What controls polar stratospheric temperature trends?

Diane Ivy, Susan Solomon, Harald Rieder, Lorenzo Polvani
(paper in preparation)
Stratospheric Climate Change

Antarctic Ozone Hole

- Caused pronounced cooling in the lower stratosphere in austral spring
- Ozone depletion has resulted in a seasonal strengthening of the polar vortex and shifting of the tropospheric jet (positive trend in the SAM)
- Influenced Southern Hemisphere surface climate

Thompson et al. (2011) Nature Geoscience
Stratospheric Climate Change

Arctic Stratosphere

Solomon et al. (2014) PNAS
Antarctic Temperature Trends

How to reconcile?

Obsvd T trends are generally smaller than models.

Here we show a way to interpret the data/model comparisons in a new way.
Stratospheric Temperatures
Roles of Radiation and Dynamics

Thermodynamic Equation

\[
\frac{dT}{dt} = Q_{rad}(t) + Q_{dy}(t)
\]

\[
\frac{dT}{dt} = -\alpha_r(T - T_r) - \overline{w}^* S
\]

\[
\overline{w}^* = \overline{w} + \frac{1}{\cos \phi} \frac{\delta \left( \frac{\cos \phi v' T'}{S} \right)}{S}
\]

http://www.ccpo.odu.edu
Stratospheric Temperatures

Dynamical contribution to stratospheric temperatures and trends

Newman et al. (2010) JGR

Bohlinger et al. (2014) ACP

Two ways to analyze contributions to \( \frac{dT}{dt} \)

- use eddy heat flux to get dynamical term and treat radiative terms as a residual

- use radiative information and treat dynamical term as a residual
Stratospheric Temperatures

*Dynamical contribution to stratospheric temperatures and trends*

...lower stratospheric temperature is dependent on the time-integrated effects of the eddy heat flux. We test this by averaging the NCEP/NCAR reanalysis total eddy heat flux at 100 hPa between 45°N and 75°N. The timescale of the integration in this term is near 30 days, as determined by the thermal damping rate ($\alpha^{-1}$) of Newman and Rosenfield [1997]. As a simple test, Figure 1a shows this total eddy heat flux over the period January 15 to February 28 versus the 50-hPa March 1–15 polar-averaged temperature (60°–90°N) for each year from 1979 to 2000. The very strong correlation ($r = 0.82$) between March temperatures and these late winter eddy heat fluxes account for 15.3 K

Newman et al. (2010) JGR

*Thermodynamic Equation*

$$\frac{dT}{dt} = Q_{rad}(t) + Q_{dyn}(t)$$

...
Stratospheric Temperatures

*Radiative contribution to stratospheric temperatures and trends*

**Parallel Offline Radiative Transfer Model**
- Radiative code of NCAR’s CAM4 (Community Atmosphere Model)
- Fixed Dynamical Heating Calculation

**Data**
- MERRA Reanalysis
- 3 Additional Ozone Databases
- BDBP (Hassler et al., 2009)
- SPARC (Cionni et al., 2011)
- RW07 (Randel and Wu, 2007)
- Include increased long-lived GHGs

**Thermodynamic Equation**

\[
\frac{dT}{dt} = Q_{rad}(t) + Q_{dyn}(t)
\]
Model Forcings
Radiative and Dynamical Temperature Trends

*Arctic Trends in the Lower Stratosphere*

- Estimates agree well with results presented in Bohlinger et al. (2014)
- Most notable difference is Bohlinger estimates stronger radiative cooling trend in winter
- Dynamical warming in winter, indicates increased wave activity
- Summer trends are due to radiation
- Error bars on radiative trends are relatively small, reflect uncertainty on ozone trends (but checking H$_2$O is TBD)
Radiative and Dynamical Temperature Trends

*Arctic and Antarctic in the Lower Stratosphere*

- Cooling trend in Antarctic spring - mainly radiative
- Cooling trend in Arctic spring – dynamical
- Cooling in Arctic summer – radiative
- Cooling in Antarctic summer – radiation and dynamics
Historical Temperature Trends
Arctic and Antarctic

- Strong cooling in both hemispheres
  - Antarctic confined to lower stratosphere
  - Arctic cooling first appears in mid and upper stratosphere
- Warming trend above Antarctic cooling
Radiative and Dynamical Temperature Trends

- Peak in radiative cooling associated with ozone lags by one month
- Cooling in the Antarctic is largely radiative due to ozone depletion
- Cooling in the Arctic is dynamical
- Dynamical “Warming above the cooling” is seen in both hemispheres and isn’t confined to just mid-stratosphere
  - Acts to weaken the radiative cooling – big effect in Antarctic summer
  - Influence on strat/trop coupling
Some Key Points

• Estimated the radiative and dynamical contributions to polar stratospheric temperature trends – lower stratospheric results are similar to those using the eddy-heat flux

• Radiative approach can be used over a broad range of altitudes (at least up to 10 mbar); depends mainly on accuracy of knowledge of ozone and T trends

• Arctic summer and fall seasons are close to radiative equilibrium; temperature trends are result of radiative cooling associated with ozone depletion (and increased greenhouse gases)

• Dynamical changes are evident in both hemispheres:
  • Arctic: Strengthening of BDC in winter and in weakening in spring
  • Antarctic: Strengthening of BDC in spring and summer; dynamical response to Antarctic ozone hole, the Antarctic dynamical response acts to weaken the radiative cooling.
  • Warming above the cooling is an indicator of circulation changes – value as a diagnostic
Additional slides, not for presentation
Stratospheric Climate Change

Antarctic Ozone Hole

- Large ozone depletion event in austral spring
- Ozone depletion occurs as heterogeneous chemistry on polar stratospheric clouds
Stratospheric Climate Change

Arctic Stratosphere

- Temperatures on the threshold for polar stratospheric cloud formation
- Coldest winters are getting colder
- Implications for future ozone loss
Stratospheric Climate Change

Comparison of Models

- CCMVal-1 gave stronger tropospheric response than CCMVal-2 but much of that traced to a single model

- CCMVal-2 shows similar results as AR4 models

- Models aren’t able to capture the seasonality in Arctic winter/spring trends and overall cool too much compared to lower stratospheric temperatures

Son et al. (2010) JGR

Wang et al. (2012) JGR
Stratospheric Temperatures

*Dynamical contribution to stratospheric temperatures*

Lower stratospheric temperatures are dependent on the time-integrated effects of the eddy heat flux. We test this by averaging the NCEP/NCAR reanalysis total eddy heat flux at 100 hPa between 45°N and 75°N. The timescale of the integration in this term is near 30 days, as determined by the thermal damping rate ($\alpha^{-1}$) of Newman and Rosenfield [1997]. As a simple test, Figure 1a shows the total eddy heat flux over the period January 15 to February 28 versus the 50-hPa March 1–15 polar-averaged temperature (60°–90°N) for each year from 1979 to 2000. The very strong correlation ($r = 0.82$) between March temperatures and these late winter eddy heat fluxes account for 15.3 K.

**Thermodynamic Equation**

\[
\frac{dT}{dt} = Q_{rad}(t) + Q_{dyn}(t)
\]

\[
\frac{dT}{dt} = -a_r(T - T_r) - \bar{w}S^*
\]

\[
\bar{w}^* = \bar{w} + \frac{1}{a \cos \phi \delta \phi} \left( \frac{\cos \phi v' T'}{S} \right)
\]

Newman et al. (2010) JGR
Radiative Temperature Trends

*Arctic and Antarctic in the Lower Stratosphere*

- Fu et al. (2010) used eddy-heat flux to estimate the dynamical contribution to trends in Arctic and Antarctic (1980-2008)
- Antarctic radiative trend peaks in November
- Arctic radiative trend peaks in March
- Antarctic fall and Arctic summer and fall trends are similar at -0.5 K/decade
Radiative and Dynamical Temperature Trends

Arctic Trends in the Lower Stratosphere

- Winter trends are subject to large uncertainties and are sensitive to end-year
- Dynamical cooling in February
- Stronger radiative cooling with trends ending in 2000
- Summer trends are robust and are driven by radiation
Dynamical Temperature Trends

*Arctic and Antarctic in the Lower Stratosphere*

- Dynamical trends show similar seasonality as Fu et al. (2010)
- Fu et al. (2010) found a strengthening of BDC SH cell in July - November; strengthening of NH cell in DJF and weakening in MAM
Historical Temperature Trends

*Warming above the cooling*

- Dynamical response to Antarctic ozone hole; enhanced gravity wave propagation (Calvo et al., 2012).
- Warming above cooling modeled in chemistry climate models
- Not seen in GCMs with prescribed ozone
- Young et al. (2013) suggests “warming above cooling” is a benchmark for models representation of middle atmospheric dynamics
Radiative and Dynamical Temperature Trends

Arctic Upper Troposphere

- Arctic summer trends in the lower stratosphere are driven by changes in radiative cooling associated with ozone depletion; these trends extend down to 250hPa.
Radiative and Dynamical Temperature Trends

Antarctic Upper Troposphere

- Antarctic summer trends in the lower stratosphere are driven changes in radiative cooling associated with ozone depletion and dynamical warming
- Lowermost stratospheric and upper tropospheric trends are driven by radiation