Stratospheric Dynamics and Sudden Stratospheric Warmings

John R. Albers[1,2]

[1]Cooperative Institute for Research in the Environmental Sciences
University of Colorado Boulder
[2]NOAA - Earth System Research Laboratory
Physical Sciences Division

October 16, 2017

The Stratosphere

...the so-what-o-sphere?

...the ignore-o-sphere?

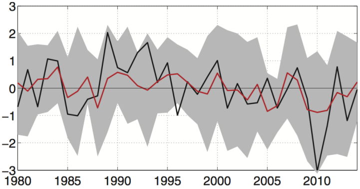
...sponge layer?

Why do we care?

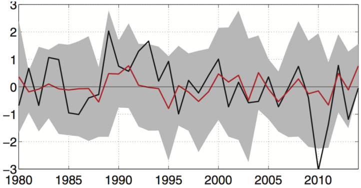
DJF NAO Index Nudging Experiments:

- ERA-Interim
- ECMWF IFS

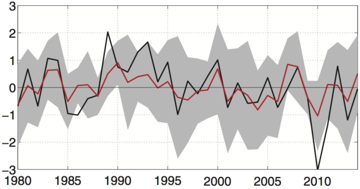
Observed SSTs, nudged tropics: r=0.51 (95% SL)



Observed SSTs, no nudging : r=0.3 (not significant)



Observed SSTs, nudged stratosphere: r=0.72 (95% SL)



(Hansen, Greatbatch, Gollan, Jung, and Weisheimer QJRM 2017)

Talk outline:

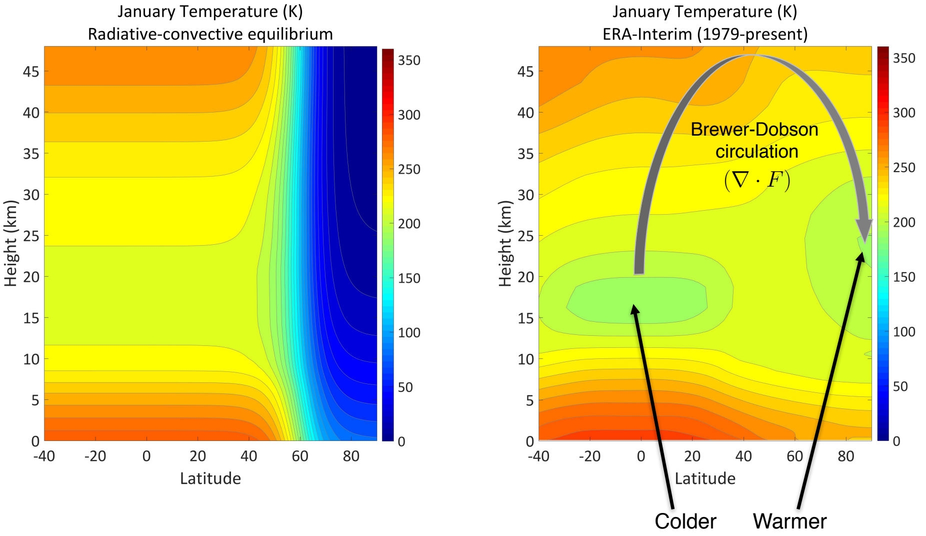
(1) Basic structure and dynamics of the polar vortex

(2) Define types of sudden stratospheric warmings (SSWs)

(3) Review possible SSW triggering mechanisms
- Anomalous tropospheric forcing
- Resonance
- Nonlinear vortex interactions
- Wave interference

(4) Prospects for deterministic forecasting

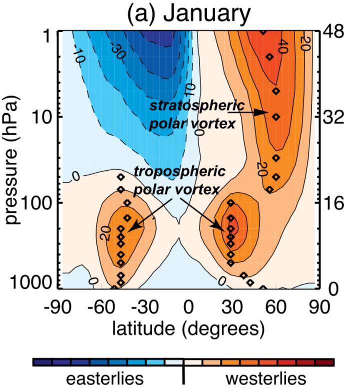
Radiation and the polar vortex

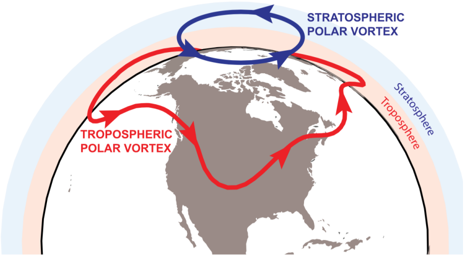


Winter season vortex formation

(Animation courtesy of Thomas Birner, Colorado State University)

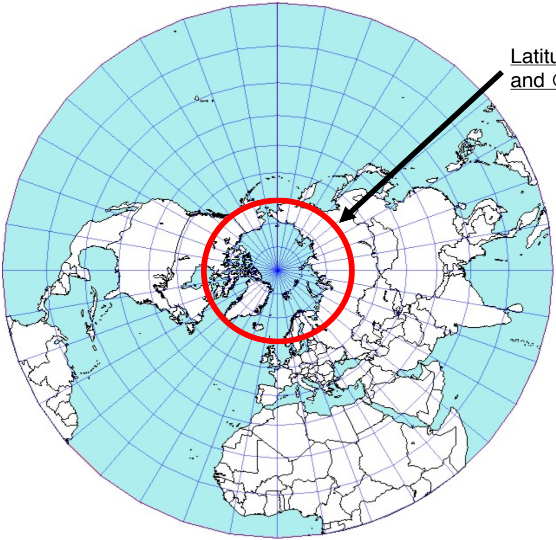
Winter season vortex formation





(Waugh, Sobel, Polvani BAMS 2017)

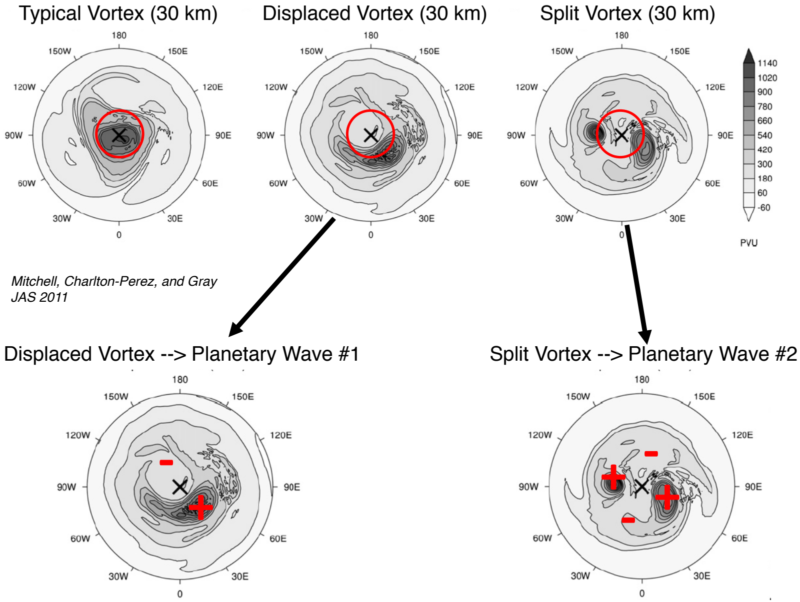
Definition of sudden stratospheric warming (SSW):



Latitude average around 60° North and @ 30 km height:

(1) Pole-to-equator temperature gradient reverses
(2) Zonal wind reverses

Two types of sudden stratospheric warmings:



Displacement SSW (planetary wave #1)

Example: January 1987

(Animation courtesy of Thomas Birner, Colorado State University)

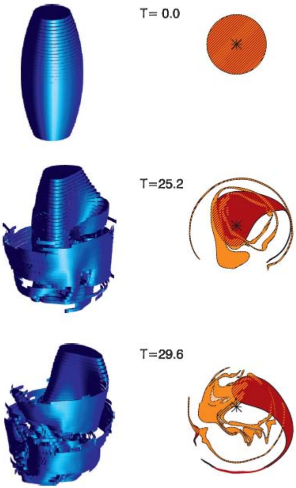
Split SSW (planetary wave #2)

Example: January 2009

(Animation courtesy of Thomas Birner, Colorado State University)

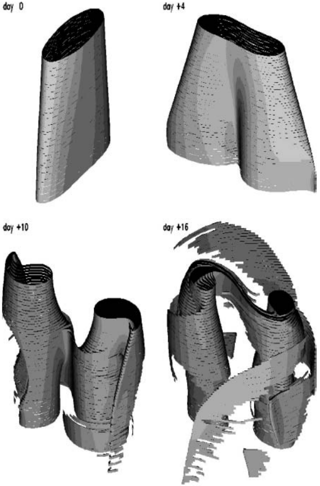
Vertical structure of the two SSW types:

Displacement:



(Esler and Matthewman 2011)

Split:



(Matthewman and Esler 2011)

To summarize:

- Two types of SSWs:
  - (1) Displacement (planetary wavenumber 1)
  - (2) Split (planetary wavenumber 2)

- Distinct vertical structure:
  - (1) Displacement $\rightarrow$ 1^{st} baroclinic (strong vertical tilt)
  - (2) Split $\rightarrow$ barotropic (altitude independent)

From an S2S standpoint, how predictable are SSWs?

- Are there conditions that enhance wave forcing that trigger SSWs? (e.g. tropospheric blocking)
- Are there stratospheric basic states conducive to a SSW? (i.e., theories of vortex preconditioning)

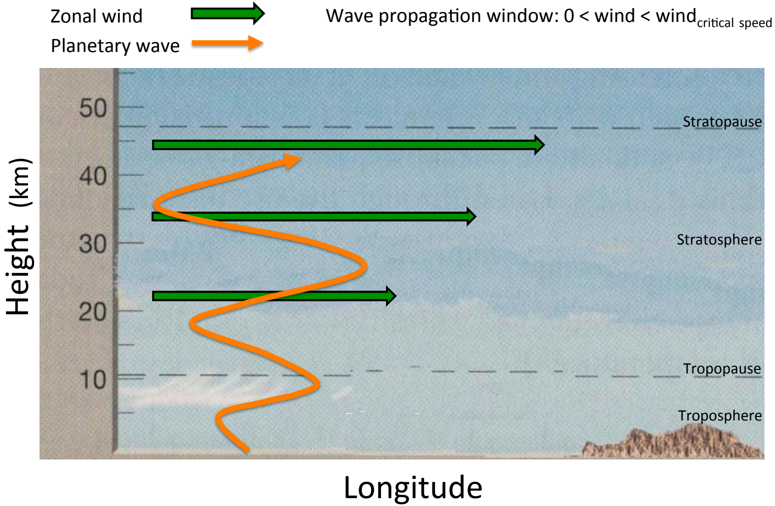
(1) Traditional Theory:

- SSW triggered by anomalously large wave forcing from troposphere
- preconditioning $\longrightarrow$ wave focusing

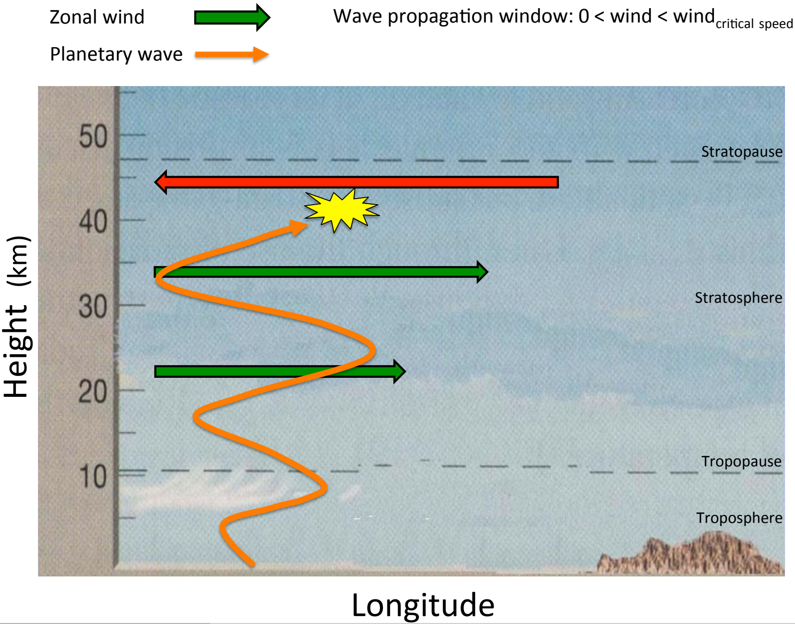
Refs: Matsuno 1971...or just close your eyes and pick a paper (bulk of literature)

Traditional SSW Theory:

<u>Traditional hypothesis:</u> Anomalous wave triggered SSWs *(Matsuno 1971)*



Traditional SSW Theory:

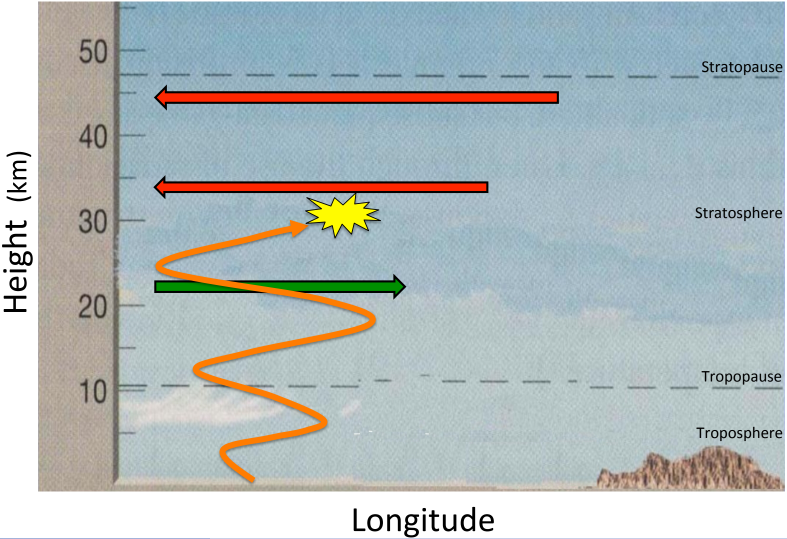


Traditional SSW Theory:

Zonal wind

Planetary wave

Wave propagation window: $0 < \text{wind} < \text{wind}_{\text{critical speed}}$

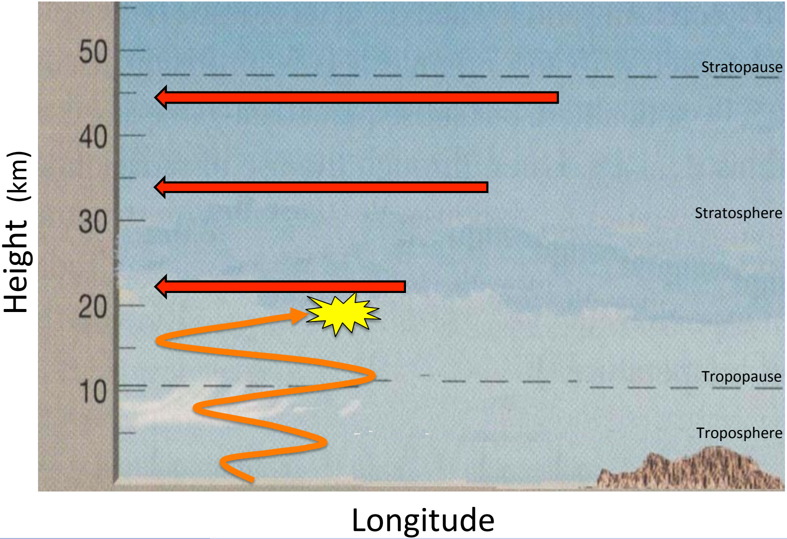


Traditional SSW Theory:

Zonal wind

Planetary wave

Wave propagation window: $0 < \text{wind} < \text{wind}_{\text{critical speed}}$



Traditional SSW Theory:

Linear or nonlinear phenomenon?

- Critical layer wave absorption is nonlinear
  (e.g., Killworth and McIntyre JFM 1985)

BUT,

- Propagation of waves to the critical layer is fundamentally a linear process

How do you trigger the critical layer cascade?

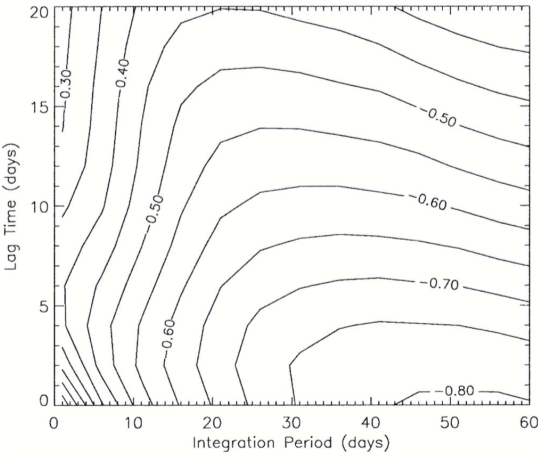
(1) Either generate enough sustained wave activity

or

(2) Focus enough existing wave activity poleward

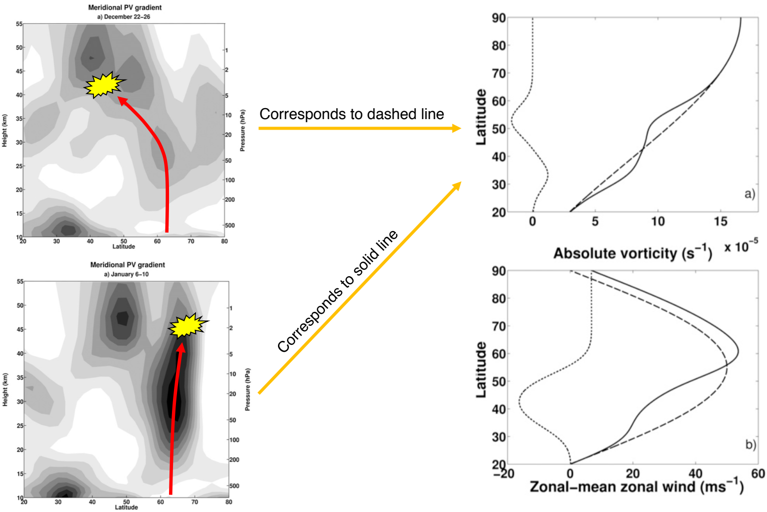
Evidence supporting anomalous tropospheric forcing?:

10 hPa NAM vs. time-averaged 100 hPa northward heat flux:



(Polvani and Waugh JClim 2004)

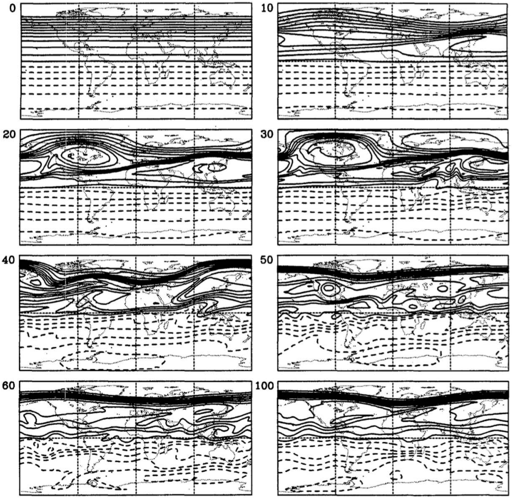
Preconditioning as wave focusing:



(Albers and Birner JAS 2014)

Traditional SSW Theory:

Preconditioning is due to prior PW #1 event:



(Polvani, Waugh, and Plumb 1995 JAS)

Current prevailing notion (based on traditional SSW theory):

Quote from Polvani and Waugh J. Climate 2004

In summary, we have shown that ***anomalous upward wave activity fluxes at 100 hPa (and below) precede extreme stratospheric events*** *and anomalous surface values of the AO up to 60 days later. Because the upward wave flux is associated with planetary-scale waves propagating from the troposphere to the stratosphere, our analysis clarifies the dynamical source of the extreme stratospheric events. In particular, it shows that the stratosphere is not the originating point of ESEs [extremes stratospheric events]. More importantly, however, our analysis shows that anomalous surface weather regimes can be traced back not just to the upper stratosphere, as noted by Baldwin and Dunkerton (2001), but even further back in time to the troposphere itself.* ***The key point that emerges from this study, therefore, is that the stratosphere is not the primary source of anomalous events.***

(2) Resonance (two types):

- Type 1 – Internal mode resonance:
  - does not require anomalous tropospheric forcing
  - preconditioning $\longrightarrow$ cavity formation

Refs: Plumb JAS 1981, Haynes MAP 1985, Smith JAS 1989

- Type 2 – External mode resonance:
  - does not require anomalous tropospheric forcing
  - preconditioning $\longrightarrow$ strong vortex edge PV gradient

Refs: Matthewman and Esler JAS 2011, Liu and Scott QJRM 2015

SSWs Theories (Part II)

(2) Resonance (two types):

- Type 1 – Internal mode resonance:
  - does not require anomalous tropospheric forcing
  - preconditioning $\longrightarrow$ cavity formation

Refs: Plumb JAS 1981, Haynes MAP 1985, Smith JAS 1989

- Type 2 – External mode resonance:
  - does not require anomalous tropospheric forcing
  - preconditioning $\longrightarrow$ strong vortex edge PV gradient

Refs: Matthewman and Esler JAS 2011, Liu and Scott QJRM 2015

(3) Nonlinear vortex interaction:

- does not require anomalous tropospheric forcing
- preconditioning is ill-posed

Refs: Fairlie and O'Neill QJRM 1988, O'Neill and Pope QJRM 1988, O'Neill, Oatley, Charlton-Perez, Mitchell, and Jung QRJM 2016

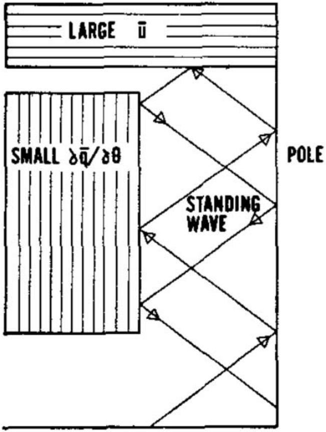
Resonance SSW Theories:

What do you need to trigger a SSW via resonance?

- You need some amount of wave forcing from the troposphere, but it does NOT need to be anomalous (i.e., climatological wave forcing may be enough).
- How does the notion of preconditioning differ for resonance scenarios?

SSW Resonance Theory I:

Preconditioning as wave cavity building:

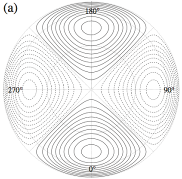


(Matsuno JAS 1970)

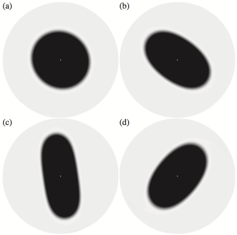
Preconditioning as PV gradient 'edge tuning':

- Vortex edge PV gradient and wind speed modulate traveling wave phase speed

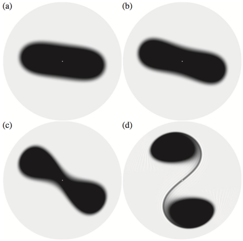
Fixed topographic forcing generates stationary Rossby wave



Traveling Rossby wave (free barotropic normal mode)



SSW triggered when phase speed of traveling wave becomes (quasi-) stationary

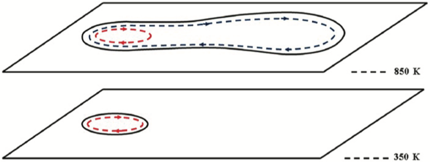


(Liu and Scott QJRM 2015)

SSW Vortex Interaction Theory:

Traditional notion of preconditioning is ‘ill-posed’

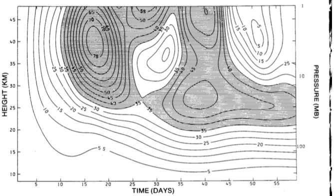
Schematic depiction of elongated PW #1 disturbance (blue dashed line) interacting with subplanetary scale (PW #4-5) cyclonic disturbance (red dashed line) [SH vorticity convention]



(O’Neill, Oately, Charlton-Perez, Mitchell, and Jung QJRM 2017)

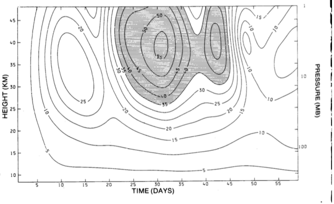
Planetary wave #1 amplitude

(a)



Planetary wave #2 amplitude

(b)



(O’Neill and Pope QJRM 1988)

To summarize:

Traditional SSW theory:

- Anomalous tropospheric forcing triggers SSW
- Forcing aided by poleward focusing of wave activity

Resonance Theories:

- No anomalous forcing required
- Preconditioning is either (1) wave cavity, or (2) sharpened PV gradient and strong vortex

Nonlinear vortex interaction:

- No anomalous forcing required
- Requires correct alignment of elongated PW and subplanetary scale cyclone

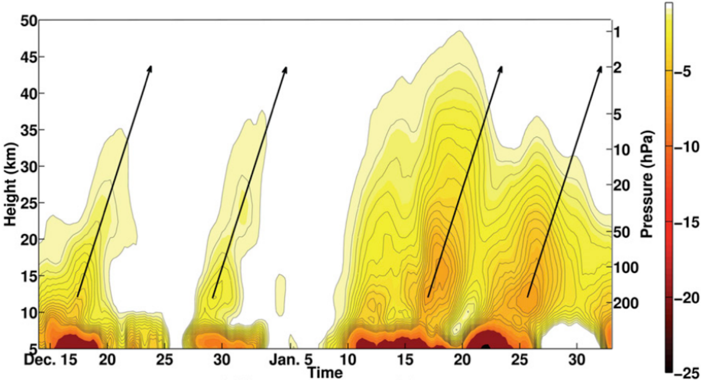
Traditional linear or nonlinear cause?

If SSW are triggered via anomalous forcing, then we should be able to trace large pulses of wave activity from the troposphere to wave absorption region in stratosphere at standard group velocity timescales

Wave phase:
January 2009 split SSW

Planetary wave #2 flux (colors)

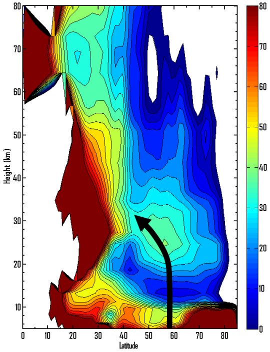
Theoretical group velocity (arrows)



(Albers and Birner JAS 2014)

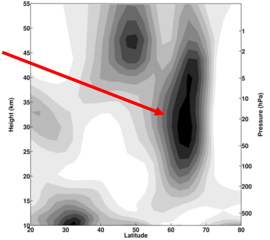
Cavity and PV gradient:
January 2009 split SSW

Refractive index DJF climatology



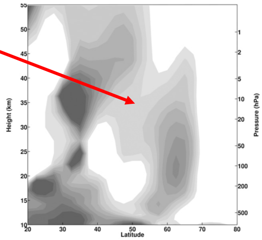
Meridional PV gradient 2009 SSW

Extremely sharp PV gradient



Refractive index 2009 SSW

High latitude wave cavity



(Albers and Birner JAS 2014)

Define anomalous wave and wind events as:

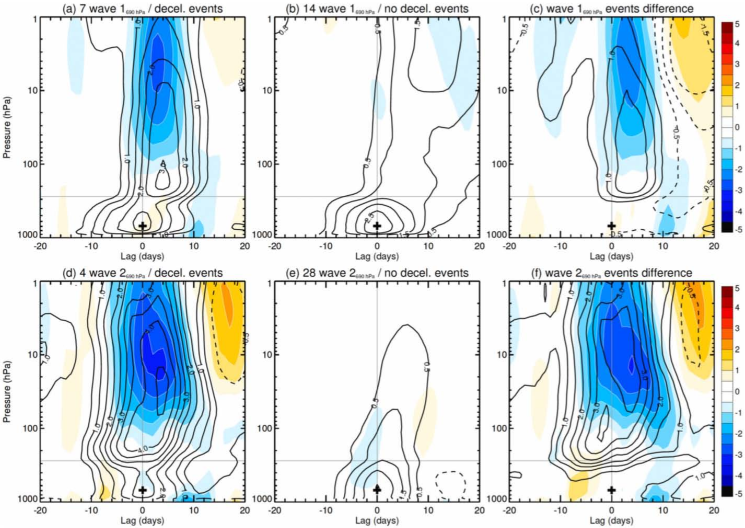
(Birner and Albers SOLA 2017)

- Anomalous wave event:
  - → Deseasonalized 10-day average vertical EP-flux (45°-75° N @ 700 hPa) exceeds 2 STDs
- Anomalous wind event:
  - → Deseasonalized 10-day average wind deceleration (45°-75° N @ 10 hPa) exceeds ∼2 STDs

Anomalous wave events

ERA-Interim Dec.-Feb. 1979-2016

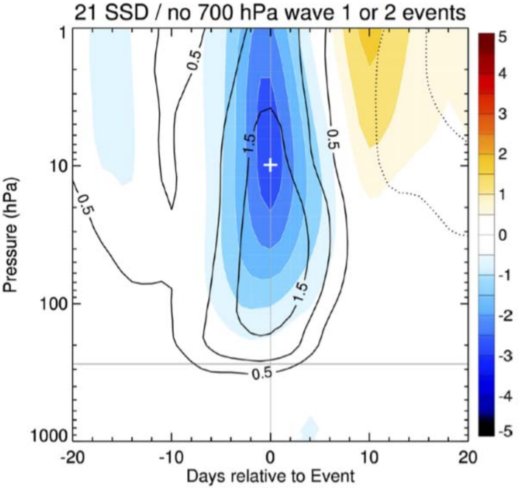
- Black contours: 10-day avgerage 10 hPa upward EP-flux
- Color contours: 10-day average 10 hPa zonal wind tendency



(Birner and Albers SOLA 2017)

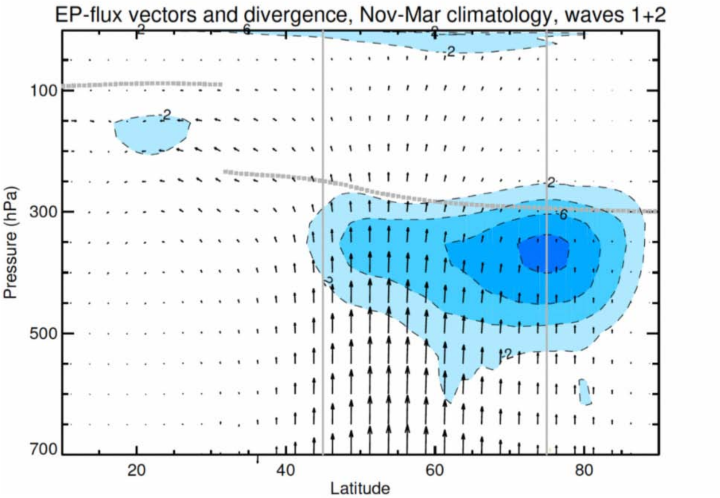
Anomalous wind events
ERA-Interim Dec.-Feb. 1979-2016

- Black contours: 10-day avgerage 10 hPa upward EP-flux
- Color contours: 10-day average 10 hPa zonal wind tendency



(Birner and Albers SOLA 2017)

Available wave forcing
Dec.-Feb. 1979-2016



- Huge pool of available wave energy below tropopause (> 85% of climatology remains below tropopause)

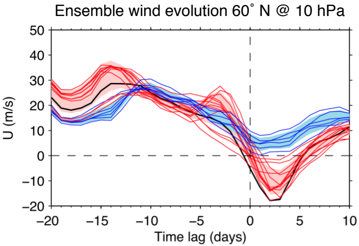
Connection between stratospheric and tropospheric events

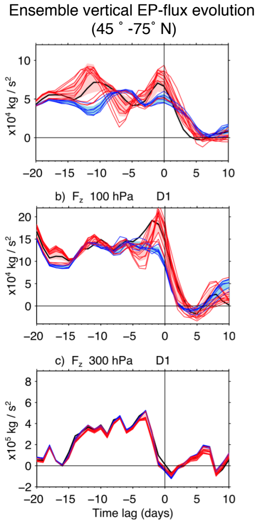
- Only 11 of 53 wave events at 700 hPa are associated with a wind event at 10 hPa
- Only 11 of 32 10 hPa wind events at 10 hPa are preceded by a 700 hPa wave event
- Only 7 of 28 SSWs are associated with a 700 hPa wave events
- More than 85% of wave 1+2 gets dissipated below the tropopause

WACCM Perturbation Experiments

<u>WACCM ensemble of SSW experiments:</u>

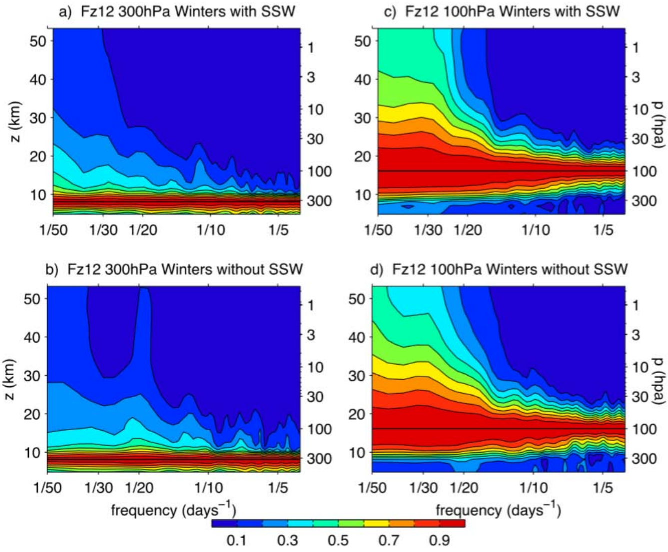
- wind and temperature nudged below 10 km (~250 hPa)
- Balanced wind/temperature perturbation ~21 days prior to SSW central date
- Experiments that result in SSW (red lines); those that don't (blue lines)





(De la Cámara, Albers, Birner, Garcia, Hitchcock, Kinnison, Smith JAS 2017)

WACCM Perturbation Experiments



(De la Cámara, Albers, Birner, Garcia, Hitchcock, Kinnison, Smith JAS 2017)

To summarize

- SSWs are not *typically* associated with anomalous *tropospheric* wave fluxes (plenty of available tropospheric wave energy)
- Stratospheric basic state matters
- SSWs have vertical wave flux signature of internal nonlinear dynamics (resonance or vortex interactions?)
- Correlating 100 hPa heat flux to 10 hPa wind is equivalent to correlating event to itself
- 300-100 hPa region appears to be critical for nonlinear dynamic evolution
- Current deterministic predictability limit is somewhere in the 7-10 day range

References

Albers, J. R. and T. Birner, 2014: Vortex preconditioning due to planetary and gravity waves prior to sudden stratospheric warmings. *J. Atmos. Sci.*, **71 (11)**, 4028–4054.

Birner, T. and J. R. Albers, 2017: Sudden stratospheric warmings and anomalous upward wave activity flux. *SOLA*, **13 (Special_Edition)**, 8–12.

Cámara, A. d. l., J. R. Albers, T. Birner, R. R. Garcia, P. Hitchcock, D. E. Kinnison, and A. K. Smith, 2017: Sensitivity of sudden stratospheric warmings to previous stratospheric conditions. *J. Atmos. Sci.*, **74 (9)**, 2857–2877.

Fairlie, T. and A. O'neill, 1988: The stratospheric major warming of winter 1984/85: Observations and dynamical inferences. *Quart. J. R. Met. Soc.*, **114 (481)**, 557–577.

Hansen, F., R. J. Greatbatch, G. Gollan, T. Jung, and A. Weisheimer, 2017: Remote control of north atlantic oscillation predictability via the stratosphere. *Quart. J. R. Met. Soc.*, **143 (703)**, 706–719.

Haynes, P. H., 1985: A new model of resonance in the winter stratosphere. *Handbook for MAP, Vol. 18: Extended abstracts of papers presented at the 1984 MAP Symposium, Kyoto, ed. S. Kato; Urbana, Ill., USA, SCOSTEP Secretariat, University of Illinois. Council of Scientific Unions Handbook for MAP.*, **18**, 126–131.

Killworth, P. D. and M. E. McIntyre, 1985: Do rossby-wave critical layers absorb, reflect, or over-reflect? *J. Fluid Mech.*, **161**, 449–492.

Liu, Y. and R. Scott, 2015: The onset of the barotropic sudden warming in a global model. *Quart. J. R. Met. Soc.*, **141 (693)**, 2944–2955.

Matsuno, T., 1970: Vertical propagation of stationary planetary waves in the winter northern hemisphere. *J. Atmos. Sci.*, **27 (6)**, 871–883.

Matsuno, T., 1971: A dynamical model of the stratospheric sudden warming. *J. Atmos. Sci.*, **28**, 1479–1494.

Matthewman, N. J. and J. Esler, 2011: Stratospheric sudden warmings as self-tuning resonances. Part I: Vortex splitting events. *J. Atmos. Sci.*, **68 (11)**, 2481–2504.

Mitchell, D. M., A. J. Charlton-Perez, and L. J. Gray, 2011: Characterizing the variability and extremes of the stratospheric polar vortices using 2d moment analysis. *J. Atmos. Sci.*, **68 (6)**, 1194–1213.

O'Neill, A., C. Oatley, A. J. Charlton-Perez, D. Mitchell, and T. Jung, 2017: Vortex splitting on a planetary scale in the stratosphere by cyclogenesis on a sub planetary scale in the troposphere [2]. *Quart. J. R. Met. Soc.*

O'Neill, A. and V. Pope, 1988: Simulations of linear and nonlinear disturbances in the stratosphere. *Quart. J. R. Met. Soc.*, **114 (482)**, 1063–1110.

Plumb, R. A., 1981: Instability of the distorted polar night vortex: A theory of stratospheric warmings. *J. Atmos. Sci.*, **38 (11)**, 2514–2531.

Polvani, L. M. and D. W. Waugh, 2004: Upward wave activity flux as a precursor to extreme stratospheric events and subsequent anomalous surface weather regimes. *J. Climate*, **17 (18)**, 3548–3554.

Polvani, L. M., D. W. Waugh, and R. A. Plumb, 1995: On the subtropical edge of the stratospheric surf zone. *J. Atmos. Sci.*, **52 (9)**, 1288–1309.

Smith, A. K., 1989: An investigation of resonant waves in a numerical model of an observed sudden stratospheric warming. *J. Atmos. Sci.*, **46 (19)**, 3038–3054.

Waugh, D. W., A. H. Sobel, and L. M. Polvani, 2017: What is the polar vortex and how does it influence weather? *Bull. Amer. Met. Soc.*, **98 (1)**, 37–44.