere” is misleading

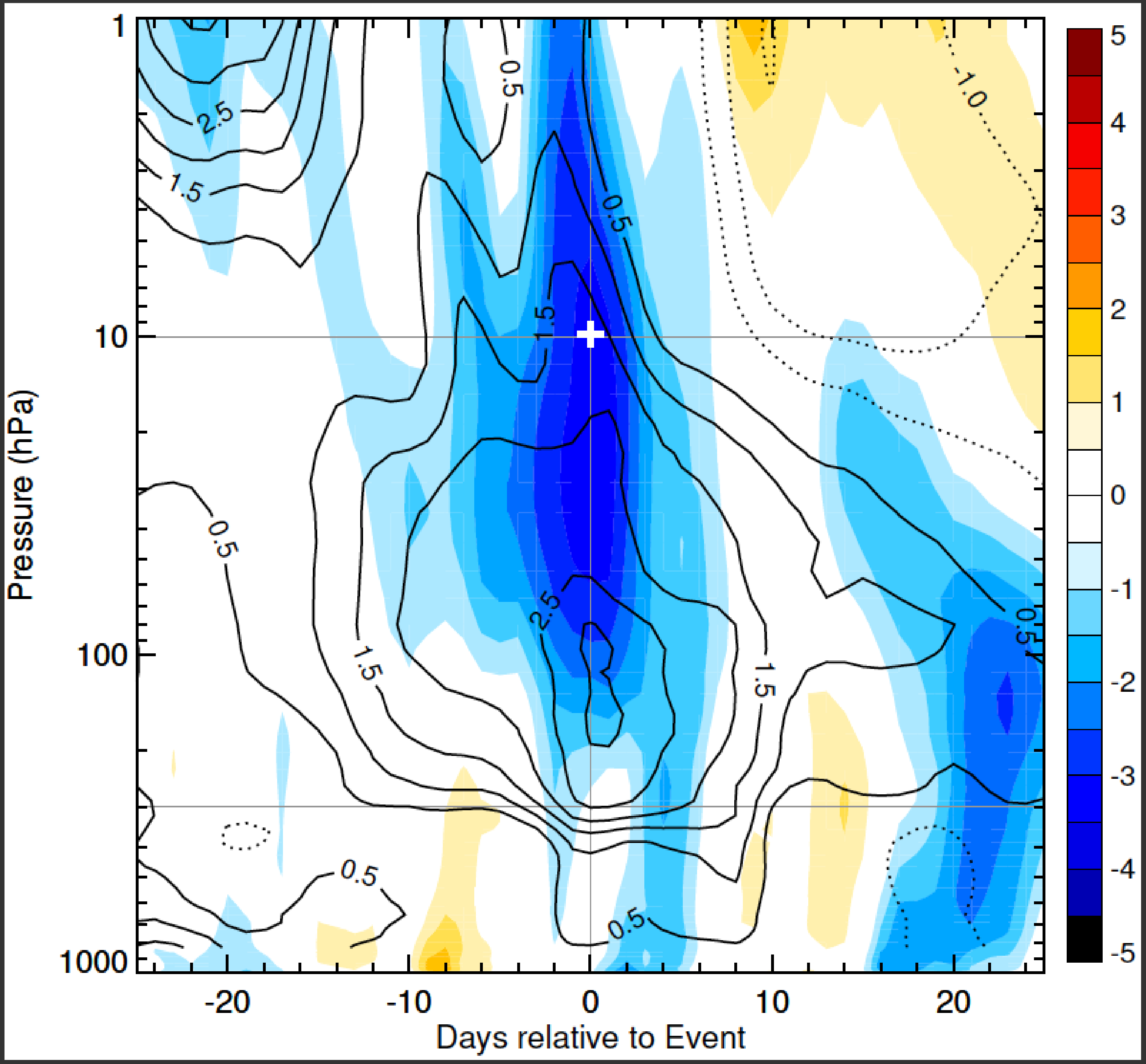
- bursts of wave activity from the troposphere seem less important (may play role for up to 40% of stratospheric events, see also White et al., 2019)

- local source of planetary wave 1 just above tropopause associated with many SSDs ...

  (similar phenomenon exists in idealized dry dynamical core experiments: ongoing work with Postdoc Lina Boljka)

Example: January 1987 deceleration / SSW event

Standardized wind tendency & <u>wave 1</u> upward EP-flux



Example: February 1979 deceleration / SSW event

Standardized wind tendency & wave 2 upward EP-flux