Middle atmosphere dynamics: The Stratopause, Polar Vortices, and Anticyclones

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- Viewing the atmosphere in 1D, 2D, 3D and 4D
- Basics
- Zonal mean temperature and wind structure
- The Stratopause
- Planetary Waves
- The Polar Vortices, Anticyclones, and SSWs

Ask questions!

CREATE summer school, Alliston, Ontario, July 2012
Basics

- Ideal Gas Law \( P = \rho R_d T \)
- Geostrophic Balance (Coriolis=PGF)
- Hydrostatic Balance (Gravity=PGF)
- Turbulence, Transience, Nonlinearity
  (Usually ignored)
Global Mean Temperature Profile
July Zonal Mean Atmosphere

Latitude-pressure plot of zonal-mean temperature (colors) and zonal wind (contours) in June. Solid circles represent the stratopause. [http://www-aos.eps.s.u-tokyo.ac.jp/~kanto/tomikawa-JGR08/index-e.html](http://www-aos.eps.s.u-tokyo.ac.jp/~kanto/tomikawa-JGR08/index-e.html)

Not this simple. SSWs in 1970s to 2009
ABSTRACT

The midwinter temperature changes of the mesosphere and stratosphere are described by means of Satellite Infrared Spectrometer and Selective Chopper Radiometer data, rocketsondes, and rocket grenade data, which show that the so-called stratospheric midwinter warmings extend at least into the upper mesosphere. Temperature changes of opposite sign take place at the same time at different levels, probably as a result of vertical motion. The event begins around a very high stratopause, \( \sim 60 \) km, which descends 20 km within several days while the warming intensifies. At the same time the upper mesosphere and lower...

Siberia to Sahara and hurricane force winds

Amazing results based on very sparse data!
40 years later…

1970-1971
Rocketsondes 57 N

January 2009
SABER 75 N

Labitzke [1972]
5 vs. ~5000 profiles

Up to 100 km in MLS

Courtesy of D. Siskind
The Arctic Winter Stratopause

Nominal Year

Elevated Stratopause

White contours are CO


Not this simple. Caution with zonal or polar cap averages.
A climatology of stratopause temperature and height in the polar vortex and anticyclones

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[1] A global climatology of stratopause temperature and height is shown using 7 years of Microwave Limb Sounder satellite data, from 2004 to 2011. Stratopause temperature and height is interpreted in the context of the polar vortices and anticyclones defined by the Goddard Earth Observing System meteorological analyses. Multyear, monthly mean geographic patterns in stratopause temperature and height are shown to depend on the location of the polar vortices and anticyclones. The anomalous winters of 2005/2006 and 2008/2009 are considered separately in this analysis. In the anomalous years, we show that the elevated stratopause in February is confined to the vortex core. This is the first study to show that the stratopause is, on average, 20 K colder and 5–10 km lower in the Aleutian anticyclone than in ambient air during the Arctic winter. During September in the Antarctic the stratopause is, on average, 10 K colder inside anticyclones south of Australia. The regional temperature and height anomalies, which are due to vertical ageostrophic motion associated with baroclinic instability, are shown to be climatological features. The mean structure of the temperature and height anomalies is consistent with moderate baroclinic growth below the stratopause and decay above. This work furthers current understanding of the geography of the stratopause by emphasizing the role of synoptic baroclinic instability, whereby anticyclones establish zonally asymmetric climatological patterns in stratopause temperature and height. This work highlights the need to consider zonal asymmetries when calculating upper stratospheric temperature trends.


Figure 1. The 7-year average annual cycle of stratopause (a) temperature and (b) height as a function of latitude based on MLS data from August 2004 through July 2011. Thick black and white contours indicate 5% of the maximum frequency of occurrence of the vortex and anticyclones, respectively, based on GEOS. February and March 2006 and 2009 are not included. Tick marks on the horizontal axis denote the 1st of each month.
A zonal mean would wash out longitudinal asymmetries!

Figure 2. Polar orthographic projections of (left) stratopause temperature, (middle) stratopause height, and (right) longitude-altitude plots of temperature averaged between 55°N and 65°N for a case study in the NH for 20, 23, and 26 January 2008. The Greenwich Meridian is oriented to the right. The polar vortex (anticyclone) edge, based on GEOS data, is indicated by the thick black (white) contours. The thick gray contour indicates the stratopause height.
Moving from the Stratopause to Planetary Waves
Planetary Wave Theory

Atmospheric Rossby waves emerge due to shear in rotating fluids, so that the Coriolis force changes along the sheared coordinate. In planetary atmospheres, they are due to the variation in the Coriolis effect with latitude.

\[ \psi = \psi_0 e^{i(kx+yt-\omega t)} \]

We obtain the dispersion relation of:

\[ \omega = \frac{U k}{k^2 + l^2} - \frac{\beta}{k^2 + l^2} \]

The zonal phase speed and group speed are given by

\[ c = \frac{\omega}{k} = U - \frac{\beta}{(k^2 + l^2)} \]

\[ c_g = \frac{\partial \omega}{\partial k} = U - \frac{\beta (l^2 - k^2)}{(k^2 + l^2)^2} \]

where \( c \) is the phase speed, \( c_g \) is the group speed, \( u \) is the mean westerly flow, \( \beta \) is the Rossby parameter, and \( k \) is the zonal wave number. The above proves that phase speed is always westward relative to mean flow, but group speed can travel both ways depending on the wave number; large zonal wave number waves (short waves) lead the mean flow, and small zonal wave number waves (long wave) retrogrades. The meaning of large and small only depends on the value of \( l \). If \( l = k \), then the group speed is the same as the mean zonal flow.

**Meaning of Beta**

The Rossby parameter is defined:

\[ \beta = \frac{\partial f}{\partial y} = \frac{1}{a} \frac{d}{d\phi} (2\omega \sin \phi) = \frac{2\omega \cos \phi}{a} \]

\( \phi \) is the latitude, \( \omega \) is the angular speed of the Earth's rotation, and \( a \) is the mean radius of the Earth.

If \( \beta = 0 \), there will be no Rossby Waves. Rossby Waves owe their origin to the gradient of the tangential speed of the planetary rotation (planetary vorticity). A 'cylinder' planet has no Rossby Waves. It also means that near the equator on Earth where \( f = 0 \) but \( \beta > 0 \) except at the poles, one can still have Rossby Waves (Equatorial Rossby wave).
Planetary Waves
Polar Jet is sometimes connected to the base of the polar vortex.
Moving from Planetary Waves to the Polar Vortex
“Tube” is fastest wind. Air in vortex stays separate from out. Daily wobbling and stretching is due to weather below.
Stratospheric Polar Vortex

Winter phenomenon
No sun for $O_3 \rightarrow$ cold strat
Polar night westerly jet
Descent from meso/thermo
Not a pole centered cylinder!

Next: Anticyclones and SSWs
The Arctic Vortex and Stratospheric Anticyclones

Anticyclones are associated with Stratospheric Sudden Warming Events
“Sudden Stratospheric Warmings”

- (1) Vortex *displaced* from pole
  - a.k.a. “Minor”, “Wave 1”, or Canadian
  - One anticyclone
  - WMO definition: 10 hPa polar T warmer than midlatitudes

- (2) Vortex *split*
  - a.k.a. “Major”, “Wave 2”
  - Two anticyclones
  - Defn: (1) and 10 hPa easterlies

The *Arctic vortex is weaker* and more variable than in the Antarctic due to land-ocean temperature differences and more mountains that force waves upward.
Jan-Feb 2008 Geopotential Height ~30 km
Jan 2009 Geopotential Height ~30 km
Met Office 2D to 3D

~35 km
Sudden Stratospheric Warmings

Arctic Vortex and Aleutian Anticyclone

• First discovered by Richard Scherhag in 1952
• **Major disruptions of the polar vortex**
• Upward propagation of PW from troposphere.
• **PW amplify with altitude and break to form closed anticyclonic vortices.**
• \( \bowtie \ \text{3-D representation: NH E Asia 10-70 km} \)
• Stratopause descends and warms.

ΔT65° C ~150° F
~1 week
Siberia to Sahara

Vortex is not usually a cylinder!

Next – Labitzke and Van Loon
Cold mesosphere during SSW’s (Roderick Quiroz, *The warming of the upper Stratosphere in February 1966 and the associated structure of the mesosphere, Monthly Weather Review, 1969*)

SSW’s favored during El Nino, QBO east phase, solar max (except for years of major volcanic eruptions) (van Loon and Labitzke 1987; 1990)


Coupling throughout whole atmosphere – the atmosphere is a fluid – SSWs also depend on the Sun
January 27th 2009

NH polar map, view from GM. Vertical axis is altitude. GEOS-5 analyses. Vortex is colored by temperature. Anticyclones in black.
Feb 20th to 27th 2008
Thanks!

http://www.youtube.com/watch?v=mHyTOcfF99o&feature=related