Dynamics of Sudden Stratospheric Warmings

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ECMWF w/s “Stratospheric Predictability & Impact on Troposphere” (Nov 2019), Reading, UK
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).
Stratospheric Vacillations

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

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

Prescribed wave forcing via bottom boundary (~tropopause) condition for \( \Psi'' \) (~geopotential height perturbation)
$U(z=25\text{km},t)$

Holton & Mass (1976)

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

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

Vacillation $\sim$ SSWs $(h > h_{\text{crit}})$

Strongly oscillating eddy heat flux & mean flow

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

$\rightarrow$ response to stratospheric zonal wind perturbation:

- 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:

- Constant incoming wave forcing at lower boundary
- Imposed initial stratospheric deceleration → SSW
Sensitivity of Sudden Stratospheric Warmings to stratospheric initial conditions:

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

*de la Cámara et al., 2017*
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 45°–75°N

• 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)
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

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

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

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

Bimer & Albers (2017)
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

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)
194 lower tropospheric wave 1 events from WACCM

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

Colors: wind tendency, normalized by std dev

Contours: upward wave activity flux, normalized by std dev

(averages between 45-75 N)

de la Cámara, Birner, Albers (2019)
200 sudden deceleration (SSD) events from WACCM

Colors: wind tendency, normalized by std dev

Contours: upward wave activity flux, normalized by std dev

(averages between 45-75 N)

dela 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)

dela Cámara, Birner, Albers (2019)
Tropopause-Level Wave Source
Net wave-induced forcing (anomaly+climatology) → source of wave 1 just above tropopause
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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 & wave 1 upward EP-flux
Example: February 1979 deceleration / SSW event
Standardized wind tendency & wave 2 upward EP-flux