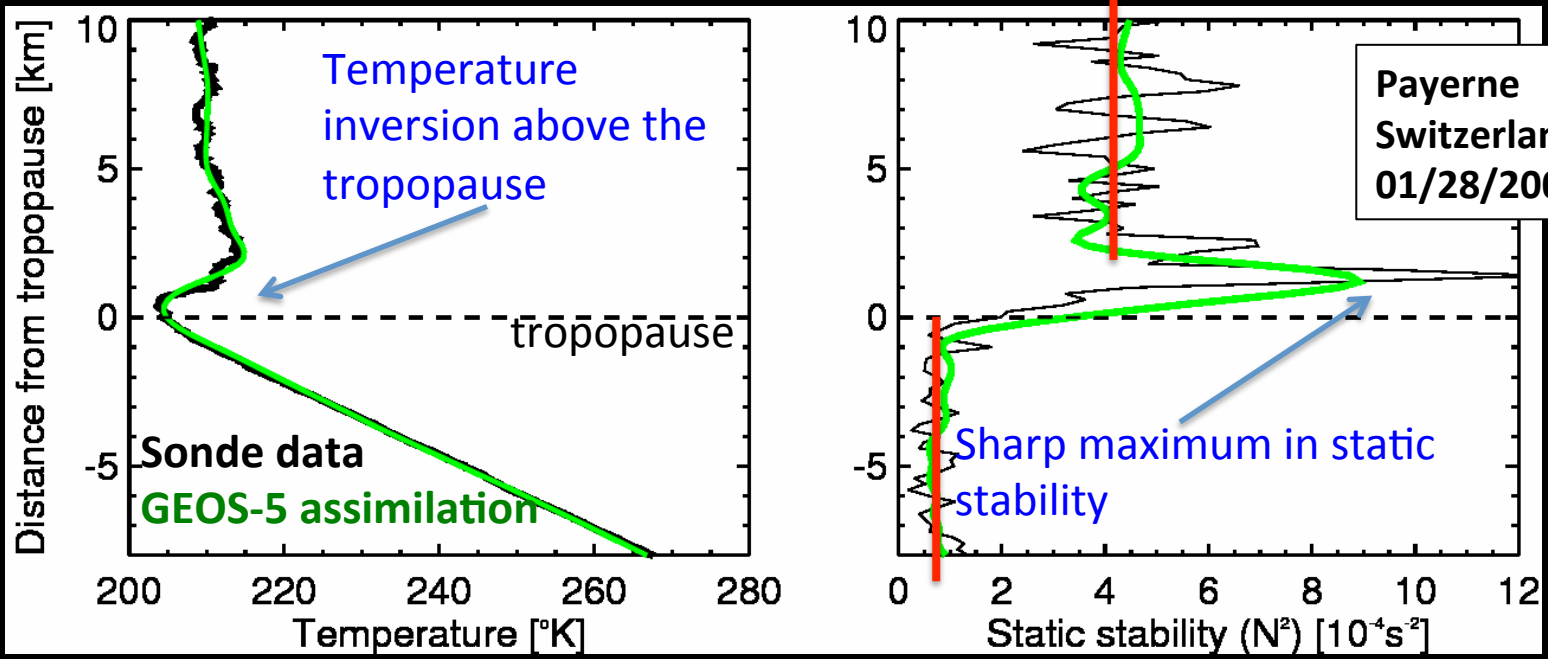
The Tropopause Inversion Layer: What can we learn from data assimilation?

K. Wargan, L. Coy, W. McCarty and S. Pawson

Global Modeling and Assimilation Office

JCSDA Seminar, 25 February 2015

Primer: What is the Tropopause Inversion Layer (TIL)?



- Positive temperature lapse rate in a 2 – 3 km layer above the tropopause
- Sharp maximum in static stability
  - Troposphere: $N^2 \sim 1\times10^{-4}s^{-2}$
  - Stratosphere: $N^2 \sim 4\times10^{-4}s^{-2}$
  - TIL: $N^2 > 5.5\times10^{-4}s^{-2}$
- A ubiquitous feature of the extratropical lower stratosphere
- Importance: consequences for wave propagation and tracer transport

Outline

- Part I: The TIL in GEOS-5
  - Is the TIL correctly represented in GEOS-5?
  - What can we learn about the GCM and how sensitive are the results to the observing system?
- Part II: The TIL and stratospheric circulation
  - Why is the TIL there in the first place?
  - Connection between the TIL/tropopause sharpness and winter polar stratospheric dynamics

System/data description

This experiment covers the period 2005-2014

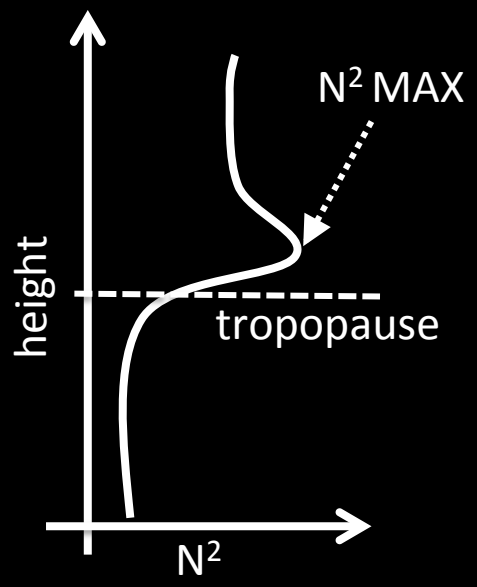
The assimilation system: The Goddard Earth Observing System (GEOS)-5.7.2.

- Resolution: 2°×2.5°, 72 layers.
- Vertical resolution near the tropopause ~1 km
- Observations
  - Radiance data: AIRS, AMSU – A&B, HIRS, MHS
  - conventional data: radiosondes, aircraft, surface data

Definitions/conventions

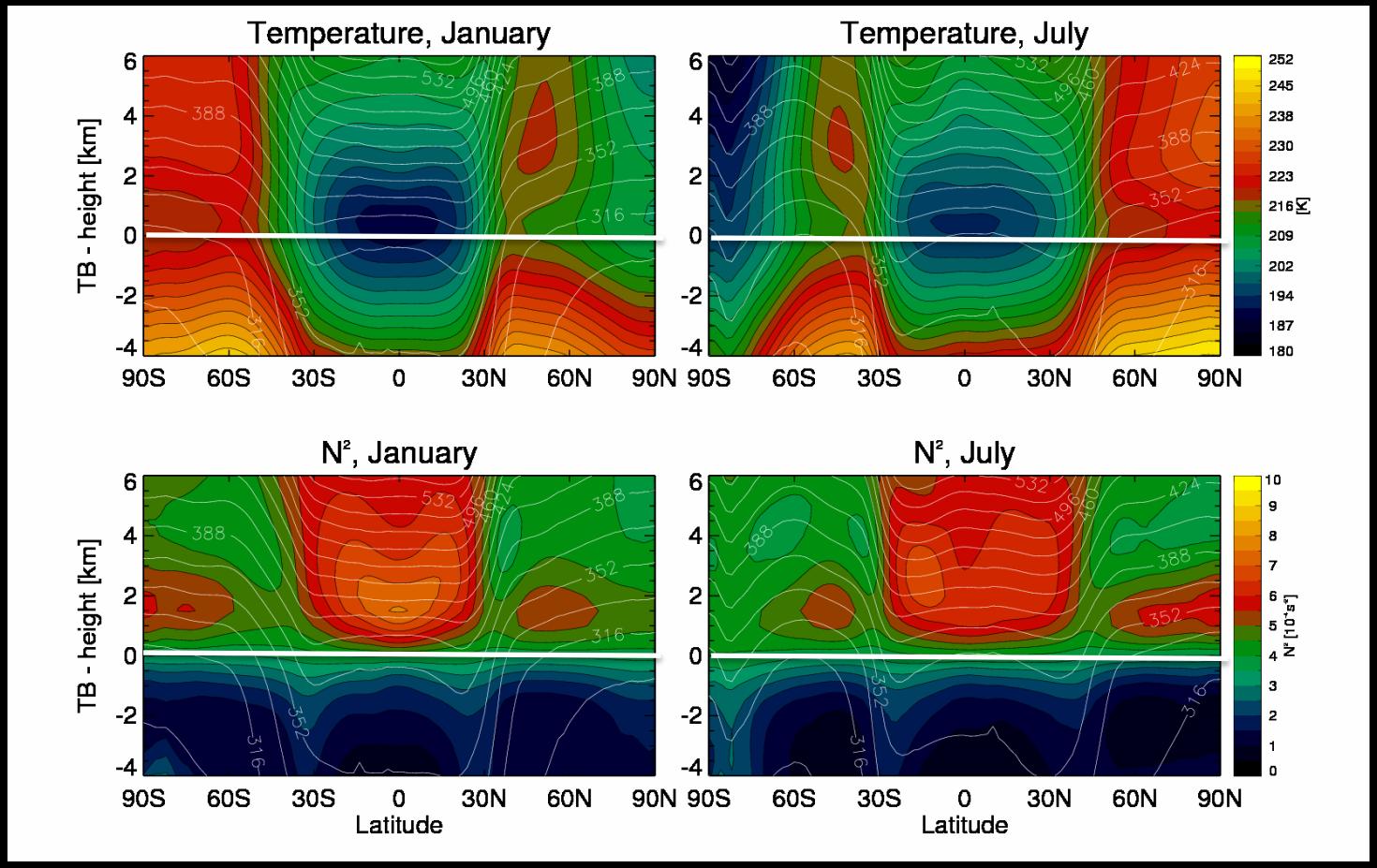
Definitions/conventions

- Tropopause – standard WMO definition
- All profiles are averaged in tropopause-based coordinates
- Measure of TIL magnitude: Maximum Brunt–Väisälä buoyancy frequency squared, N^2 MAX, within 3 km above the tropopause
- Validation against radiosondes (assimilated) and the High Resolution Dynamics Limb Sounder (HIRDLS, **not** assimilated in these experiments)



$$N^2 = \frac{g}{\theta}\frac{d\theta}{dz}$$

The UTLS structure in GEOS-5



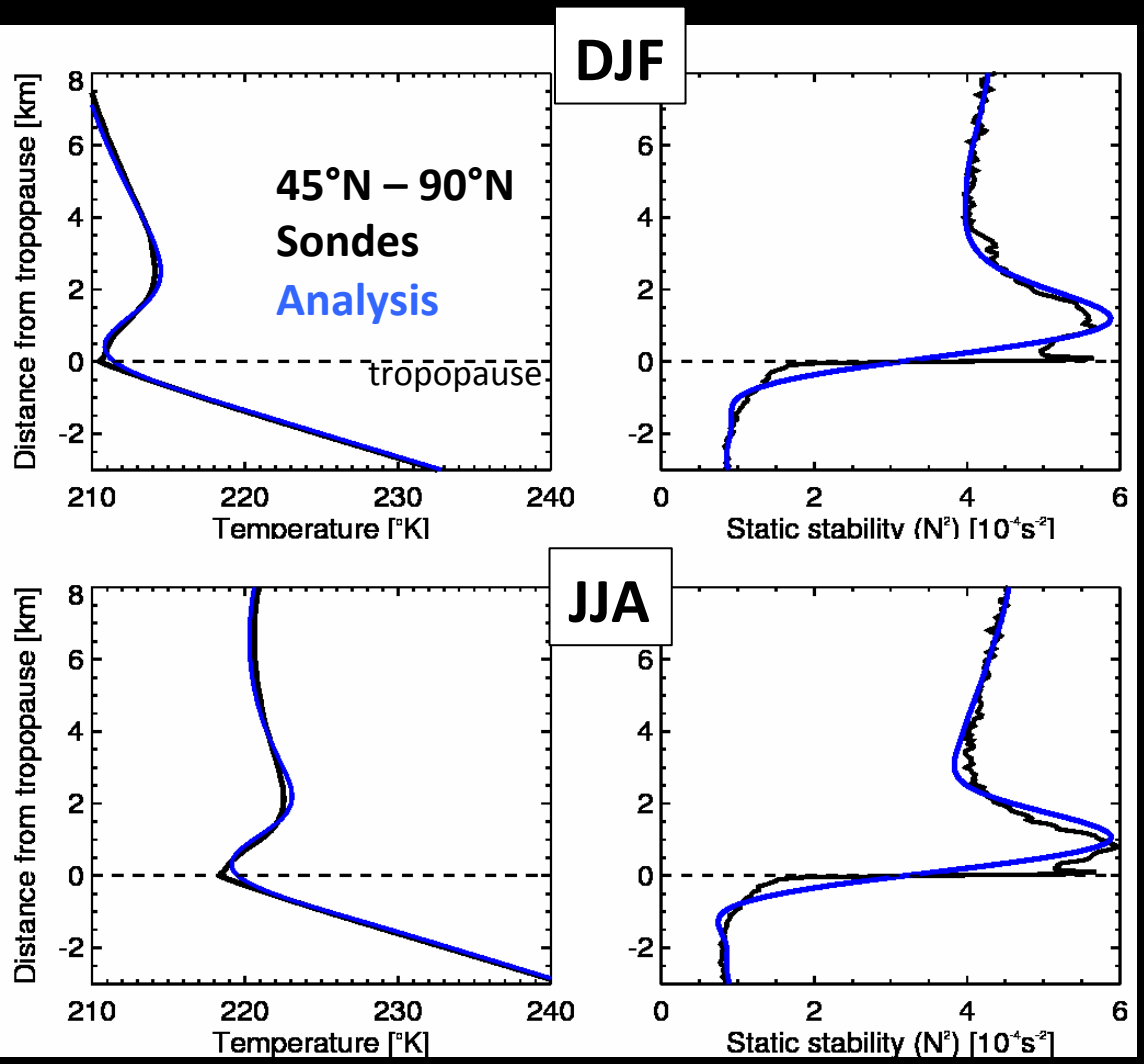
GEOS-5 zonal mean temperature and static stability in January and July 2007.

All data are interpolated to a constant vertical altitude grid with 500 m spacing

- **The tropopause inversion layer is reproduced in the assimilation**
- Winter: the TIL has smaller latitudinal extent and is deeper
- Summer: the TIL extends to the pole and is shallower

This is the 'winter-summer contrast' [*Birner et al., 2006*]

Assimilation vs. radiosondes



Analysis reproduces temperature and static stability profiles

The tropopause is less sharp in the analysis than in the sonde data – this is expected given its coarser vertical resolution (~1 km)

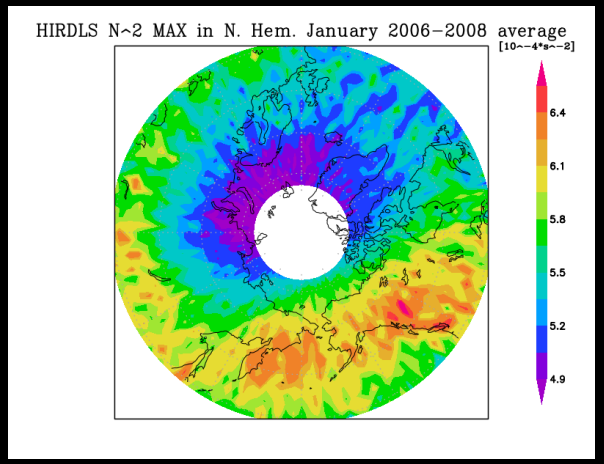
The tropopause inversion layer is seen in both data sets

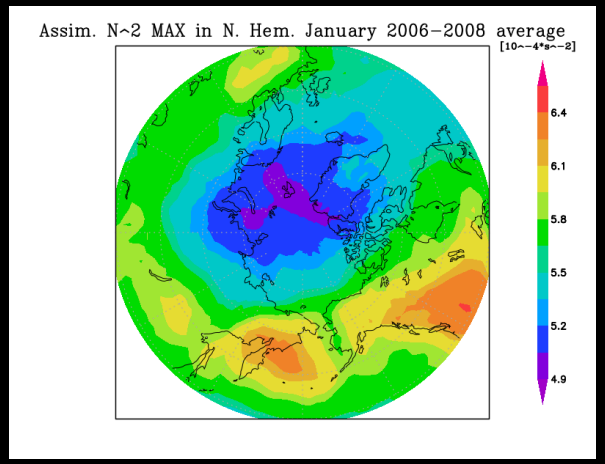
Sondes and analysis data are interpolated to a 50 m vertical grid.
The tropopause is calculated from sonde data

Assimilation vs. HIRDLS – Maps – Zonal Asymmetry

HIRDLS | ASSIMILATION

January 2006-2008

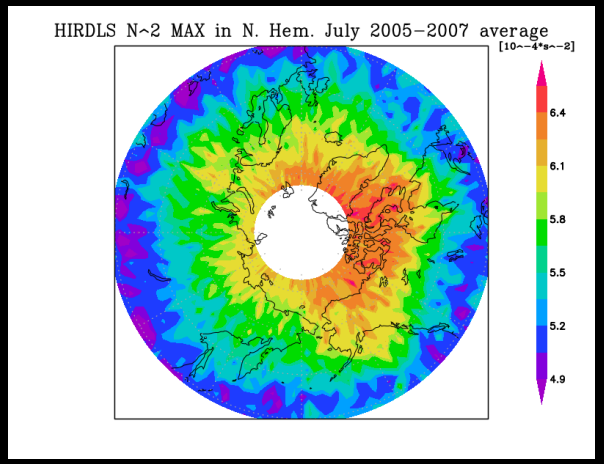


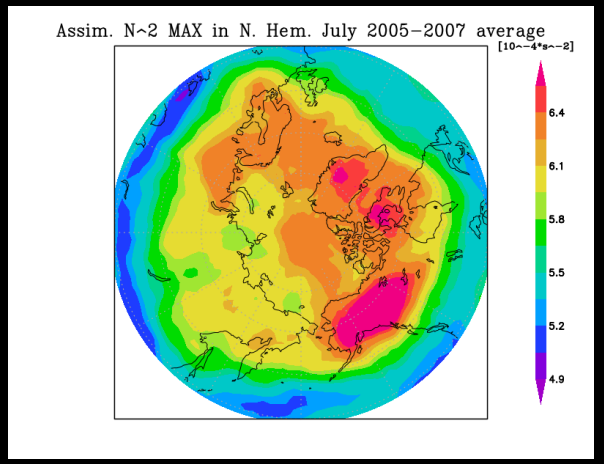


January 2006 - 2008

- Good agreement with HIRDLS.
- Maxima over Aleutian Islands and Rocky Mountains
- Low N^2 in high latitudes and over the Atlantic

July 2006-2008





July 2005 - 2007

- Maxima in high latitudes
- Similar zonal asymmetry
- Assimilation has maxima over Alaska and Europe – not seen in HIRDLS

HIRDLS is not assimilated

The tropopause inversion layer is represented in data assimilation

… but this has not always been the case

History: The Tropopause Inversion Layer in Models and Analyses, *Birner et al., 2006*

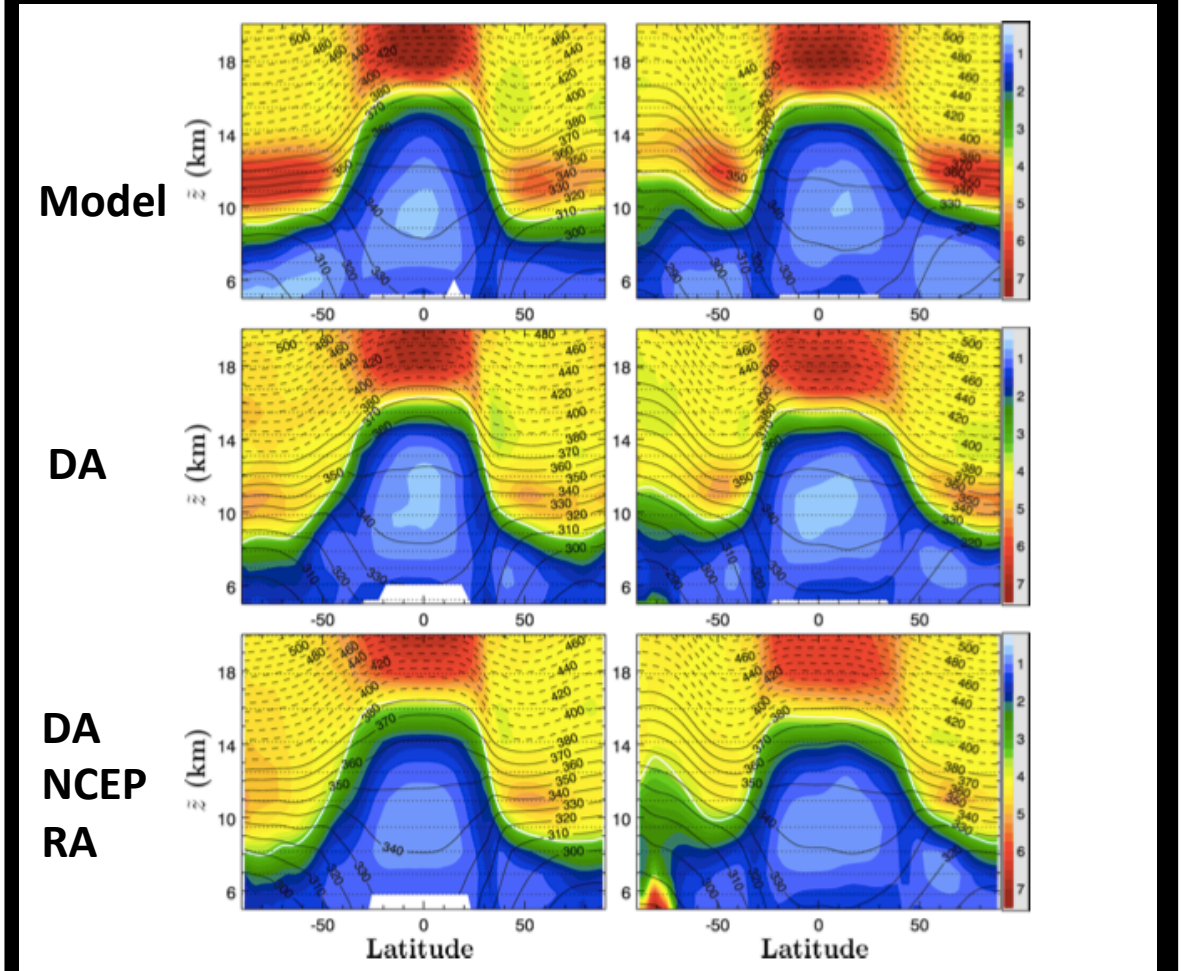
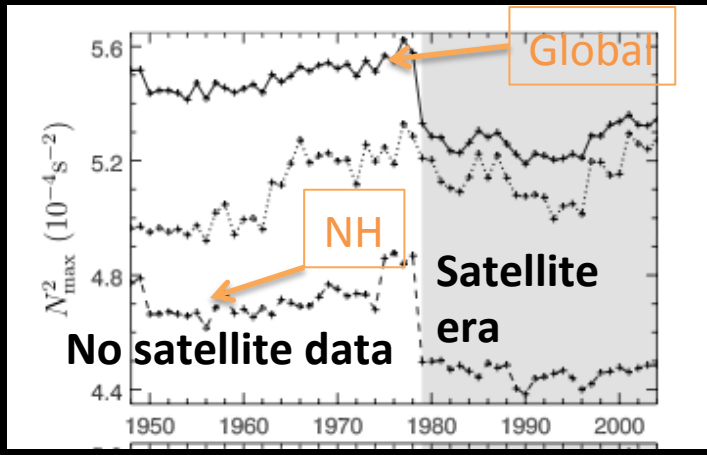


Figure 2. Zonal mean TB-mean buoyancy frequency squared (10^{-4} s^{-2}, color shading) and isentropes (contours, overworld dashed). (left) January, (right) July. From top to bottom: CMAM, CMAM-DA (year 2002), NCEP-RA (years 1998–2002). Thick white lines denote $\bar{z}_{TP}$. Dotted horizontal lines mark approximate location of model levels.

Birner et al., 2006



Yearly averaged maximum N^2 from the NCEP Reanalysis. Sharp drop in static stability when radiance data are included

The conclusion of that study

General circulation models correctly generate the TIL but assimilation erases it

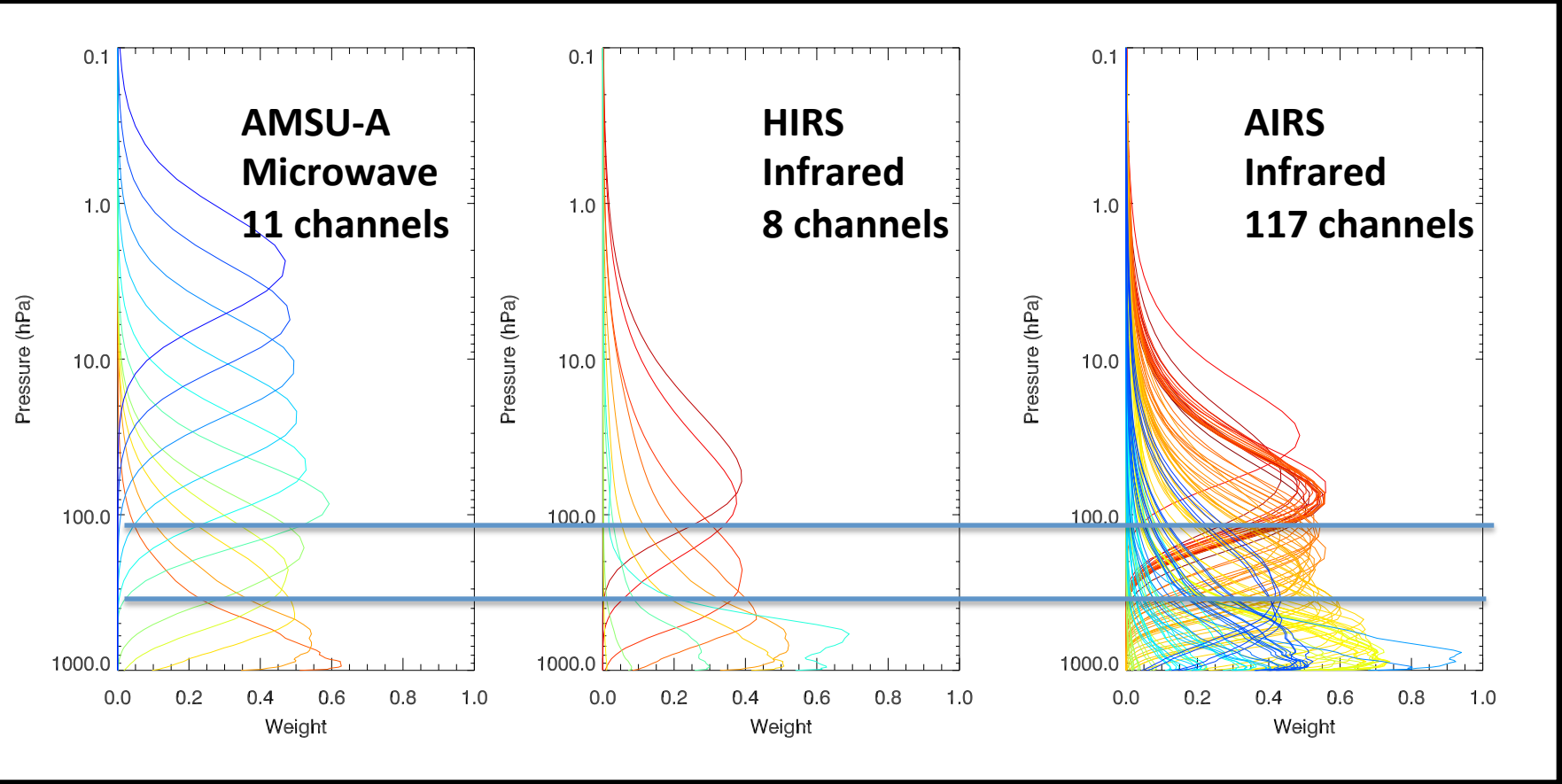
Why did these older reanalyses fail to produce a realistic TIL?

- Too much vertical smoothing by the B-matrix?
- Insufficient vertical resolution of the observing system?

Why did these older reanalyses fail to produce a realistic TIL?

- Too much vertical smoothing by the B-matrix?
- Insufficient vertical resolution of the observing system?

Spectral channels and weighting functions



Typical weighting functions for three sensors relevant to the tropopause. 45°N-90°N. Assimilated channels are shown. *Plot generated using July 2007 data*

AIRS has the highest spectral resolution: a potential to resolve shallow features in temperature profiles.

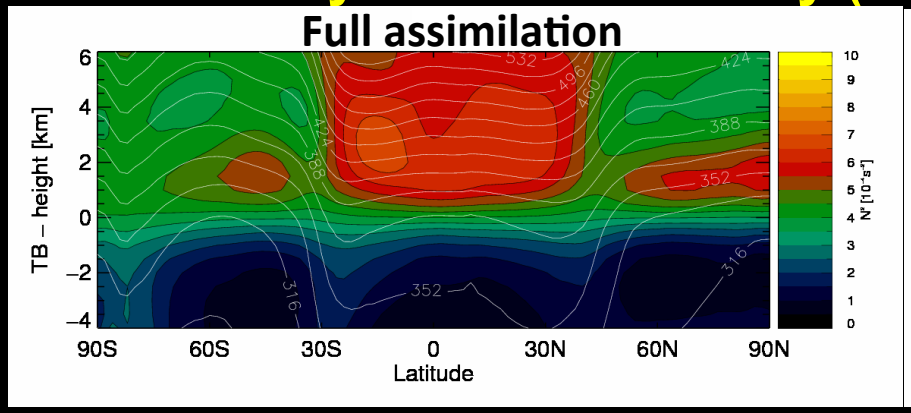
Representation of the TIL – sensitivity to the observing system

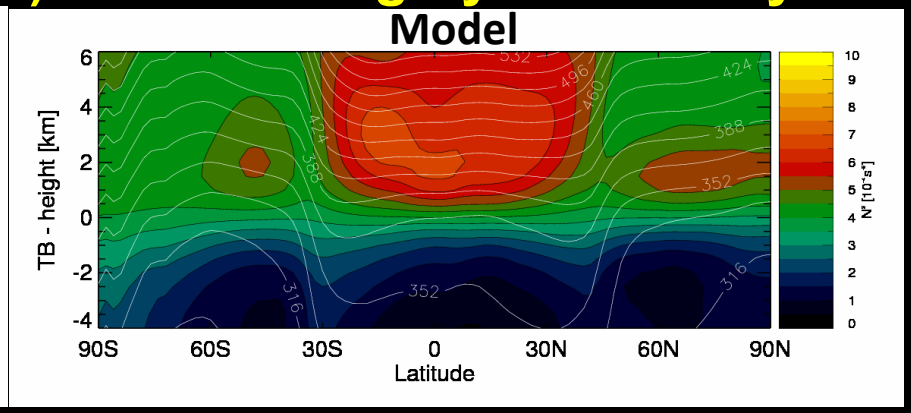
Low resolution | Hyperspectral

	AMSU A&B	HIRS	AIRS	Conventional data
Full Assimilation	X	X	X	X
Radiance Assimilation	X	X	X	-
AMSU & Conventional	X	-	-	X
AMSU only	X	-	-	-
Model	-	-	-	-

AMSU: Advanced Microwave Sounding Unit

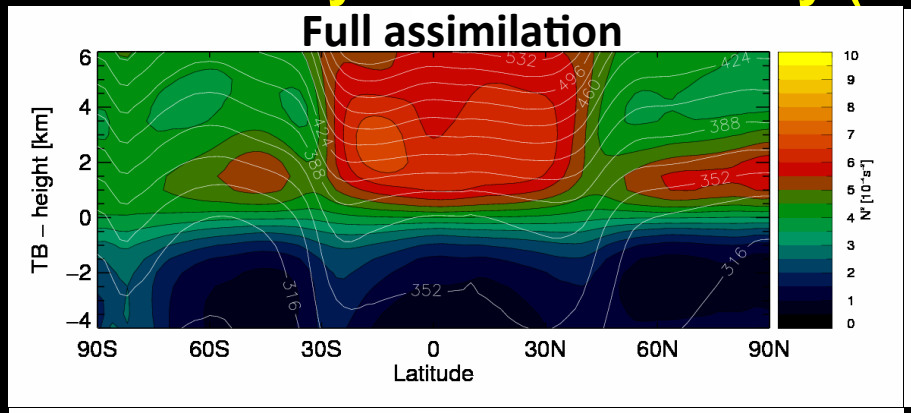
Sensitivity of Static Stability (N^2) to Observing System – July 2007

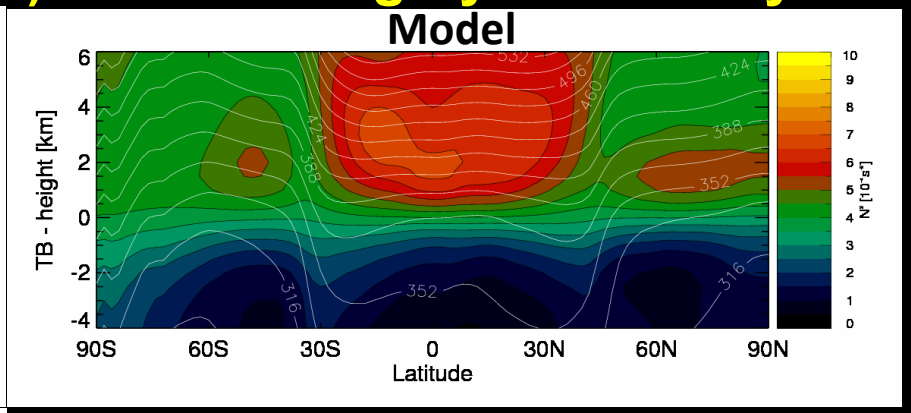


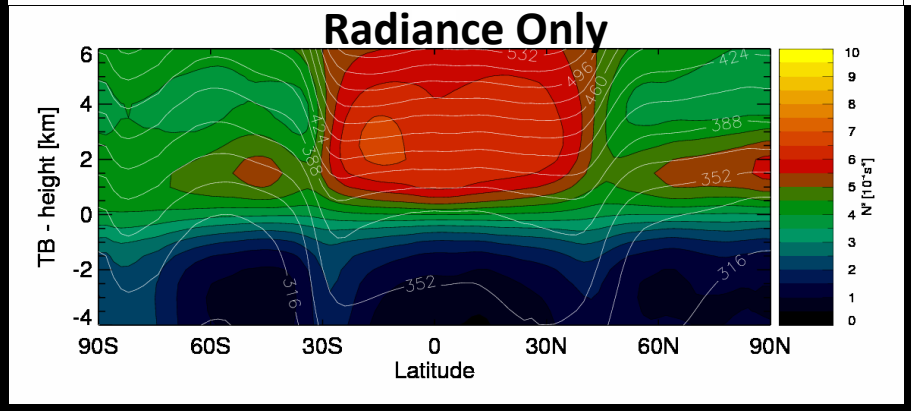


- Assimilation and model correctly represent the morphology of the TIL
  - Assimilation: sharper TIL

Sensitivity of Static Stability (N^2) to Observing System – July 2007

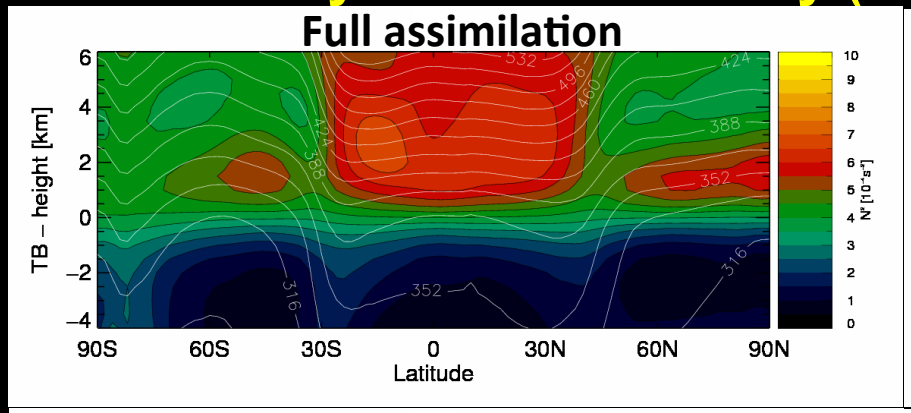


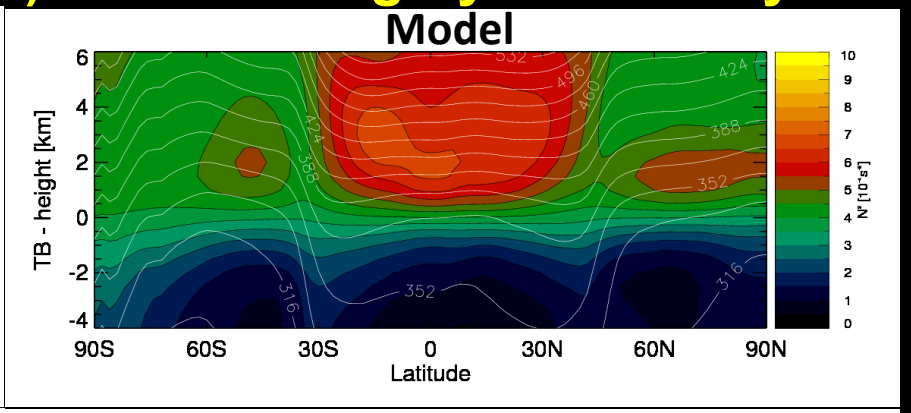


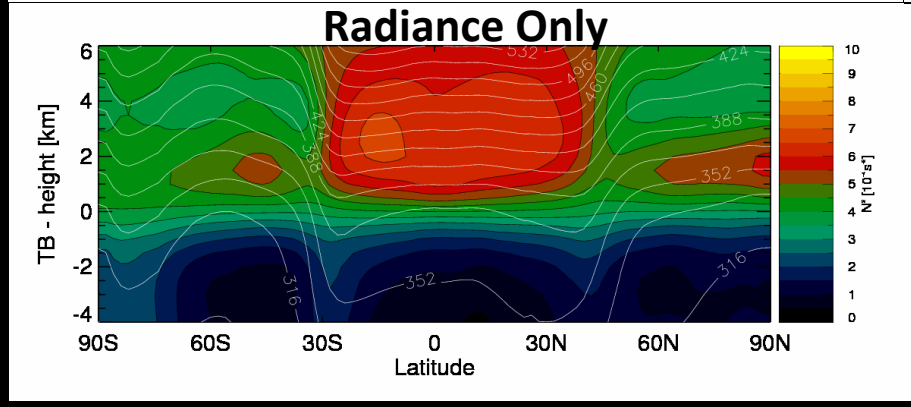


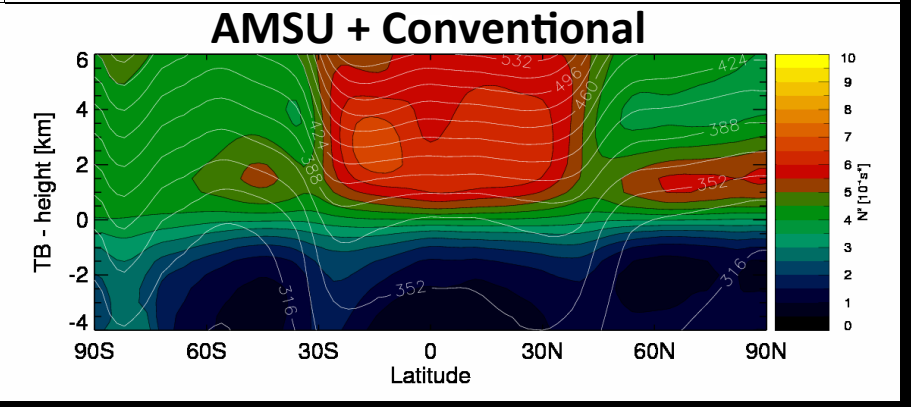
- Assimilation and model correctly represent the morphology of the TIL
  - Assimilation: sharper TIL
- **Radiance assimilation – in between**

Sensitivity of Static Stability (N^2) to Observing System – July 2007



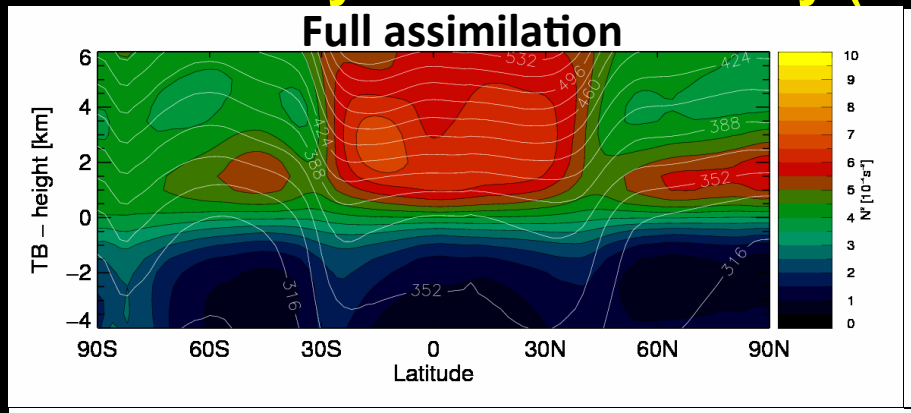


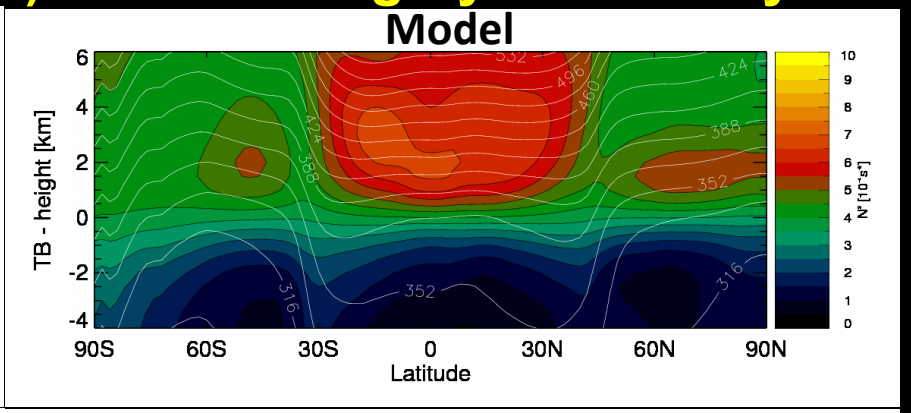


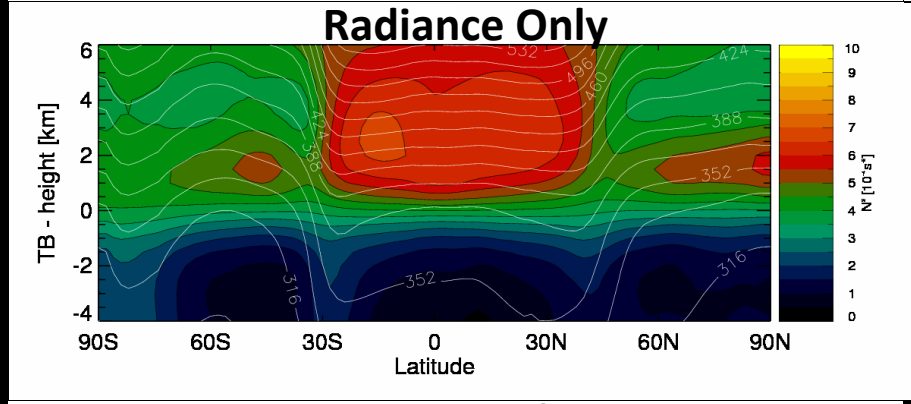


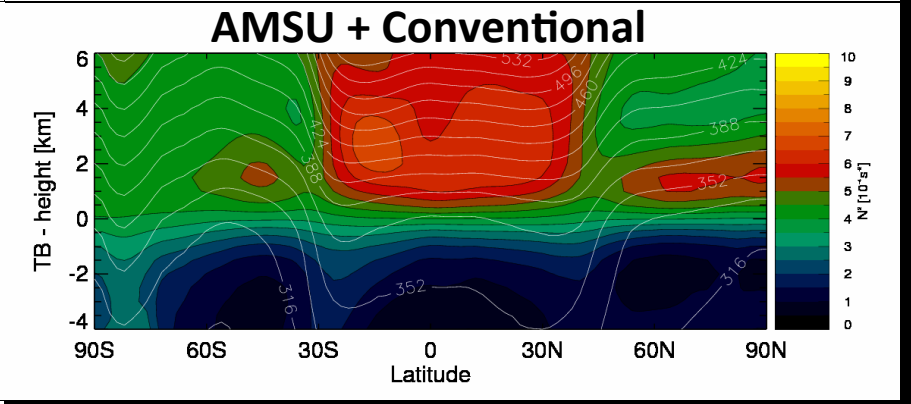
- Assimilation and model correctly represent the morphology of the TIL
  - Assimilation: sharper TIL
- Radiance assimilation – in between
- **AMSU and conventional data:**
  - **Like full assimilation in NH**
  - **Weaker TIL in SH**

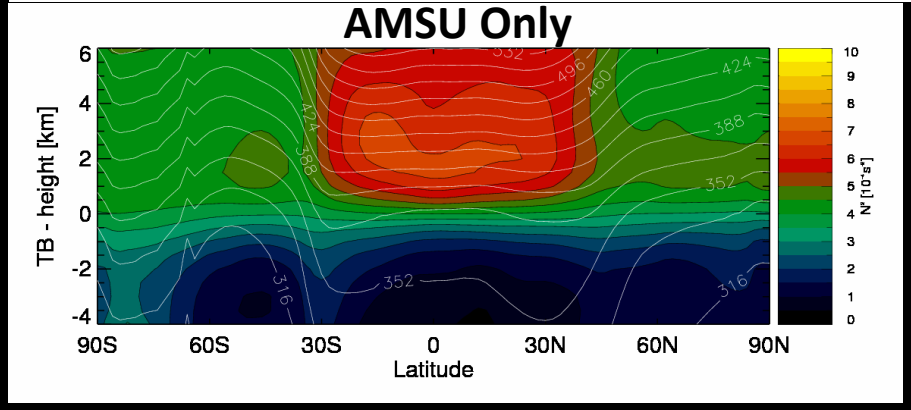
Sensitivity of Static Stability (N^2) to Observing System – July 2007





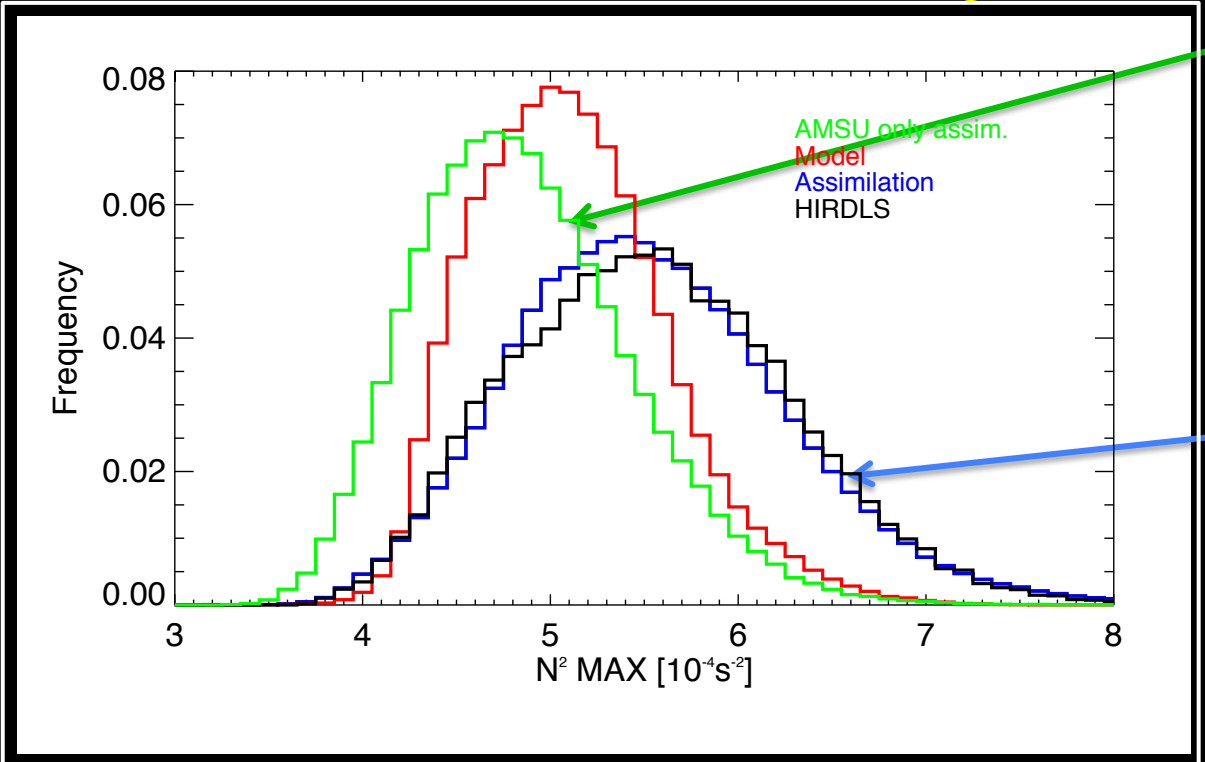






- Assimilation and model correctly represent the morphology of the TIL
  - Assimilation: sharper TIL
- Radiance assimilation – in between
- AMSU and conventional data:
  - Like full assimilation in NH
  - Weaker TIL in SH
- **AMSU-only assimilation: no TIL**

Distributions of N^2 MAX in the Northern Hemisphere in January 2007



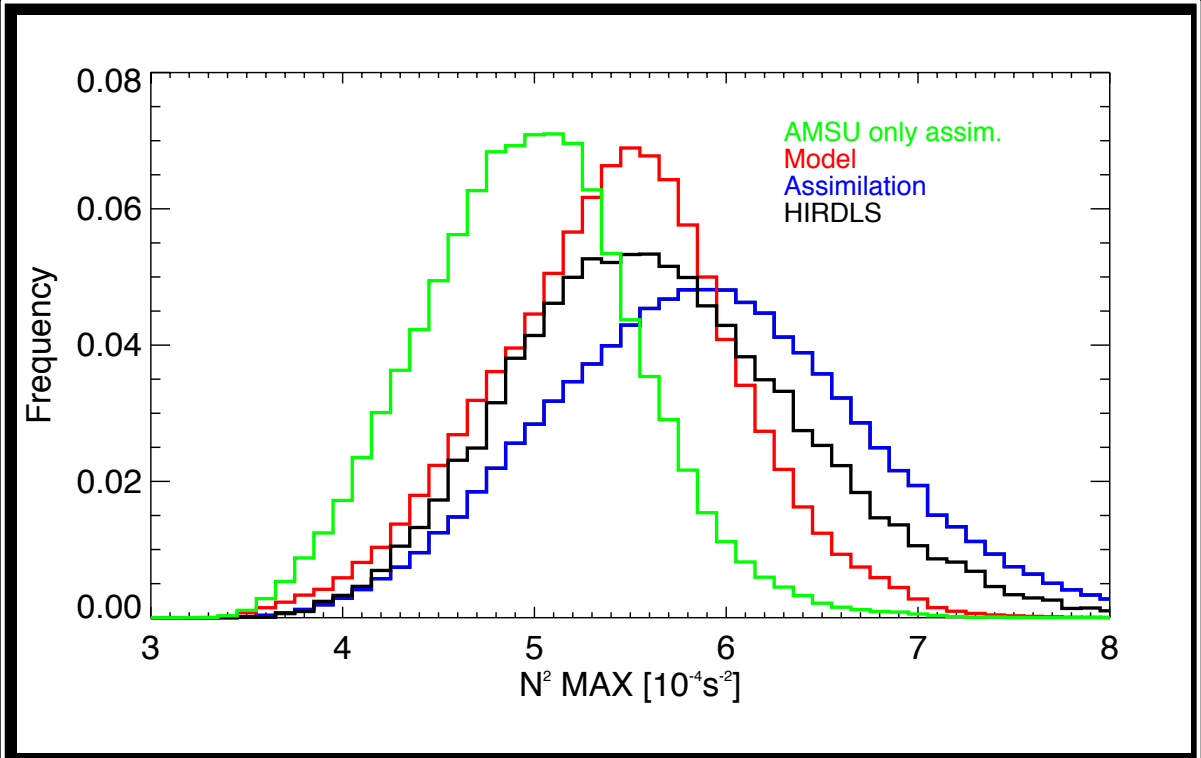
Distributions of N^2 between 45°N - 75°N in the 3 km layer above the tropopause from HIRDLS, full assimilation, model and AMSU-only assimilation

The TIL in the AMSU-only is weaker than in the model

Full assimilation reproduces the distribution of N^2 reported by HIRDLS very well.

- **Very good agreement between the full assimilation and HIRDLS**
- In this case, the assimilation enhances the TIL compared to the model
- The use of AMSU as the only data source → degraded TIL
- **The GCM underestimates the TIL's strength**

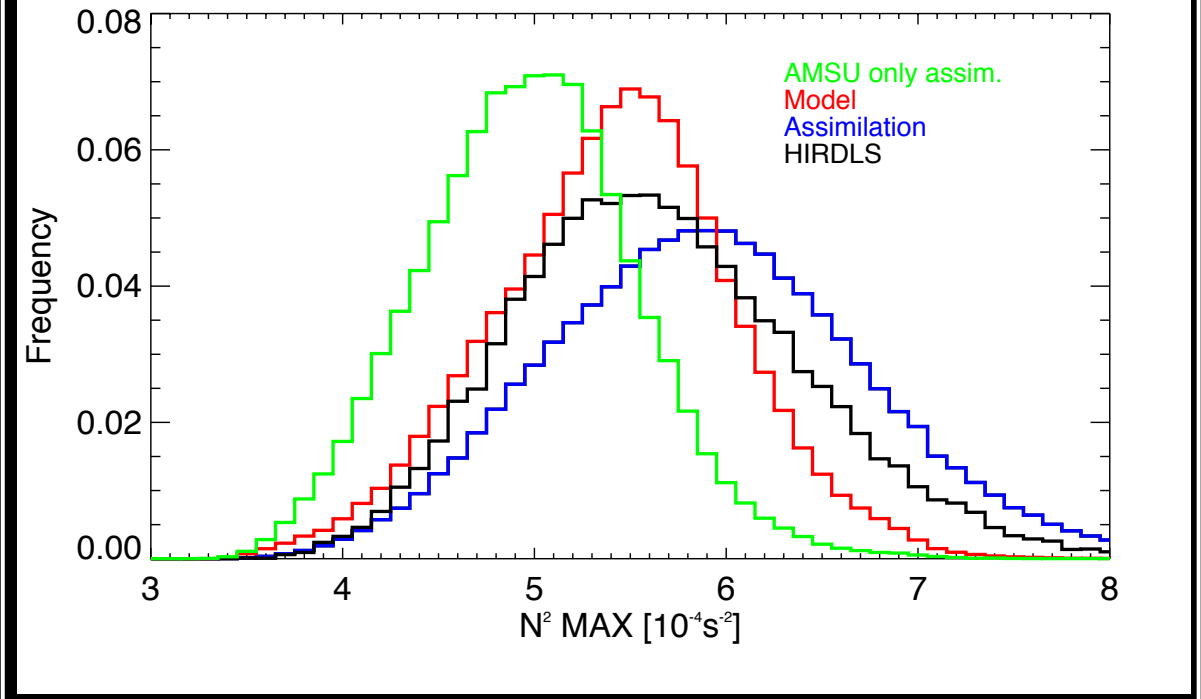
Distributions of N^2 MAX in the Northern Hemisphere in July 2007



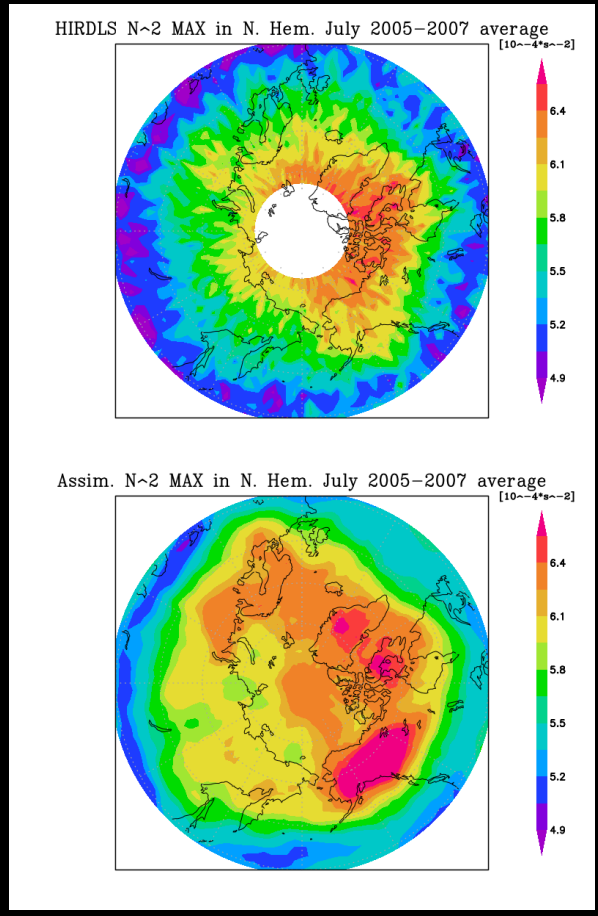
Distributions of N^2 between 45°N - 75°N in the 3 km layer above the tropopause from HIRDLS, full assimilation, model and AMSU-only assimilation

- **Full assimilation overestimates the TIL**
- Again, the use of AMSU as the only data source → degraded TIL
- **Again, he GCM underestimates the TIL's strength**

Distributions of N^2 MAX in the Northern Hemisphere in July 2007



Distributions of N^2 between 45°N - 75°N in the 3 km layer above the tropopause from HIRDLS, full assimilation, model and AMSU-only assimilation



- **Full assimilation overestimates the TIL**
- Again, the use of AMSU as the only data source → degraded TIL
- **Again, he GCM underestimates the TIL's strength**

Summary of Part 1

Done!

- The Tropopause Inversion Layer is represented in GEOS-5 DAS.
- The use of hyperspectral and conventional data is essential. AMSU alone erases the TIL

Future work

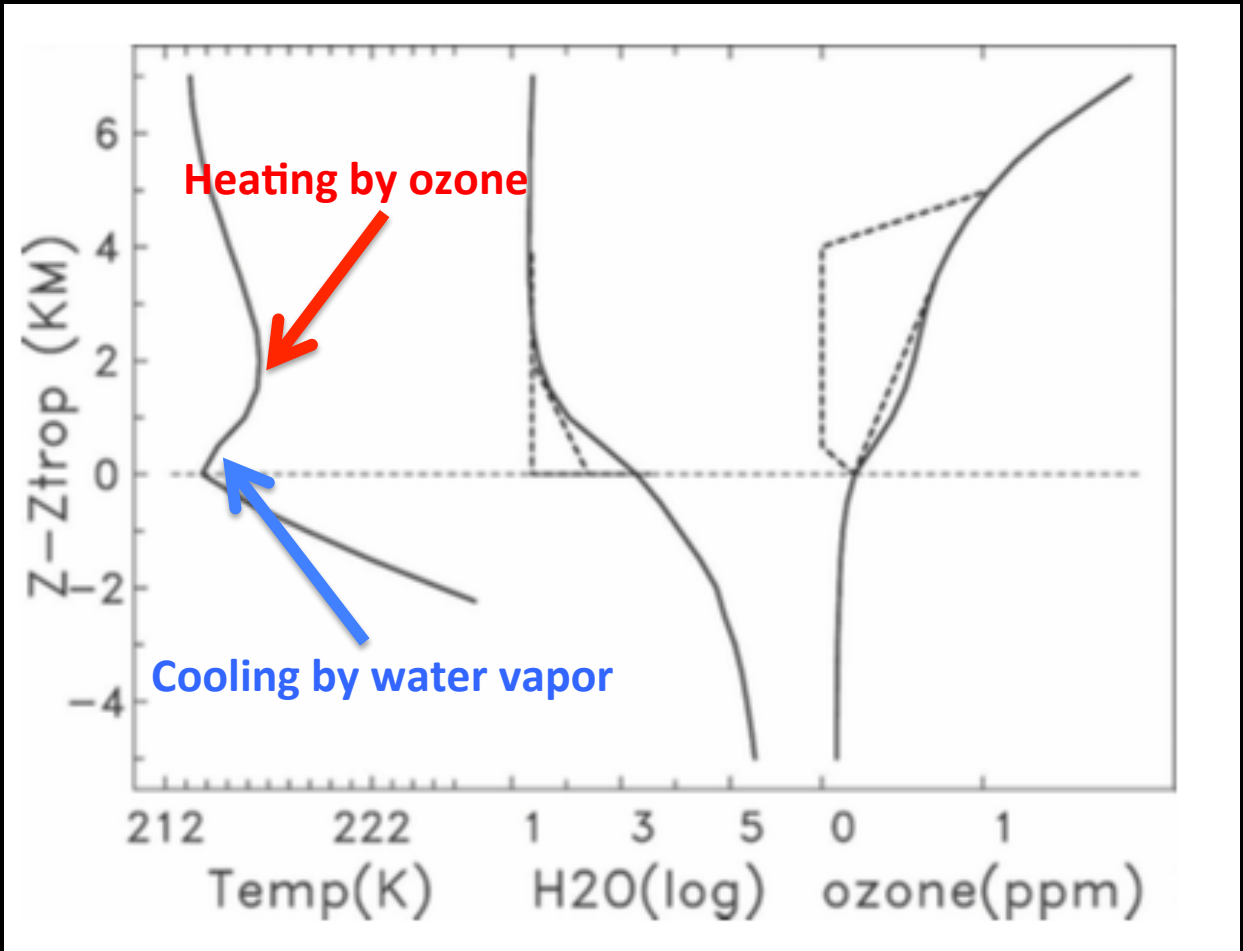
- It may be beneficial to increase the vertical resolution in the UTLS
- The TIL is reproduced by the GCM but it is too weak. A missing process?

Mechanisms responsible for the formation and maintenance of the TIL

- Not fully understood
- Two mechanisms have been proposed and backed up by model simulations:
  - Radiative
  - Dynamical

Likely, several processes contribute to the TIL

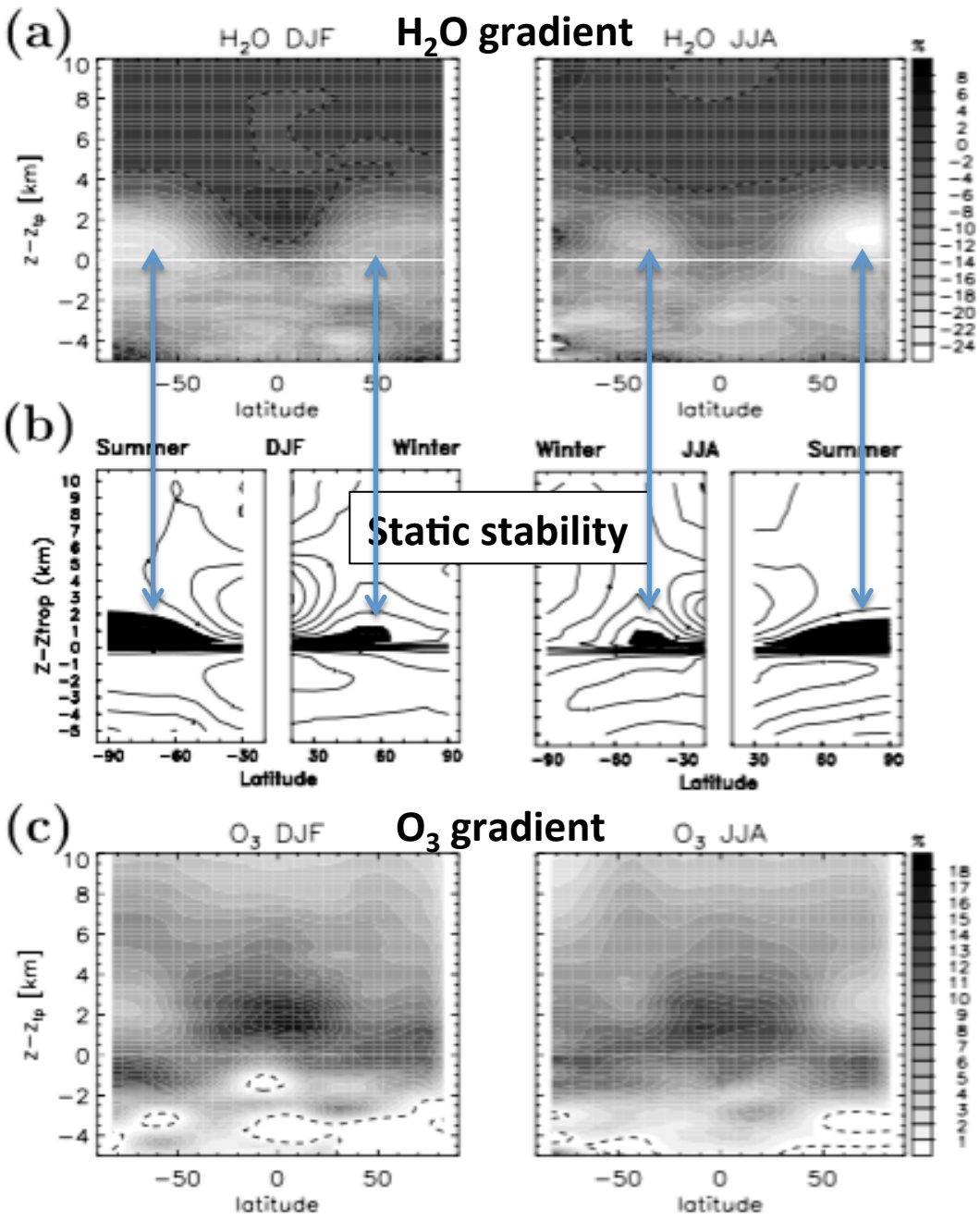
Radiative mechanism



Differential cooling and heating by water vapor and ozone, respectively.

This mechanism may play a role in summer months

Randel et al. 2007



Hegglin et al., 2009:

There is a similarity between the zonal structures of N^2, ozone and water vapor gradients.

The same mechanism involved?

Tracer distribution is important for radiative heating → radiative formation of the TIL

Are these features correctly represented in the GCM?

'Missing mechanism'?

Dynamical mechanism

(a simplified version)

$$PV = \frac{1}{\rho}(f + \zeta) \bullet \nabla\theta$$

Potential vorticity Absolute vorticity Static stability

- There is an inverse relationship between absolute vorticity and static stability
- Upper level anticyclones favor high static stability above the tropopause – strong TIL
- Weak TIL over cyclones
- Baroclinic wave breaking can lead to large areas of anticyclonic circulation at the tropopause → Strong TIL arises in the zonal average
- Seen in idealized model simulations

Dynamical mechanism

Erler and Wirth 2011:

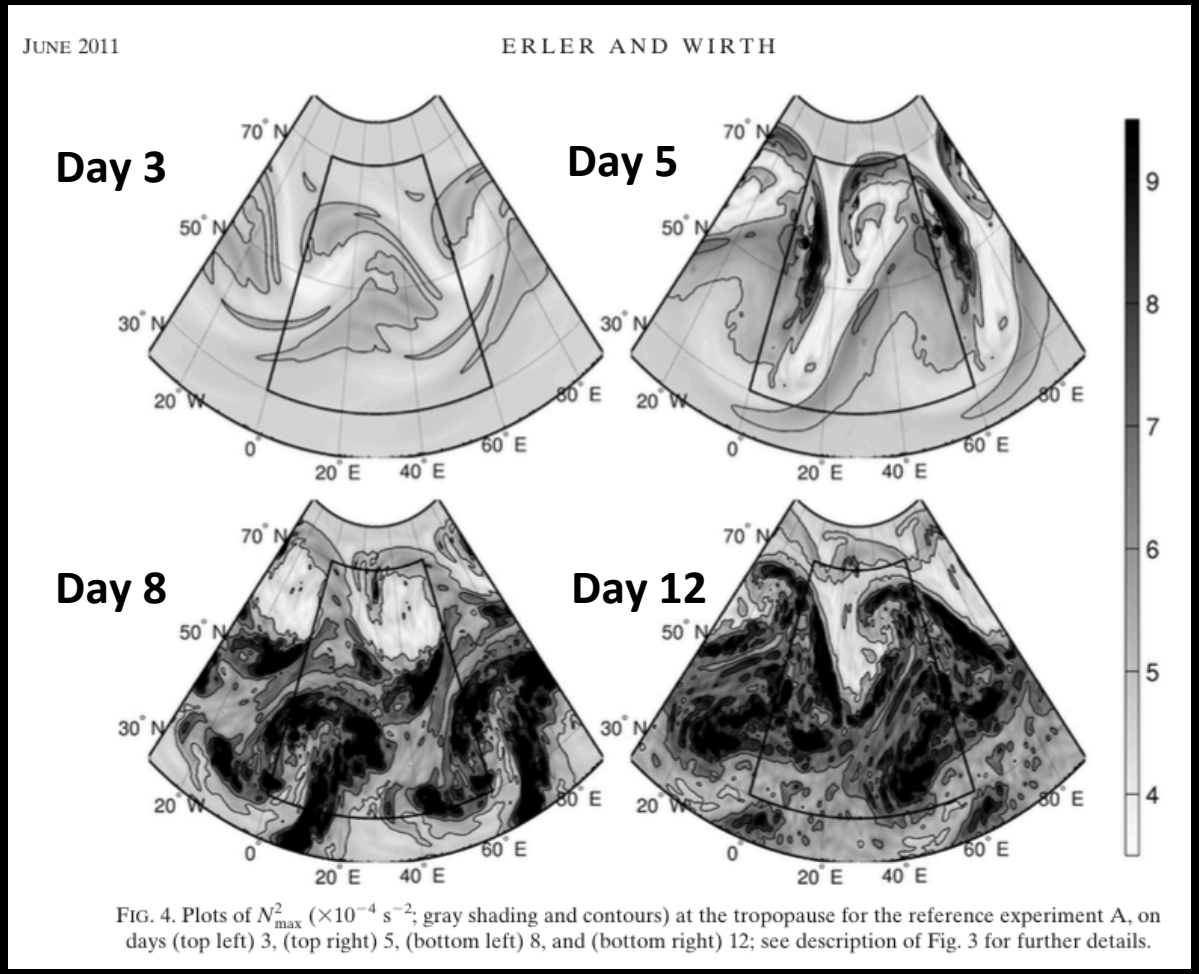


FIG. 4. Plots of N^2_{max} ($\times 10^{-4}$ s^{-2}; gray shading and contours) at the tropopause for the reference experiment A, on days (top left) 3, (top right) 5, (bottom left) 8, and (bottom right) 12; see description of Fig. 3 for further details.

A model simulation of a baroclinic life cycle, initialized with no TIL.

The TIL forms over anticyclonic anomalies.

Strong enhancements of near-tropopause static stability cover large parts of the domain

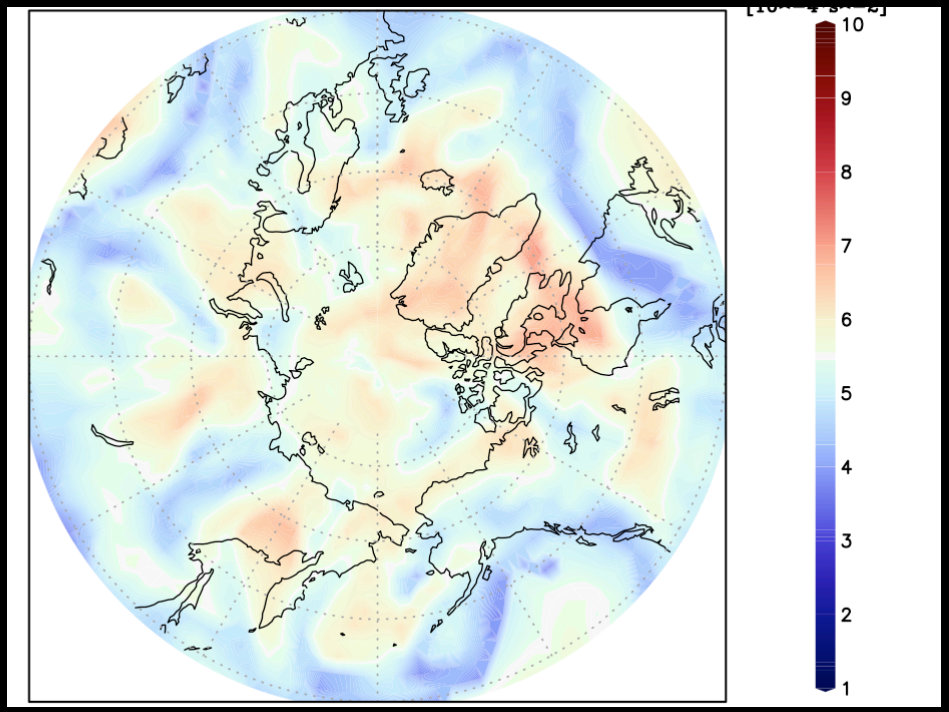
Shading: N^2 MAX (the TIL's strength)

Let's see if this is corroborated by the GEOS-5 analysis

Horizontal distribution of N^2 MAX – connection with dynamics

Colors: N^2 MAX.
Blue: weak TIL
Red: strong TIL

N^2 MAX from assimilation on 10 July 2010



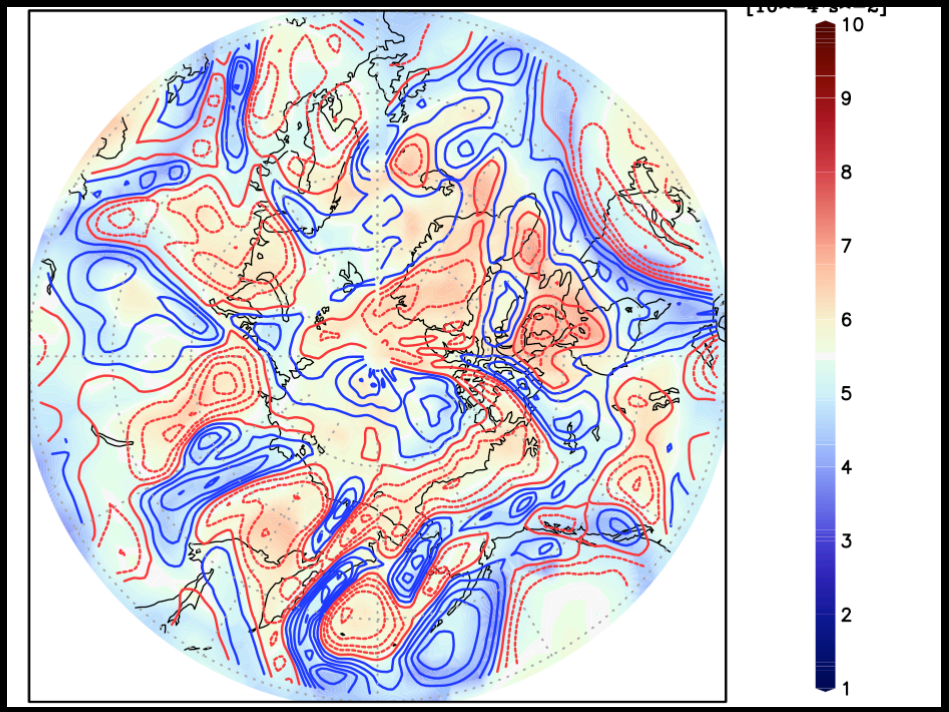
- The TIL exhibits rich synoptic-scale structure

Horizontal distribution of N^2 MAX – connection with dynamics

Colors: N^2 MAX.
Blue: weak TIL
Red: strong TIL

Contours: relative vorticity at 250 hPa
Blue: cyclonic
Red: anticyclonic

N^2 MAX from assimilation on 10 July 2010

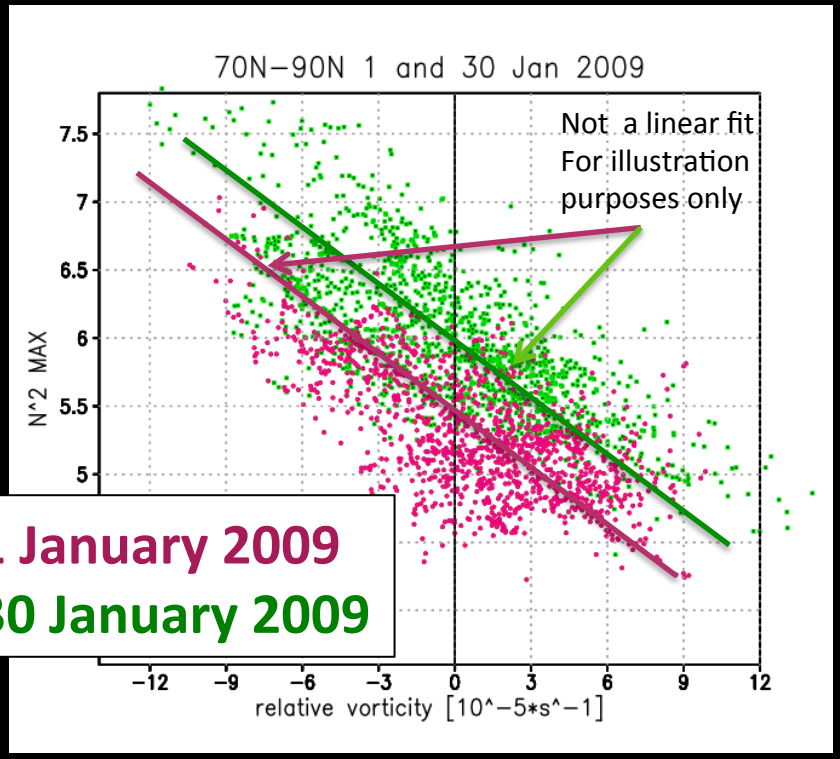


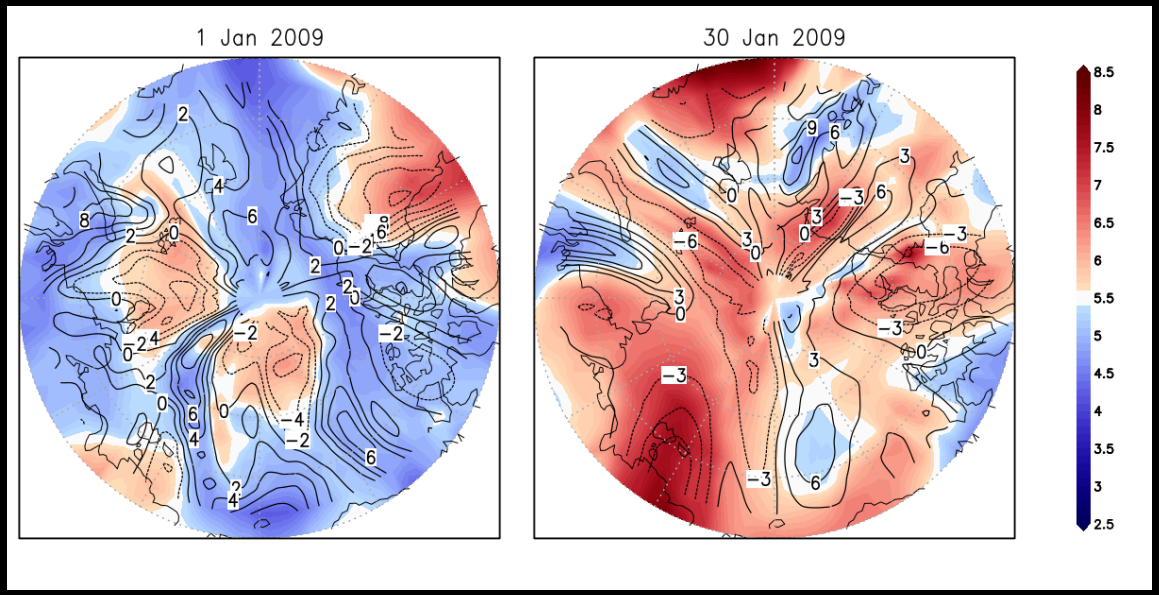
- The TIL exhibits rich synoptic-scale structure
- Cyclonic circulation – weak TIL; anti-cyclonic – sharp TIL, consistent with *Erdel and Wirth 2011* (a model simulation)
- Negative relative vorticity → N^2 MAX ,< 5.5 $10^{-4}s^{-2}$

TIL's strength and vorticity on two days in January 2009

Relative vorticity at the tropopause and N^2 MAX on two selected days.

- Anticorrelated as expected
- Overall shift in N^2 MAX between 1 and 30 January





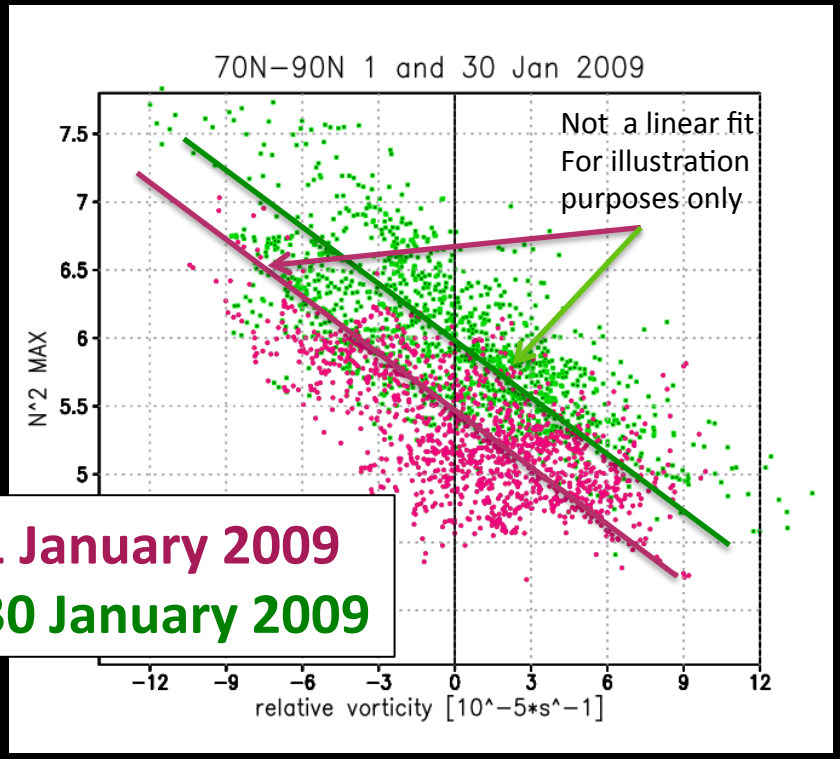
So… what happened between 1 and 30 January 2009?

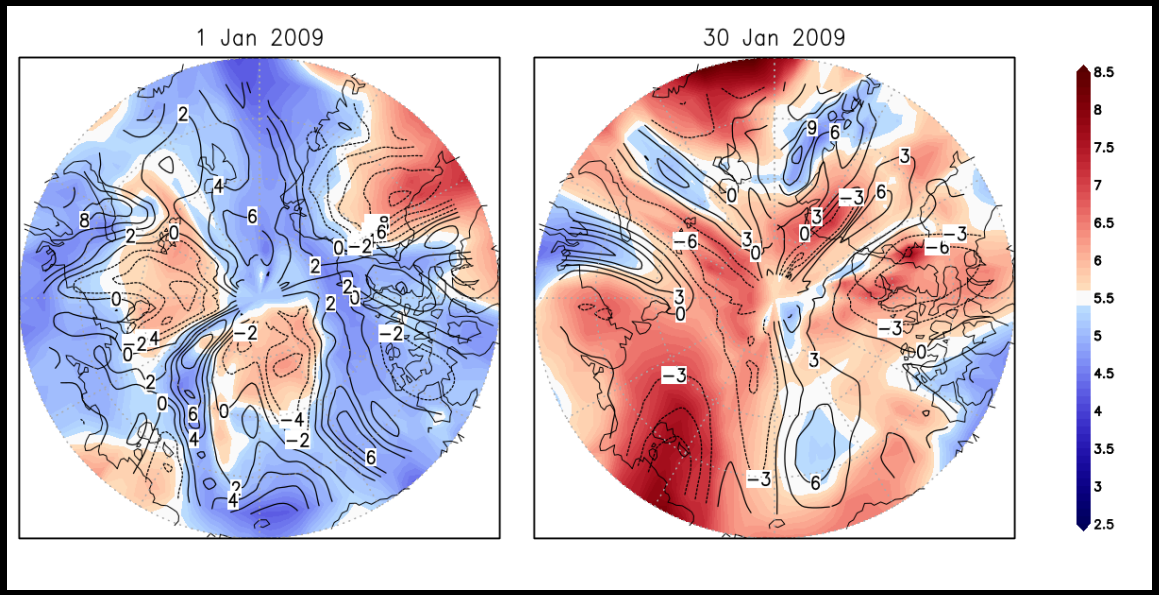
Colors: N^2 MAX, contours: relative vorticity at the tropopause

TIL's strength and vorticity on two days in January 2009

Relative vorticity at the tropopause and N^2 MAX on two selected days.

- Anticorrelated as expected
- Overall shift in N^2 MAX between 1 and 30 January





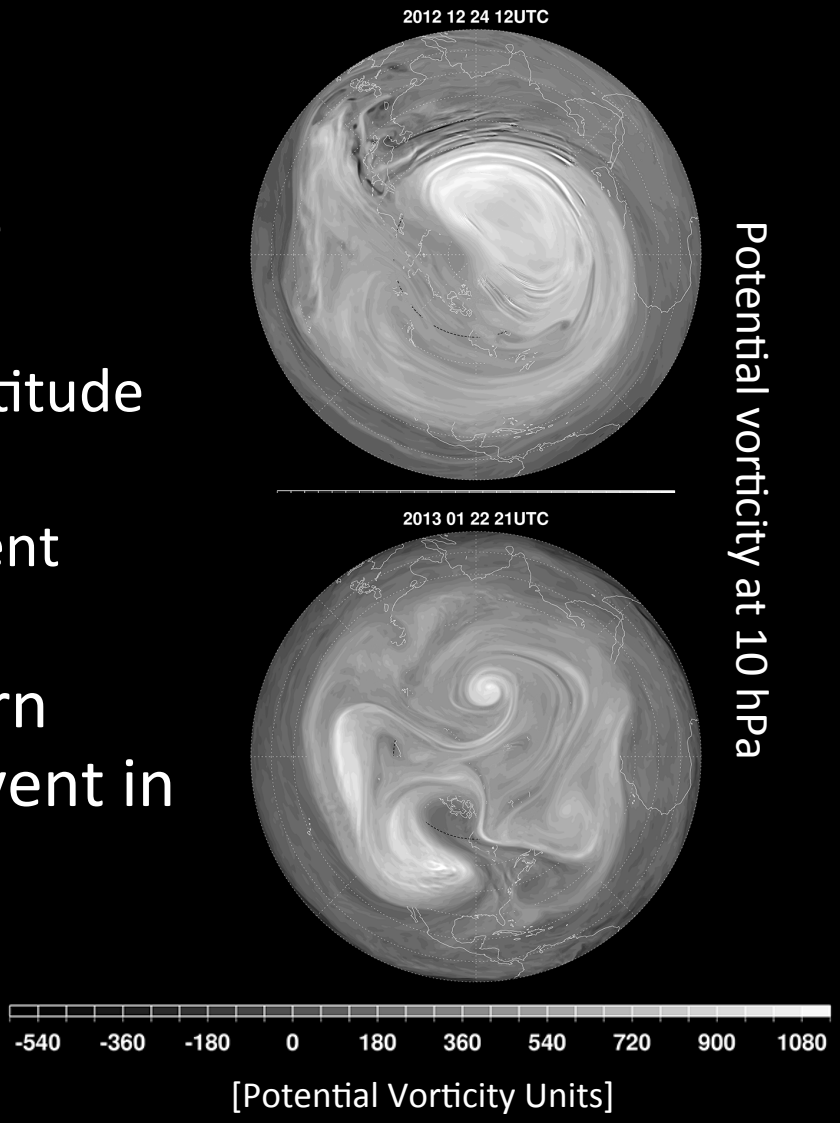
Colors: N^2 MAX, contours: relative vorticity at the tropopause

So… what happened between 1 and 30 January 2009?

A sudden stratospheric warming occurred!

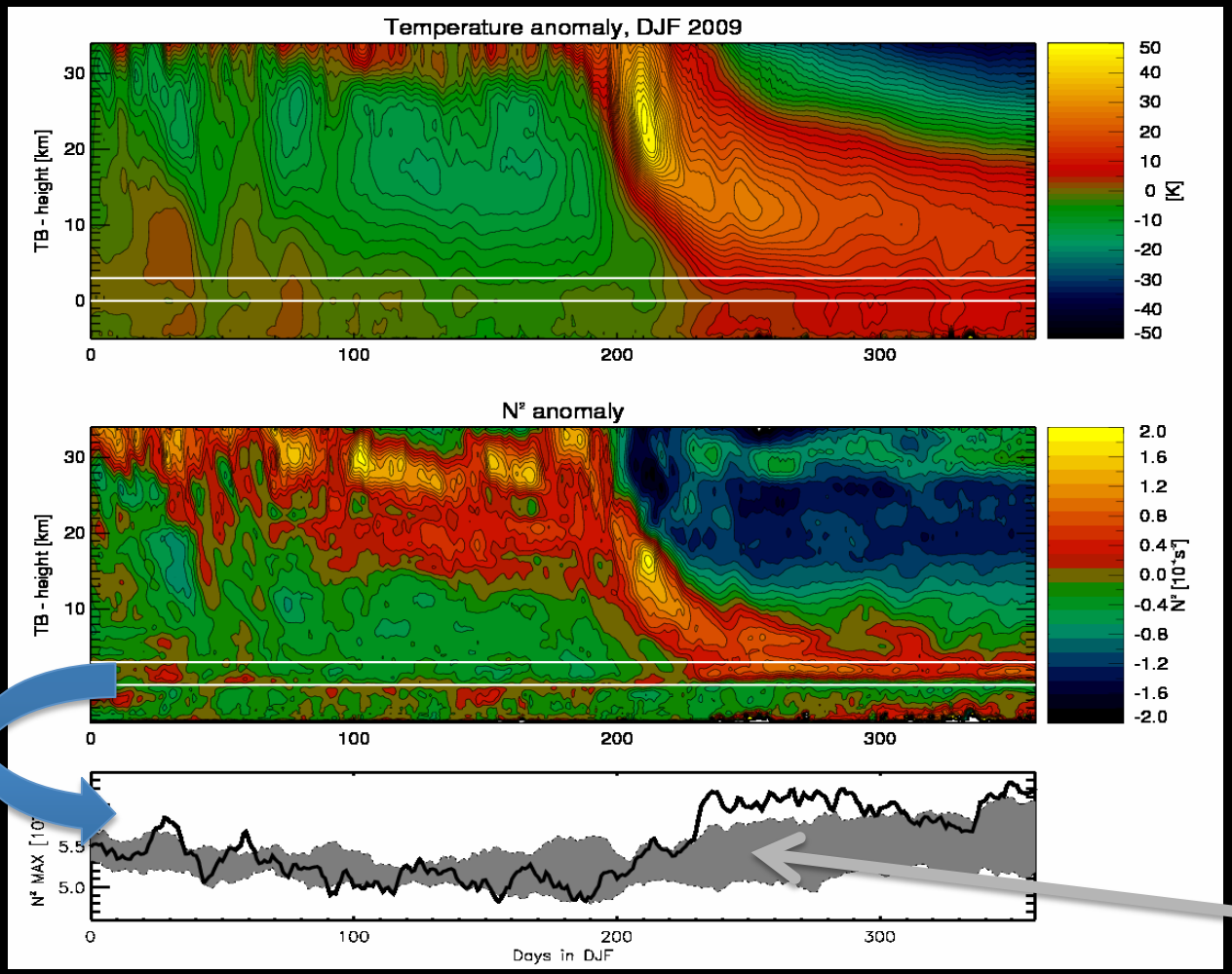
Sudden Stratospheric Warming Events

- Major sudden stratospheric warming (SSW): large-scale disturbance of the wintertime stratospheric polar vortex
  - Mean zonal wind at 60 deg. latitude reverses at 10 hPa
  - Horizontal temperature gradient becomes positive
- Every few years in the northern hemisphere. Only one such event in the SH on record (2002)



- **Do SSW events impact the TIL's strength?**
- **…and how?**

SSW 2009

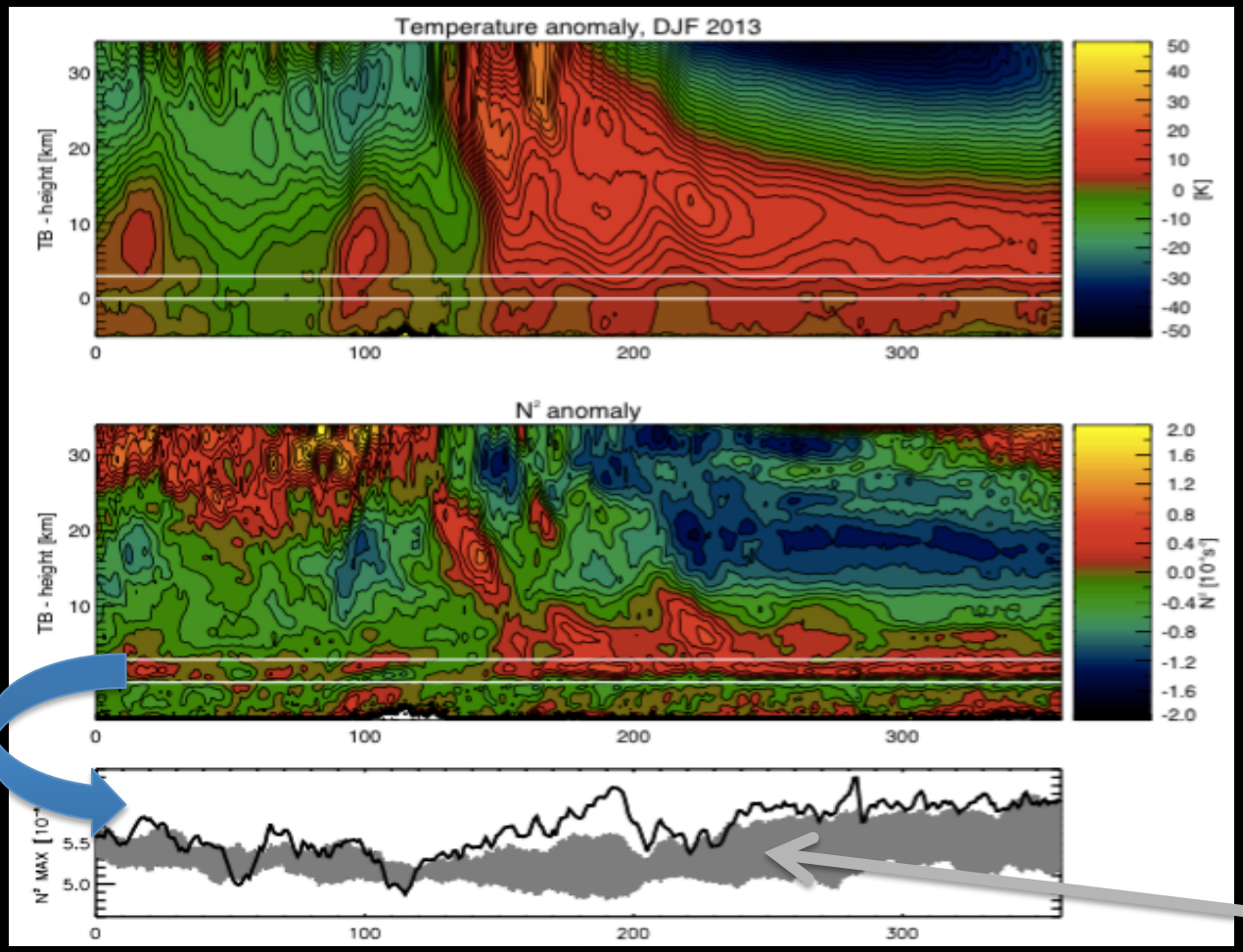


Evolution of high-latitude area-averaged temperature and static stability anomalies and the TIL's strength during the 2009 SSW.

1-σ envelope, 2006-2014

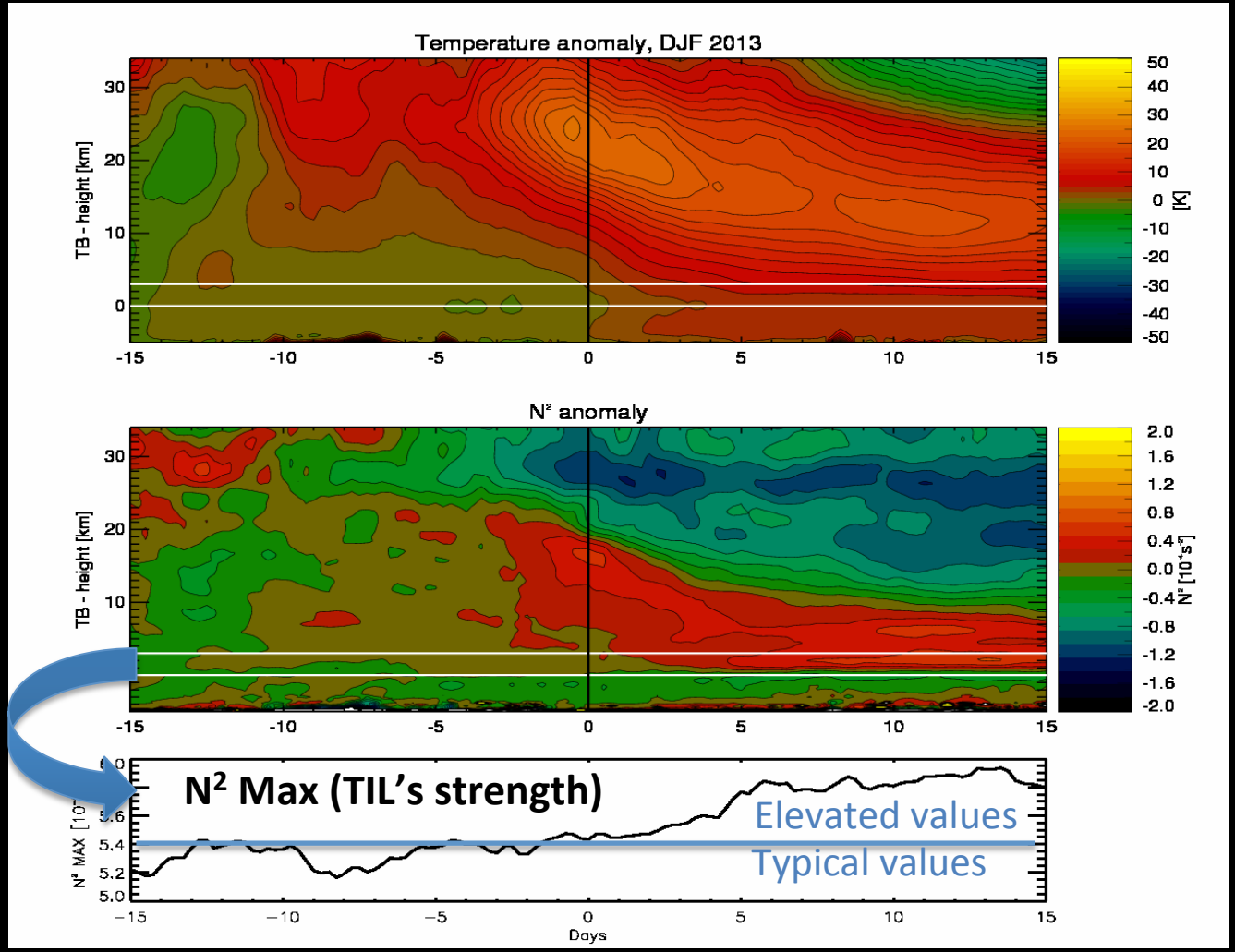
- Positive temperature anomaly develops in the upper stratosphere
- Static stability anomalies propagate downwards along the lower edge of the temperature anomaly leading to an increase of the TIL's strength

SSW 2013



Evolution of high-latitude area-averaged temperature and static stability anomalies and the TIL's strength during the 2013 SSW.

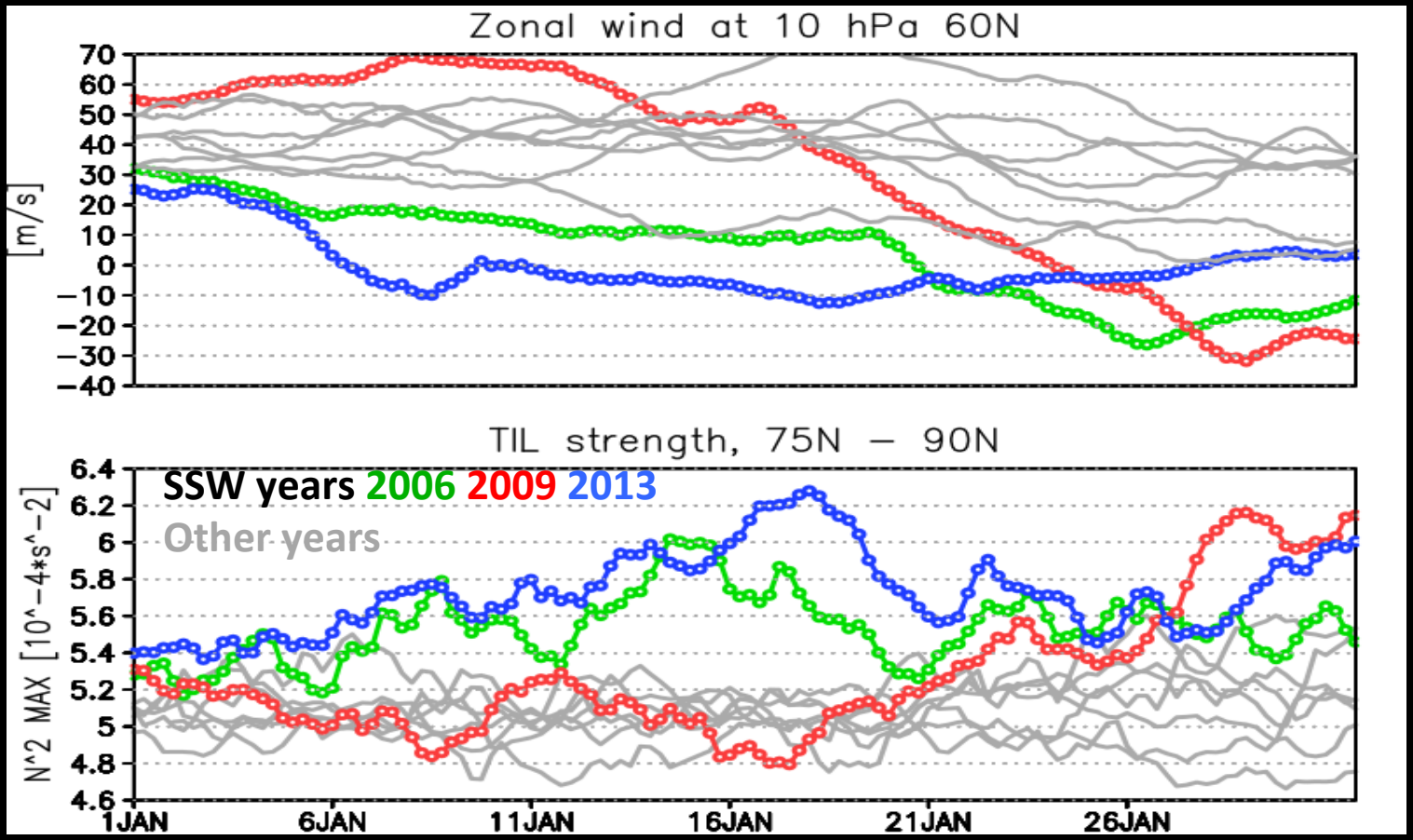
- Positive temperature anomaly develops in the upper stratosphere
- Static stability anomalies propagate downwards along the lower edge of the temperature anomaly leading to an increase of the TIL's strength



A composite of 4 SSW events: January 2006, 2009, 2013 and February 2010. Day zero: zonal wind reversal at 10 hPa 60°N

- Positive temperature anomaly develops in the upper stratosphere
- Static stability anomalies propagate downwards along the lower edge of the temperature anomaly leading to an increase of the TIL's strength

SSW – TIL connection



- Mean N^2 MAX in **high latitudes** stays below 5.4 [$10^{-4}s^{-2}$] in 'quiet' Januarys
- During the onset of an SSW static stability above the tropopause increases
- The 2006 and 2013 winters: gradually disturbed polar vortex throughout January. 2009: Rapid SSW in the end of the month

The connection was first noted by *Grise et al. 2010*

Summary

- GEOS-5 reproduces the tropopause inversion layer
  - Correct representation of the summer-winter contrast in the zonal mean
  - Assimilation agrees with independent data very well in January but the tropopause is too sharp in July
  - Assimilating hyperspectral radiance data and conventional observations is essential
  - Possibly, there is a process missing in the GCM
- Assimilation confirms model-based studies: upper level anticyclones are associated with enhanced TIL
- Stronger TIL in high latitudes during SSWs. Consistent with a previous study.

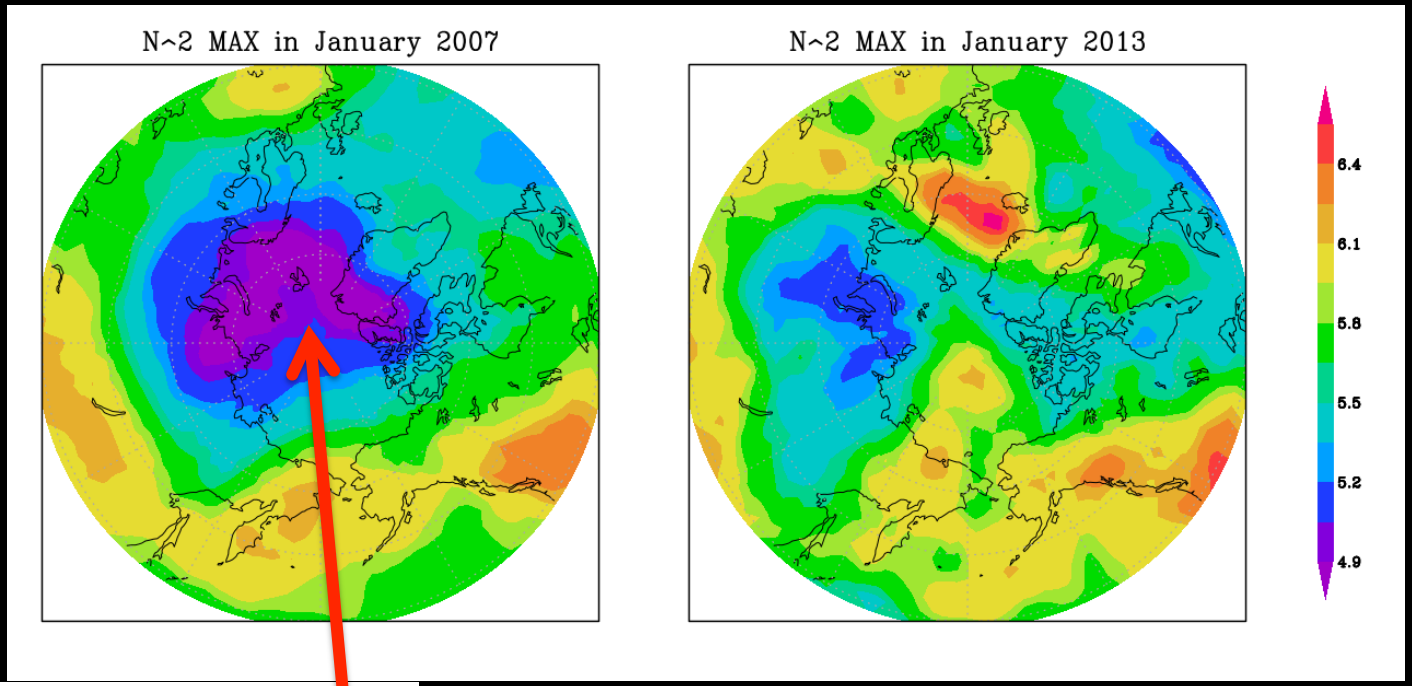
Conclusion

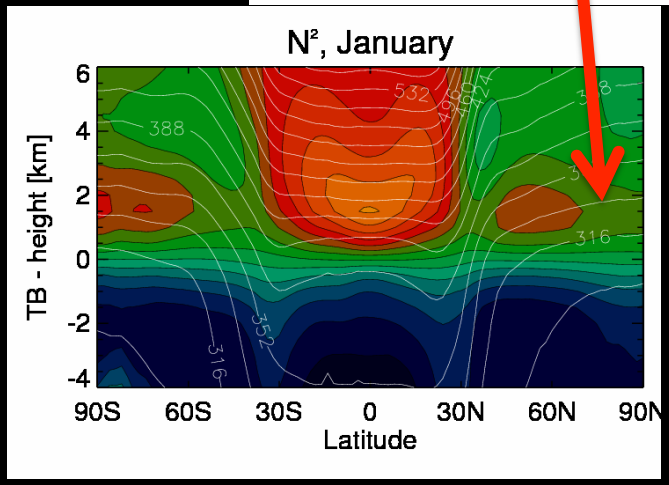
Modern data assimilation is a suitable tool to study the TIL. The MERRA-2 reanalysis (in production at GMAO) will provide a time series long enough to study the climatology of the TIL and its connections to dynamics and radiative heating in more detail.

BACKUP

SSW – TIL connection

2007: Strong vortex **2013: Weak vortex**





- 2007 - typical summer-winter contrast: The TIL is present in mid-latitudes but weak in high latitudes
- 2013 - Stronger TIL in high latitudes
- Nonuniform pattern