Strengthening of the tropopause inversion layer during the 2009 sudden stratospheric warming in the MERRA-2 analysis

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Outline

We use the MERRA-2 analysis and model simulations to study the behavior of the polar tropopause during the 2009 major sudden stratospheric warming (SSW)

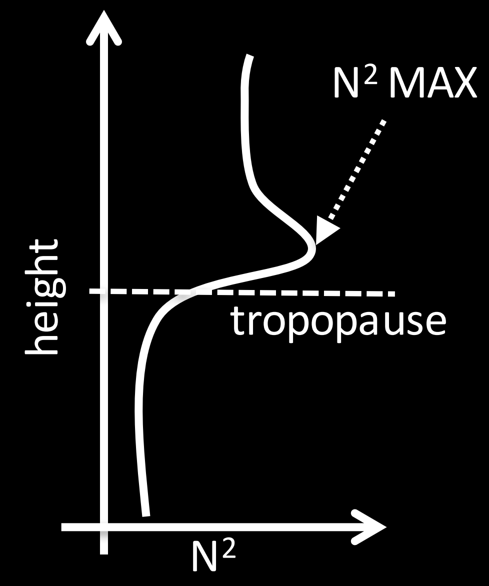
- Definitions/conventions
- The tropopause inversion layer during SSWs in MERRA-2
- The mechanisms involved – an analysis of model forecasts
- Summary

MERRA-2
(features most relevant to this study)

- Resolution: 0.635° by 0.5° longitude by latitude, 72 layers, ~1 km in the vertical near the tropopause
- Observations include hyperspectral IR radiances, GPS radio occultation, radiosondes and aircraft – capable of resolving vertical structures near the tropopause

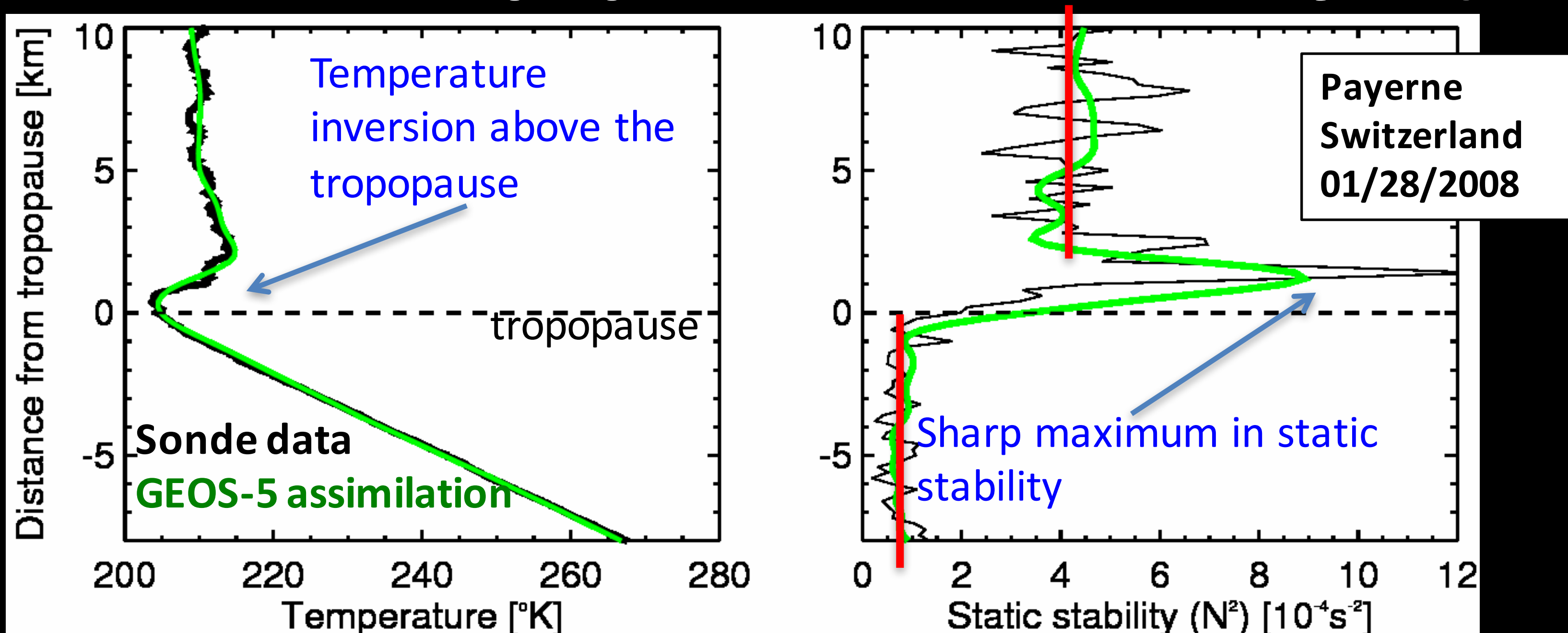
Definitions/conventions

- Tropopause – standard WMO definition
- 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



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

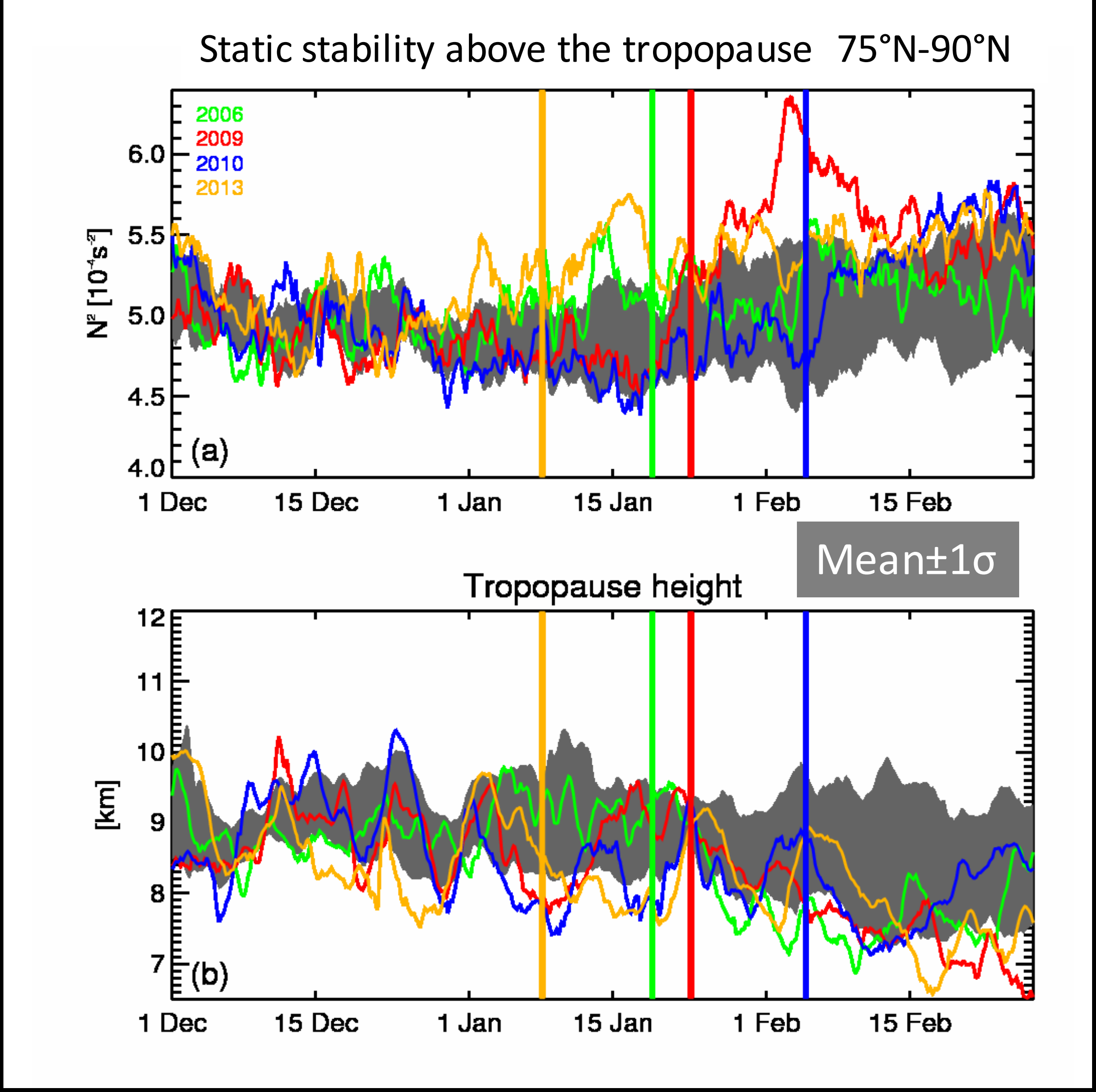
What is the Tropopause Inversion Layer (TIL)?



- 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

In the past, analyses produced weak TIL compared to models

Motivation: Behavior of static stability during sudden stratospheric warming events



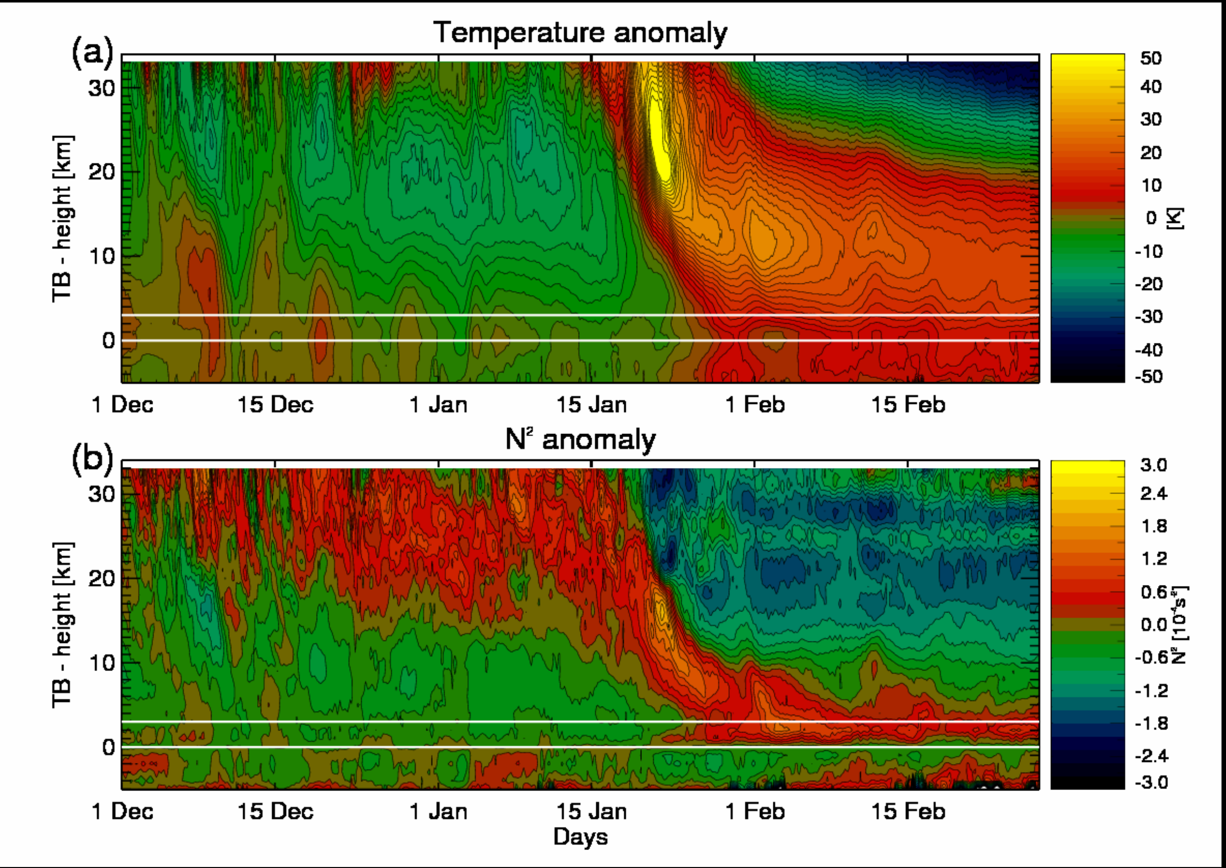
Data: MERRA-2 reanalysis

- Static stability above the high-latitude tropopause increases sharply following strong SSWs
- The tropopause height decreases
- Consistent with a result based on GPS-RO data (*Grise et al.* 2010)

The TIL gets stronger during SSWs. What is the mechanism?

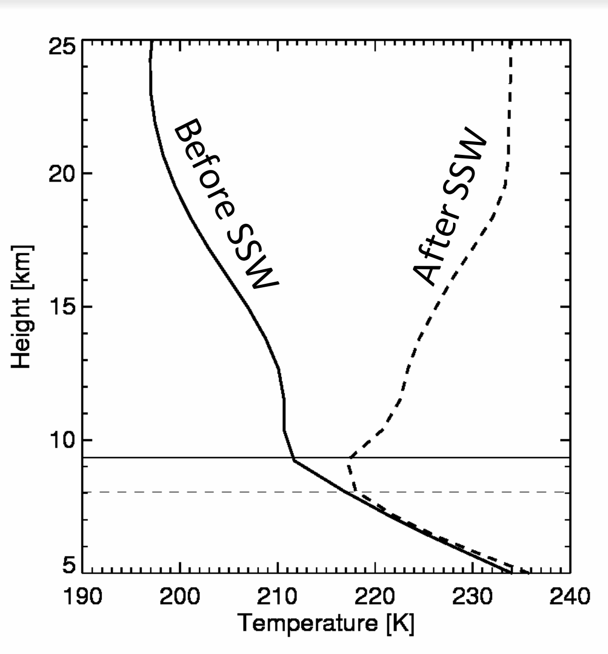
We investigate the 2009 case

High-latitude TIL gets stronger and the tropopause drops during the SSW



75°N-90°N average

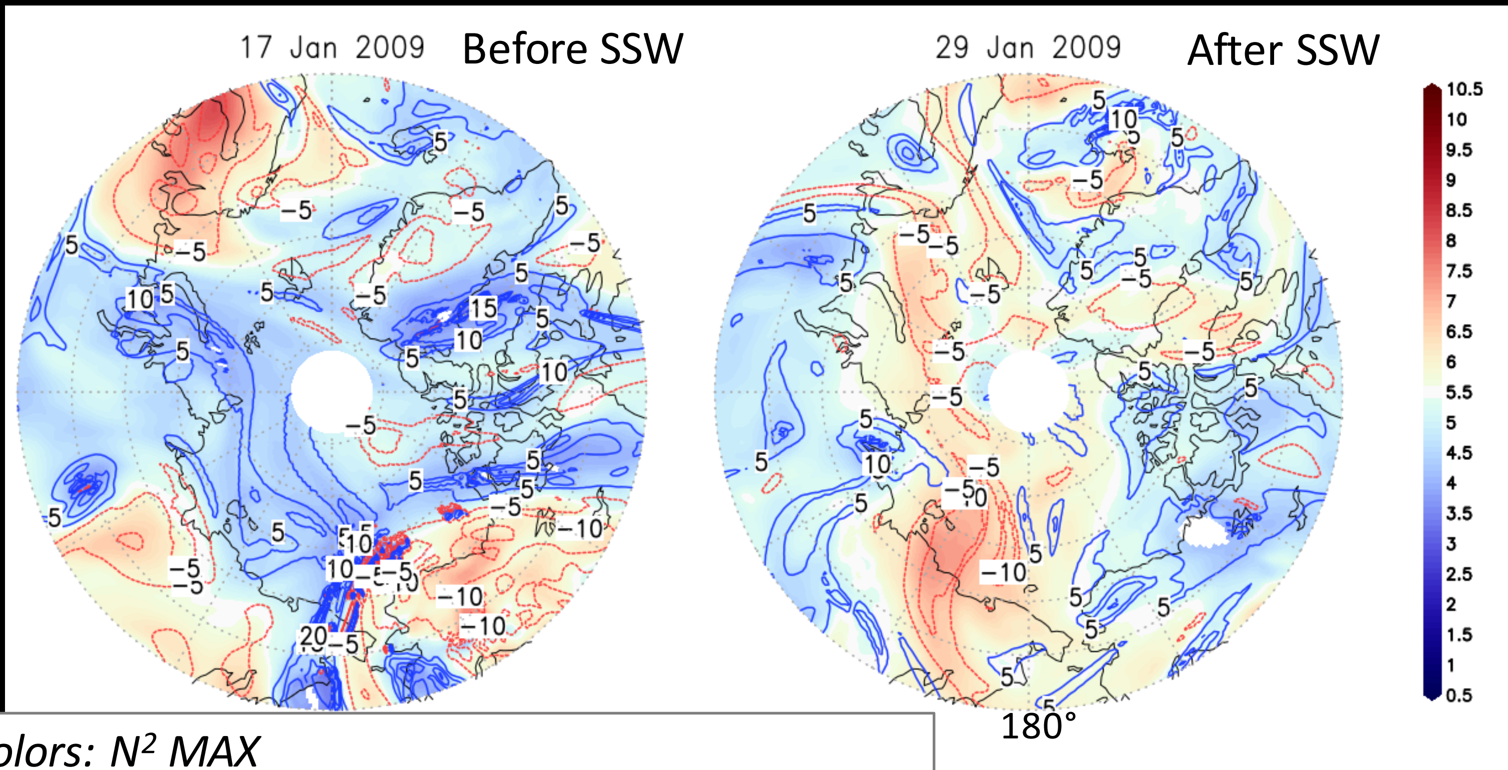
- Rapid downward propagating increase in temperature associated with the SSW
- Positive anomaly in static stability develops along the lower edge of the temperature anomaly



As the lower stratosphere gets warmer the lapse rate decreases → the tropopause moves downward.
Most of the apparent warming of the upper troposphere is the result of the decreased tropopause height

Static stability and circulation at the tropopause

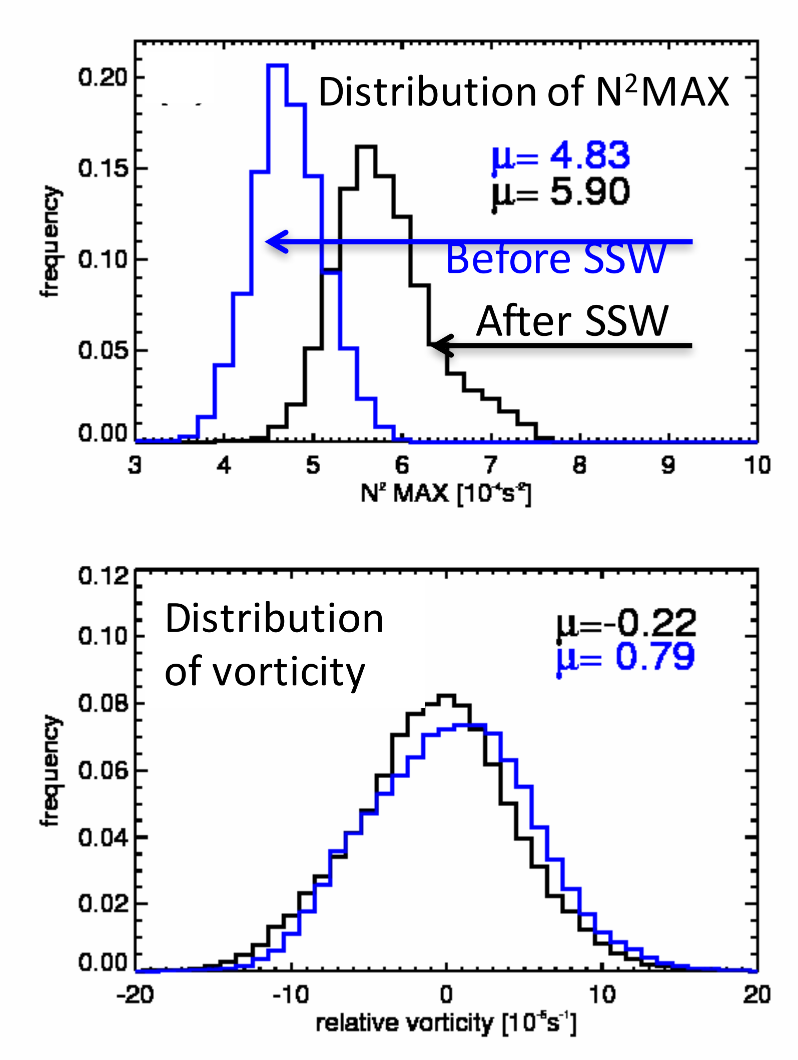
N^2 MAX and relative vorticity at the tropopause on 2 days

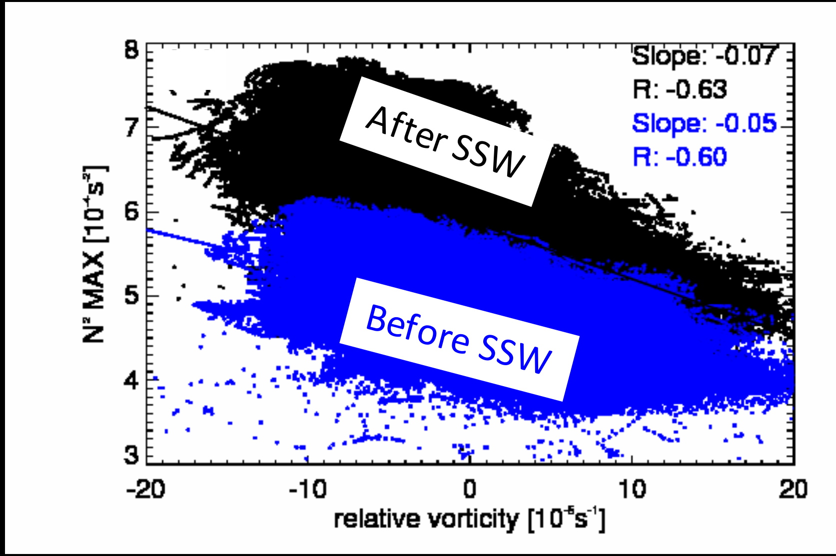


Colors: N^2 MAX
Contours: relative vorticity cyclonic anticyclonic

- Areas of high/low *N^2 MAX* coincide with anticyclonic/cyclonic circulation at the tropopause. This is consistent with previous studies
- Again, higher *N^2 MAX* in high latitudes after the onset of the SSW

How much of the static stability increase is due to anticyclonic wave breaking (more negative relative vorticity)?





75°N-86°N between 1-15 January 2009 (blue) and 28 January - 11 February (black)

A back-of-the-envelope calculation

[average slope]×Δ[vorticity]=-0.06×1.01= =-0.0606 ≈ 6 % of $\Delta N^2 MAX$

At most 6 % of the stability increase is attributed to the decreased vorticity.

Another mechanism is dominant

The budget equation

Vertical component of the residual circulation

Diabatic heating rate

$$\partial_t \overline{N}^2_{MAX} \approx \underbrace{-\overline{N}^2_{MAX}\partial_z \overline{w^*}|_{MAX}}_{\text{Convergence term}} + g\partial_z(\overline{\theta}^{-1}Q)|_{MAX}$$

Birner 2010

The budget equation

$$\partial_t \overline{N}^2_{MAX} \approx \underbrace{-\overline{N}^2_{MAX}\partial_z \overbrace{\overline{w^*}}^{\text{Vertical component of the residual circulation}}|_{MAX}}_{\text{Convergence term}} + \underbrace{\cancel{g\partial_z(\overline{\theta}^{-1}\overbrace{Q}^{\text{Diabatic heating rate}})|_{MAX}}}_{\text{Small}}$$

Birner 2010

The budget equation

Vertical component of the residual circulation

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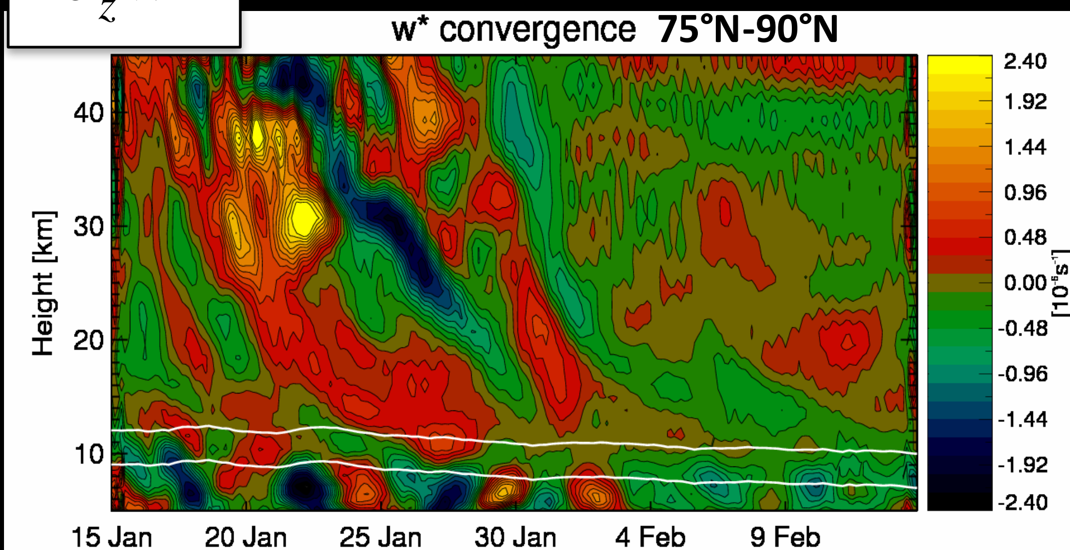
Birner 2010

$$-\partial_z \overline{w^*}$$



<u>SSW : downward propagation of</u>

⇕

disturbance of the vortex

⇕

acceleration of downward motion (w*)

⇕

Convergence of w*

Hypothesis: the main driver of the increase in static stability (TIL strengthening) during the SSW is the enhanced vertical convergence of the downward residual circulation

$$\partial_t \overline{N}^2_{MAX} \approx -\overline{N}^2_{MAX} \partial_z \overline{w}^* |_{MAX}$$

But in MERRA-2 (or any other analysis), by construction

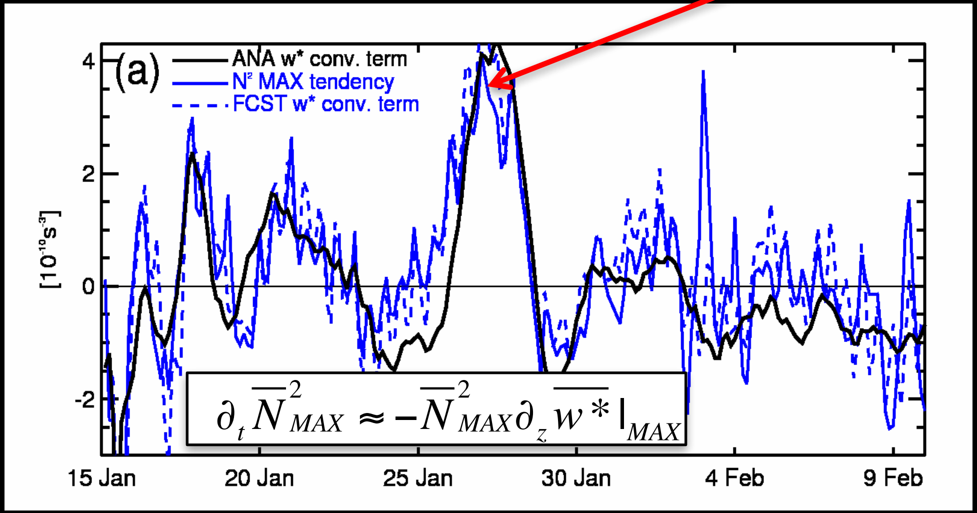
Tendency = tendency due to model physics + tendency due to data insertion

We can't expect the budget to close **in the analysis** because the left-hand side contains the (unphysical) analysis correction term ('the analysis increment')

Instead, we use an ensemble of forecasts to evaluate the budget:
23 10-day forecasts initialized from MERRA-2 between 14 January and 4 February 2009

Computing the N^2 MAX budget

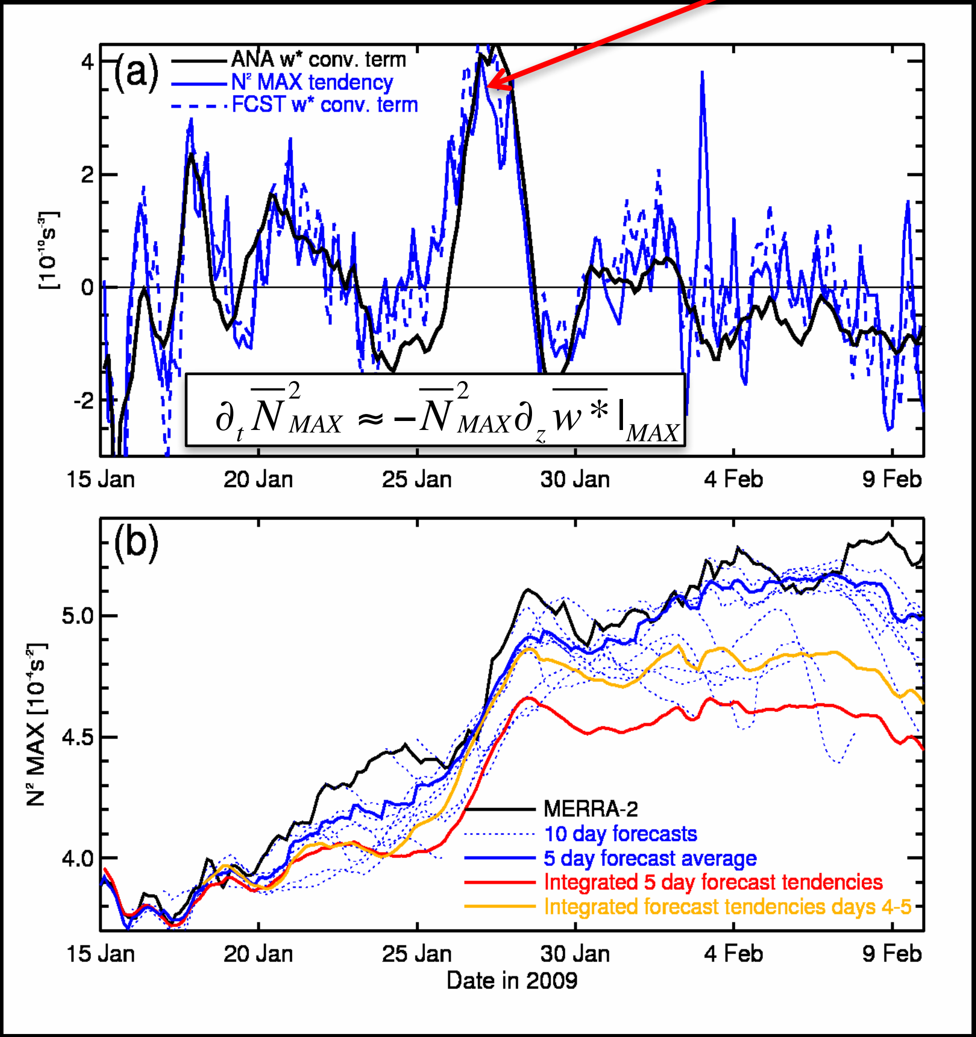
The TIL's rapid strengthening



- The budget closes: Most of the TIL strengthening in the model is explained by enhanced vertical convergence of the vertical residual velocity (ensemble mean)
- The convergence in the MERRA-2 analysis agrees with that in the model

Computing the N^2 MAX budget

The TIL's rapid strengthening



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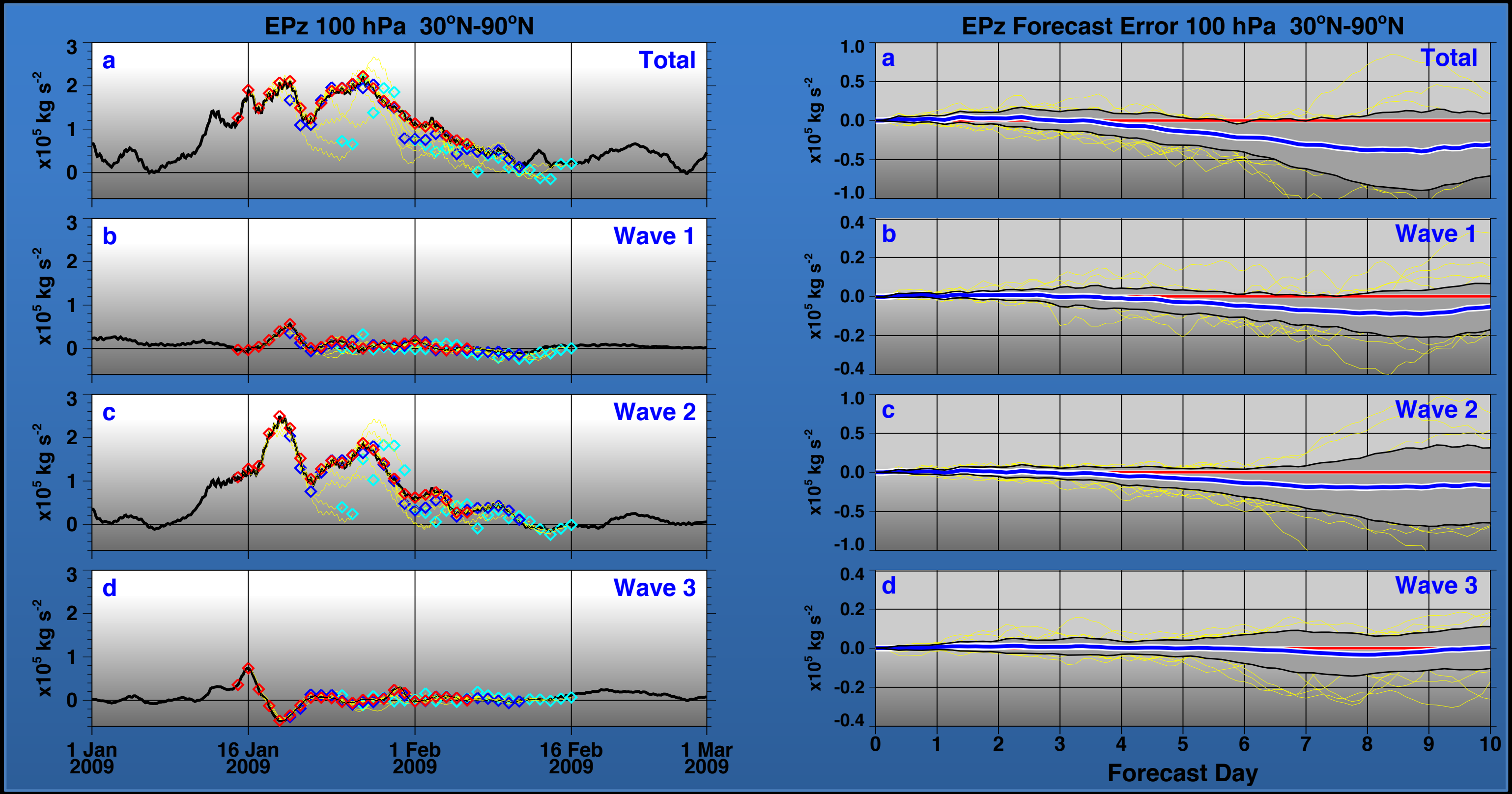
- The convergence in the MERRA-2 analysis agrees with that in the model

Model simulations underestimate the strengthening of the TIL compared to MERRA-2: the model tendencies are biased low.

Why does the model underestimate the static stability increase?

SSWs are forced by planetary wave pulses from the troposphere



100 hPa vertical EP flux from MERRA-2, 5-day, 10-day forecasts

Forecast error with respect to analysis

- In 2009 the forcing is dominated by wave 2 (*Harada et al., 2009*)
- There is a tendency for the forecasts to underestimate the wave forcing
- Overall, 5-day forecasts agree with the analysis but there is some underestimation near the wave 2 maximum

Summary of the results

- MERRA-2 shows strengthening of the polar tropopause inversion layer during major SSW events in agreement with previous studies
- Model simulations reveal that the primary mechanism (in 2009) involves an enhanced convergence of the vertical residual wind at the tropopause
- The model underestimates the TIL's strengthening and wave forcing

Final remarks

- DA is useful for studies of dynamical coupling in the stratosphere but one has to keep in mind that model tendencies ≠ analysis tendencies: be careful with budget calculations!
- Older data assimilation systems underestimated the TIL compared to models. Now the model produces a weaker TIL
- GMAO plans to double the model vertical resolution in near future. How will the results change? (The optimal vertical-to-horizontal resolution ratio is ~300 m/degree *Erler and Wirth 2007*)