Lower stratospheric aerosol and temperature trends: How well do we understand the Pinatubo period?

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Motivation I: Volcanoes and geoengineering

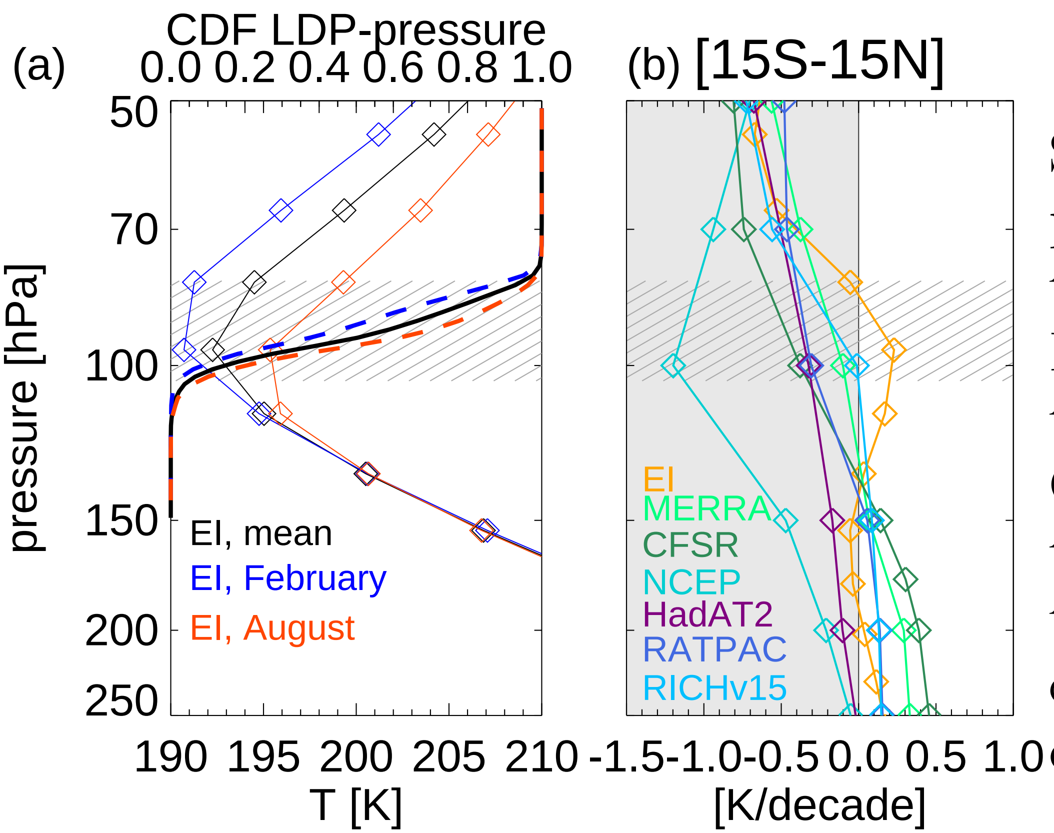
2 major volcanic eruptions during 'satellite era', **El Chichon** (1982) and **Pinatubo** (1991).

Pinatubo is the best observed analogue to 'geo-engineering' with stratospheric aerosol.

$\longrightarrow$ Do models capture the changes in the Pinatubo period?

Eruption of Mt Pinatubo, June 1991.

Motivation II: Interpretation of the observational record

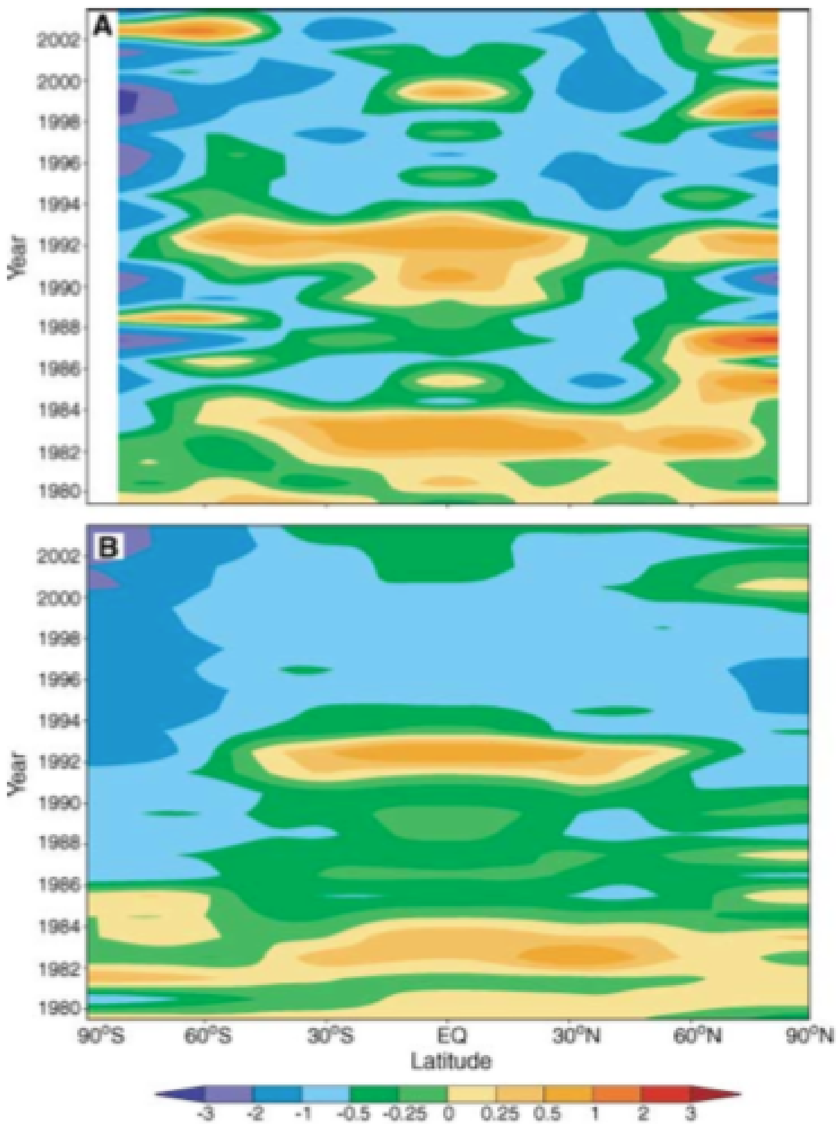


Since 1980's observations of temperatures and tracers allows better constraining 'climate change'. In stratosphere, radiatively active tracers other than CO_2 and CH_4 (such as ozone, aerosol, and to lesser degree H_2O) are important. Unfortunately, the tracer observations also have large uncertainties.

(a) Tropical temperature profiles (annual mean, February, August).
(b) Tropical temperature trends 1980-2009 from range of datasets.

(Fueglistaler et al. 2013).

Modeling results



Ramaswamy et al. 2006 (Science).

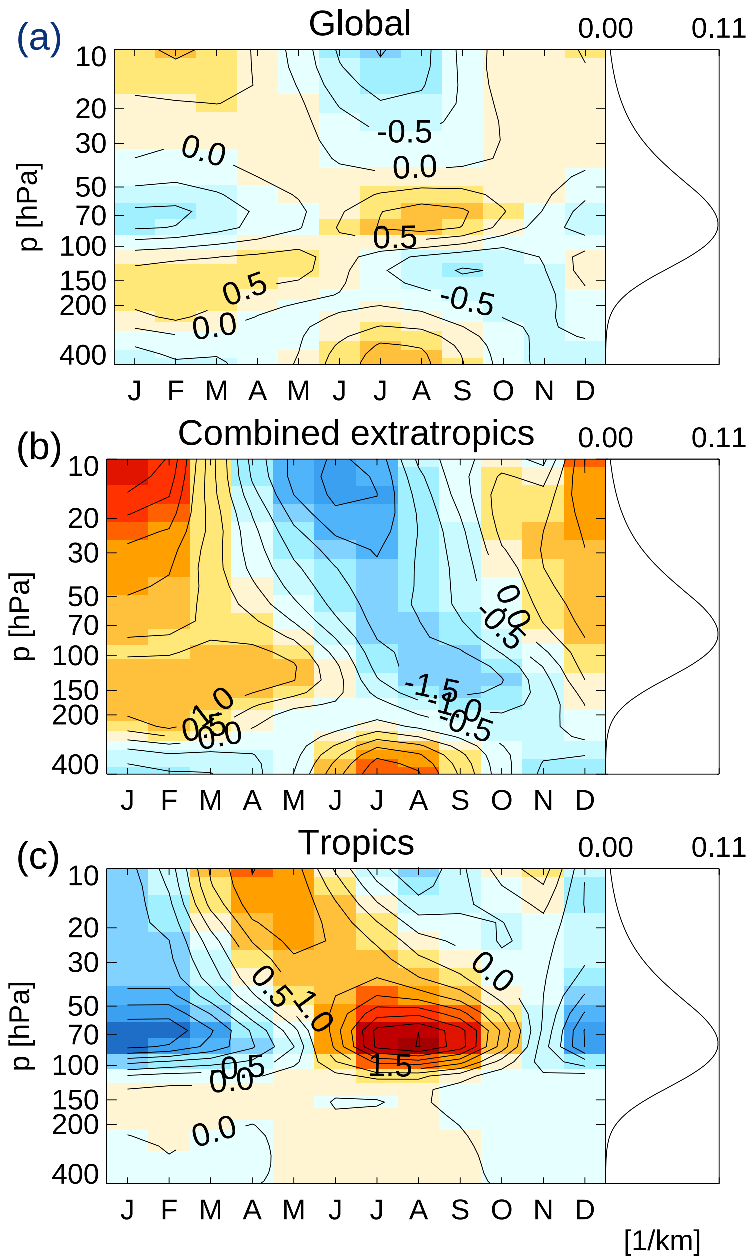
Modelled and observed temperature anomalies in the lower stratosphere ('MSU-4').

→ Overall reasonable agreement.

→ End of talk?

MSU-4 broad averaging kernel that tends to obscure important aspects.

Problematic aspects of MSU-4 weighting

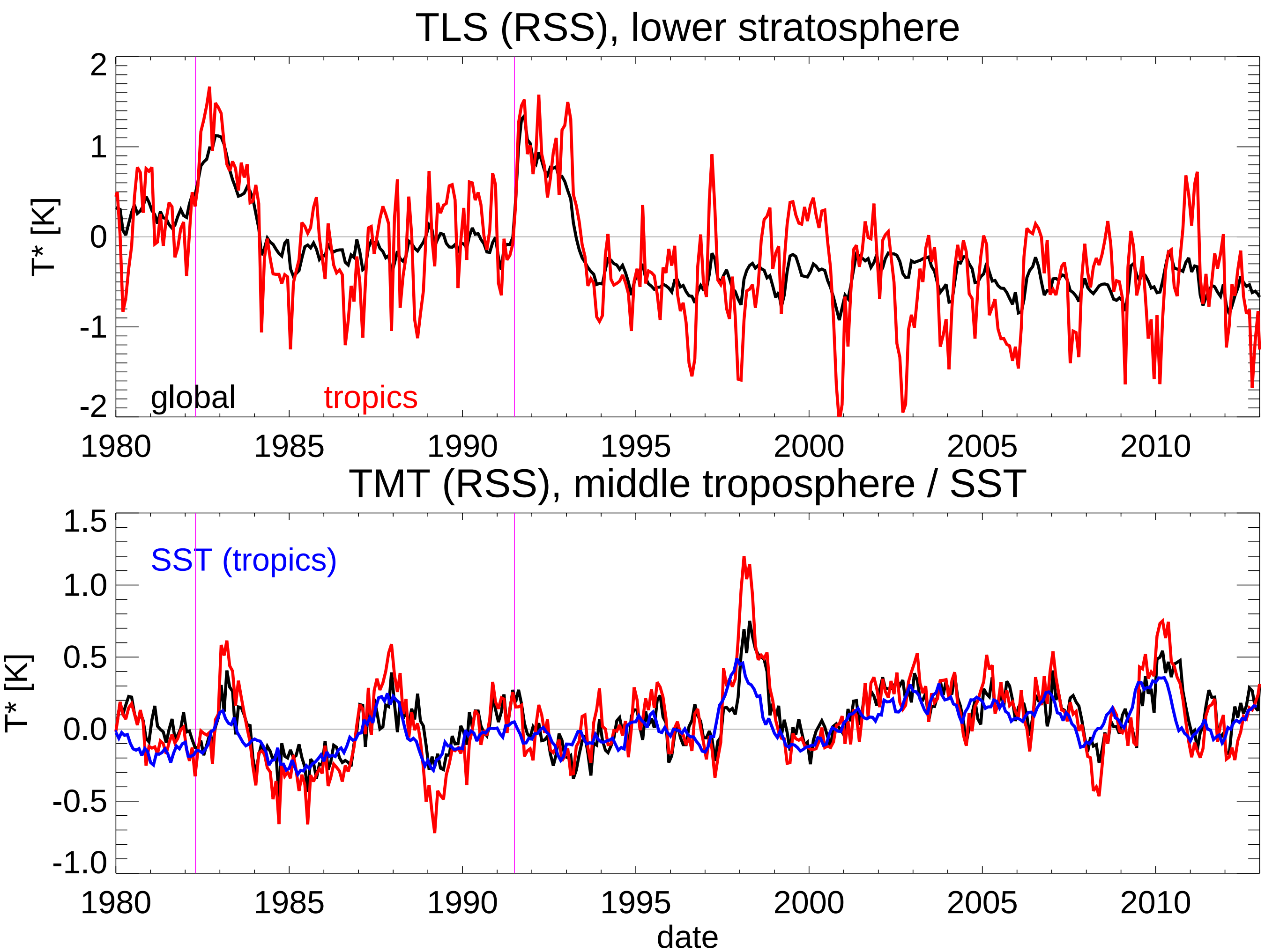


Temperature signal in tropics to many forcings see-saw between upper troposphere - lower stratosphere.
For analyses of tracer (incl. aerosol) / radiation /dynamics interactions, the channel is not ideal (reducing model resolution for comparison of course ok).

Left: Mean annual cycle of temperatures, (a) global average, (b) combined extratropics, (c) tropics. The MSU-4 weighting function shown right of panels.

[Fueglistaler et al. 2011].

Observed temperatures - role of volcanoes



MSU temperatures in tropics and global, and tropical SST. **2 forcings:** Albedo increase (tropospheric cooling), and increased absorption in stratosphere (stratospheric warming).

Radiative forcing of temperature and circulation

Quasi-geostrophic, TEM, thermodynamic energy equation with diabatic heating term approximated by Newtonian cooling,

$$\frac{T_{\mathrm{E}} - T}{\tau_{\mathrm{rad}}} = (N^2 H/R) \cdot w^* + \frac{\partial T}{\partial t} \tag{1}$$

τ_{rad} is the radiative relaxation time scale, T_{E} is the radiative equilibrium temperature, N^2 is the buoyancy frequency, H is the scale height, R is the gas constant, w^* is the diabatic residual velocity, T is temperature, and t is time, and all quantities are zonal means.

Consider $Q \equiv (T_{\mathrm{E}} - T)/\tau_{\mathrm{rad}}$, $Q = Q^{\mathrm{gas}} + Q^{\mathrm{aerosol}}$.

$$\frac{(T_{\mathrm{E}}^{\mathrm{gas}} - T)}{\tau_{\mathrm{rad}}} + Q^{\mathrm{aerosol}} = (N^2 H/R) \cdot w^* + \frac{\partial T}{\partial t} \tag{2}$$

Dynamics: system is forced by w^*, response to perturbation Q^{aerosol}?

(Note that radiative forcing can be seen as a change in equilibrium temperature: $\delta T_{\mathrm{E}}^{\mathrm{aerosol}} \equiv Q^{\mathrm{aerosol}} \cdot \tau_{\mathrm{rad}}$.)

Radiative forcing of temperature and circulation

How will the system respond? Rearrange eqn.:

$$\frac{\partial T}{\partial t} + \frac{T}{\tau} = \frac{T_{\mathrm{E}}^{\mathrm{gas}}}{\tau} + Q^{\mathrm{aerosol}} - K \cdot w^* \tag{3}$$

- Dynamical forcing w^*, $T_{\mathrm{E}}^{\mathrm{gas}}$ =const, $\longrightarrow T$ (initially $\frac{\partial T}{\partial t}$)
  Note: Tracers may respond to w^*, in which case $T_{\mathrm{E}}^{\mathrm{gas}}$ is not constant (e.g. ozone amplification discussed before).

- Radiative forcing Q^{aerosol}, $T_{\mathrm{E}}^{\mathrm{gas}}$ =const,
  $\longrightarrow T$, or
  $\longrightarrow w^*$

- In steady state, Q^{aerosol} does not directly force a circulation, but impact on T may change dynamics $\rightarrow w^*$ can change.

If w^* $\sim$constant, T will increase $\rightarrow$ **warming**.
If ΔT changes dynamics (think $T \leftrightarrow u$, wave propagation), w^* may change substantially $\rightarrow$ difficult to predict ΔT.
In tropical average, dyn. feedback probably does not overcompensate temperature forcing from Q^{aerosol}, $\rightarrow$ **expect a warming.**

Modeling

A numerical model is required to solve the problem, but:

Computers may **explode** -

but **GCM's don't do volcanoes** on their own.
⟶ Must prescribe volcanoes.

Modeling

Possibilities:

(i) Inject S → need detailed aerosol model.

(ii) Prescribe aerosol, from:
- observations
- other model run

(iii) Prescribe aerosol radiative heating Q^{aerosol} based on offline radiative calculation based on aerosol (see ii).

Different models/groups use different approaches, → difficult to compare results.

For comparison with 'real' volcanoes, it is probably best to use aerosol estimates from observations - avoids errors in aerosol model, but still affected by observational uncertainties. (Extinction measurements at some wavelengths, not Q^{aerosol}.)

Data and methods

- Observations: MSU, (homogenised) radiosonde temperatures, tracers, reanalyses.
- CCMVal2 runs: temperature, eddy heat fluxes (100hPa).
- Aerosol heating Q^{aerosol}.:
  - Stenchikov/SPARC CCMVal aerosol heating rates Q^{aerosol}.
  - SOCOL run with new aerosol dataset (Arfeuille et al., ETHZ-4L), temperatures, eddy heat fluxes, total radiative heating and aerosol radiative heating Q^{aerosol}.
- From Q to T: Newtonian cooling approximation, Fixed dynamical heating calculations

Model failure I: Temperature response

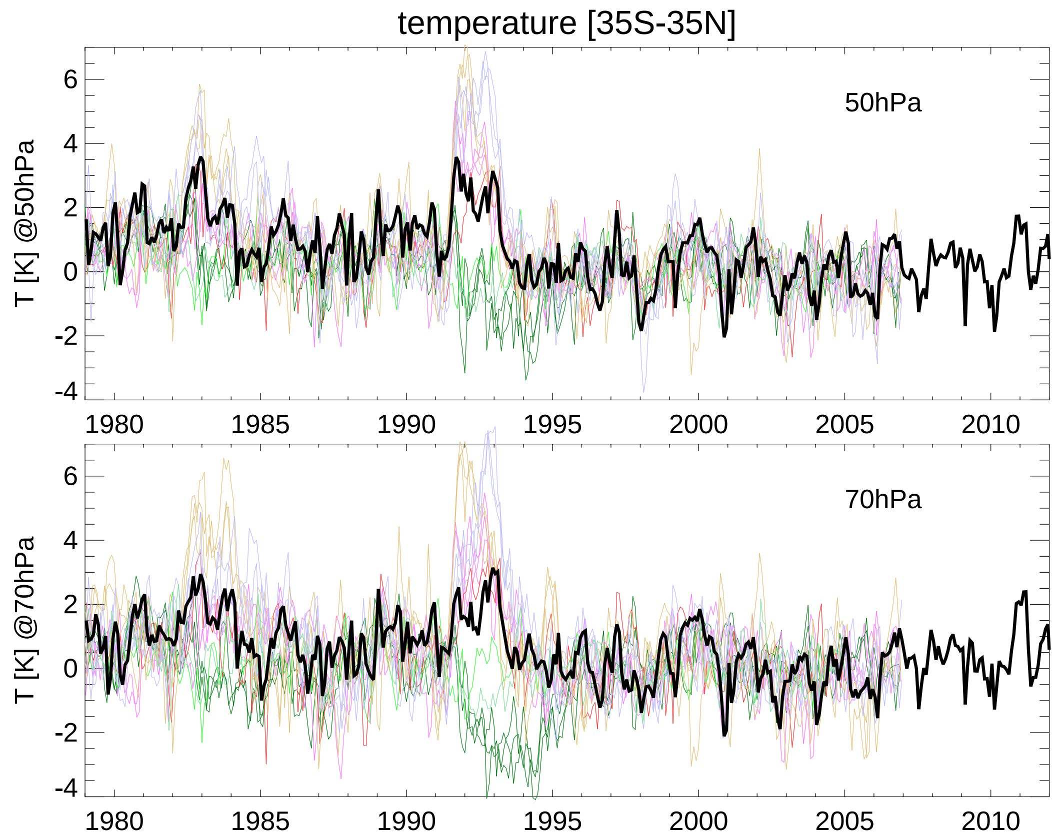
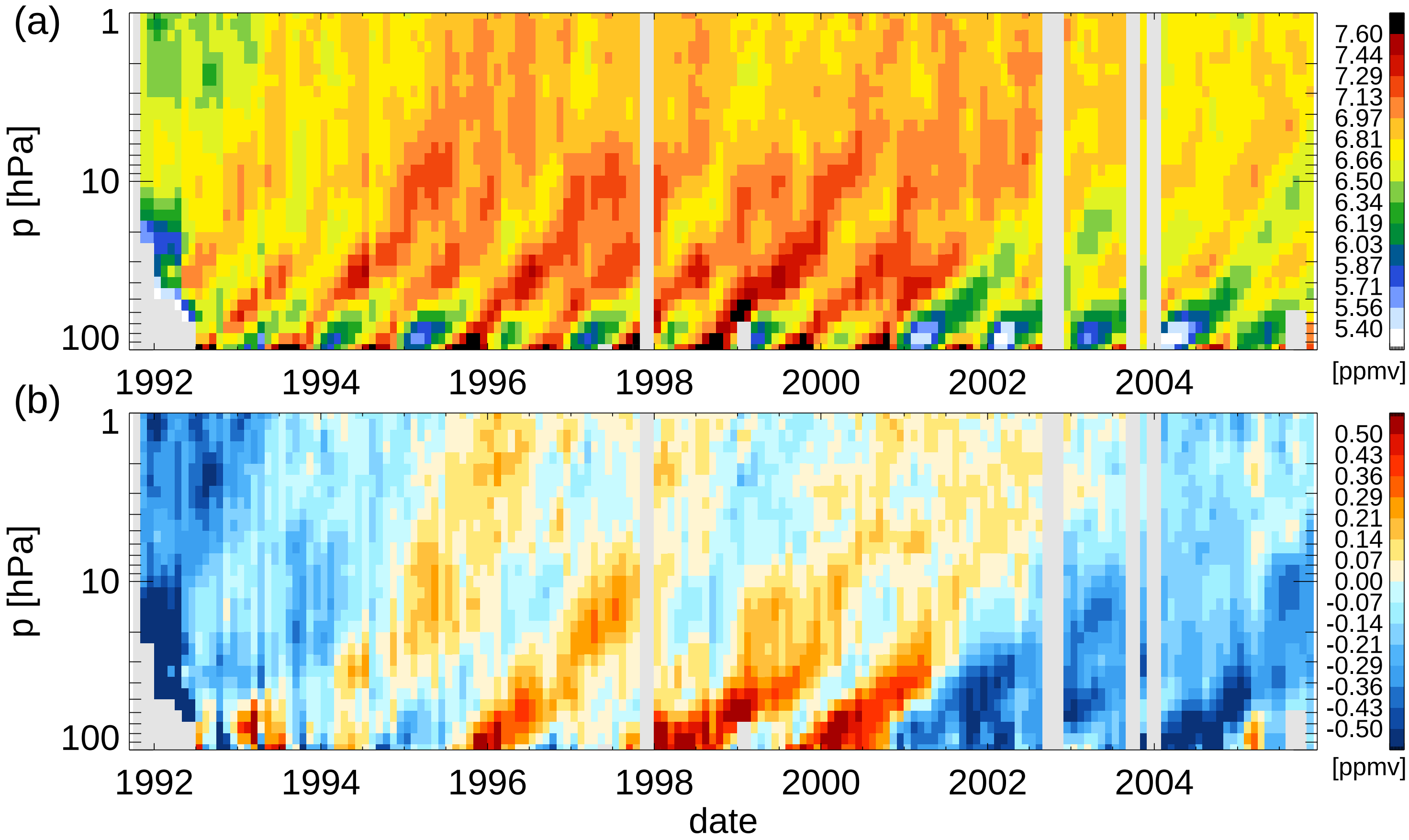


Figure: CCMVal2 (colors) and ERA-Interim temperature anomalies.

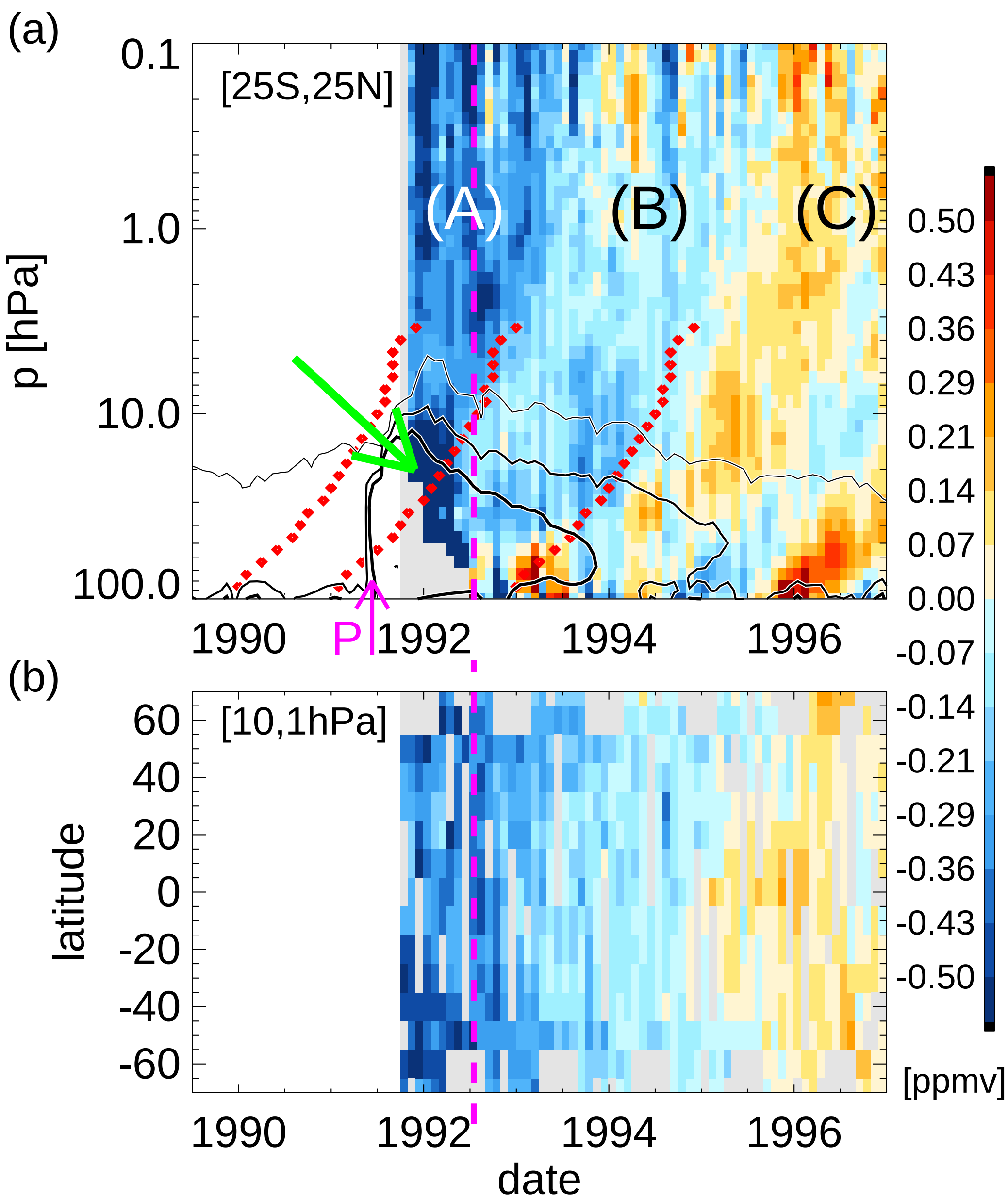
Models tend to **overestimate** temperature response.
Implications: Flooding of stratosphere, increase in GH-effect (counter aerosol cooling), $\Delta T = 1\text{K} \sim 0.5\text{ppmv} \sim 0.1\text{W/m}^2$.
Q: Observations?
Error sources: (i) Other tracers (ozone) - small compared to aerosol.
(ii) Aerosol heating Q^{aerosol} wrong.
(iii) Dynamical response (w^*) wrong.
→ Implications for geo-engineering model results?

Flooding of stratosphere?



Tropical HH (H2O+2CH4) from HALOE (lower panel: deseasonalised).

Flooding of stratosphere?

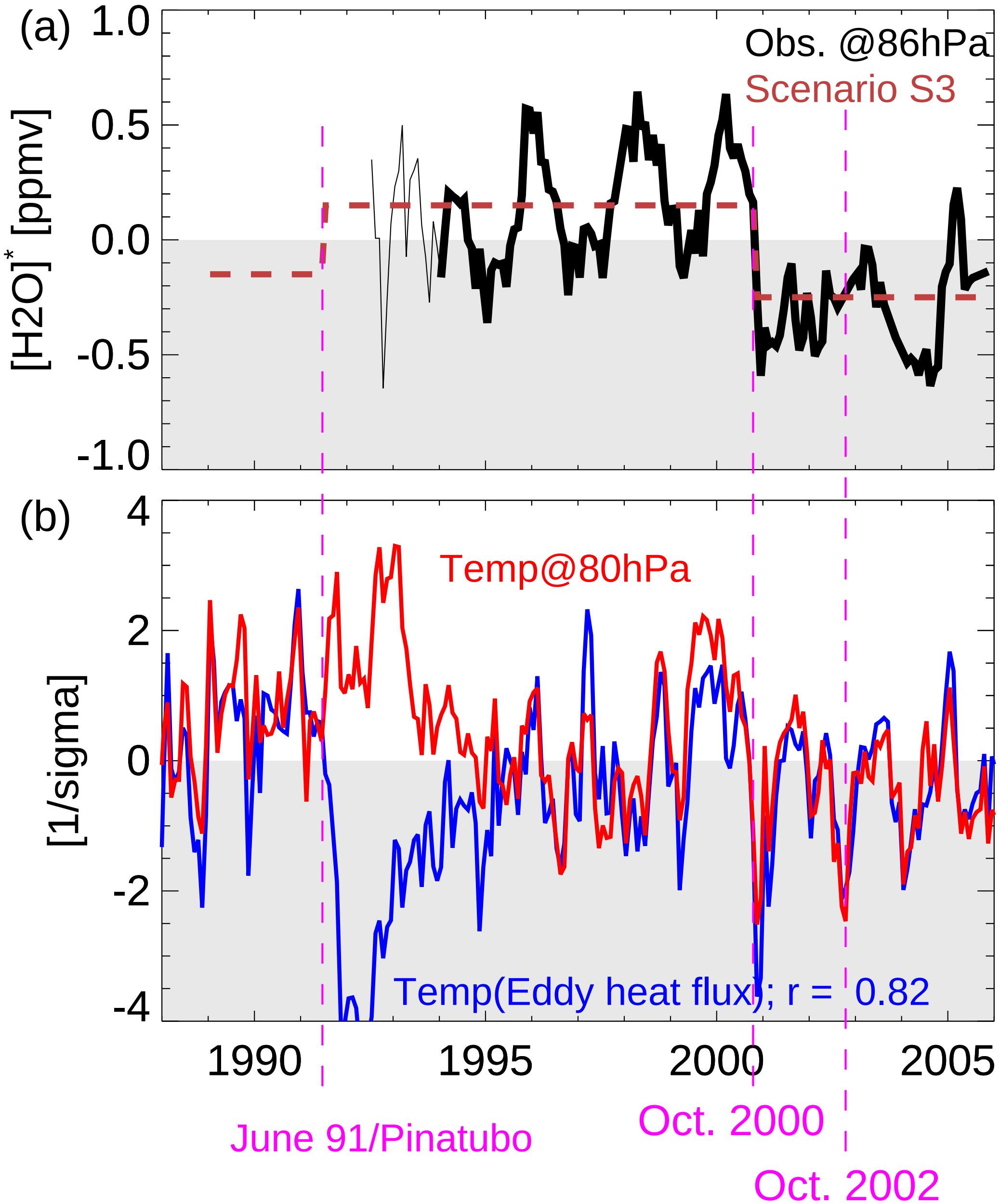


Fueglistaler (2012) argues ...

(i) increase from late '80's to 90's is real,
(ii) but not due to Pinatubo.

→ At **tropopause levels**, Pinatubo had only a small effect on temperature.

Model failure II: Dynamical response



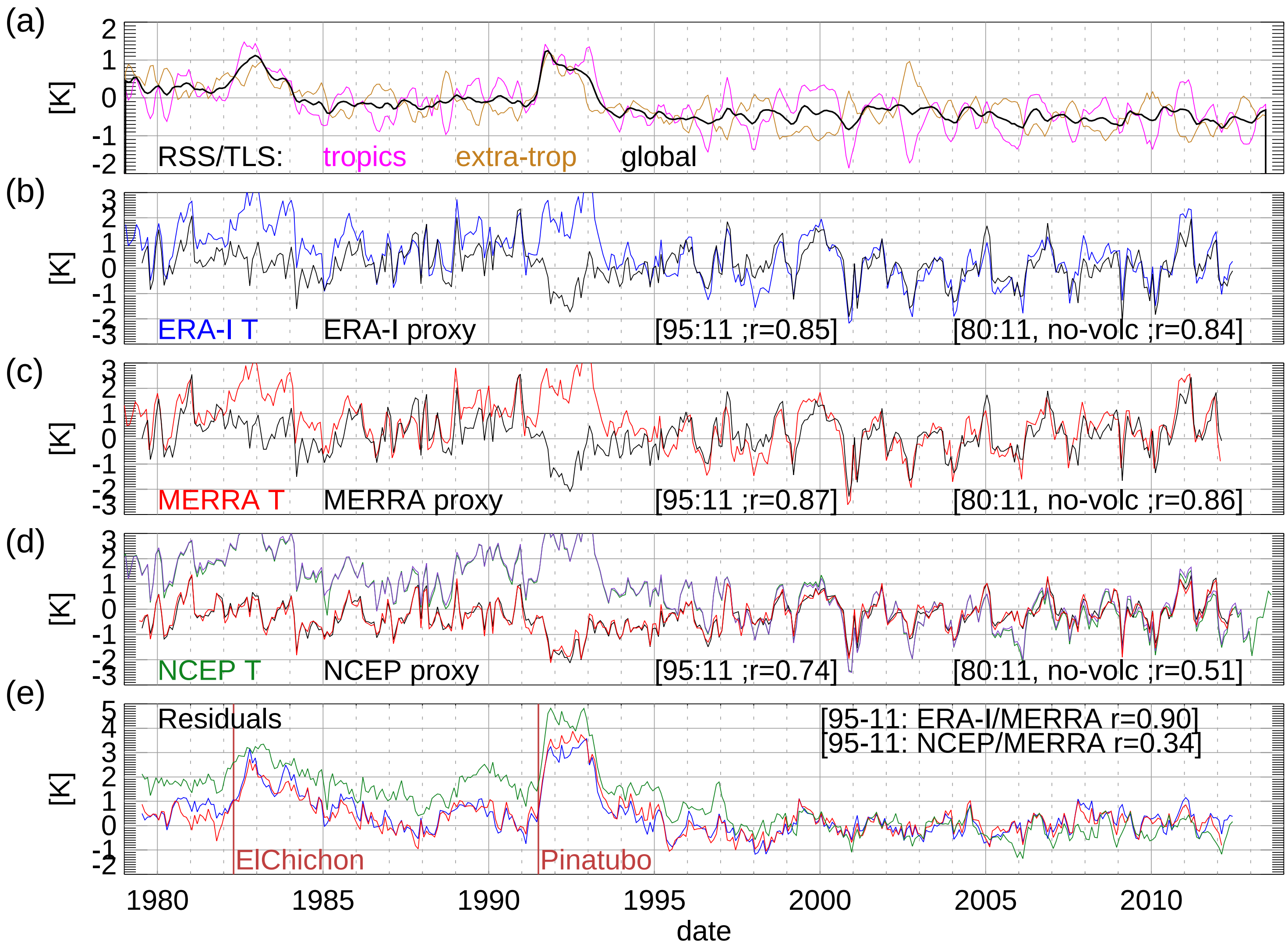
Fueglistaler (2012): extratropical eddy heat flux e-folded with about 90 days is highly correlated with tropical lower stratospheric average temperatures

(Depending on reanalysis and exact formulation of proxy, correlation coefficients are up to about 0.9.)

Except during the period following the eruption of Pinatubo.

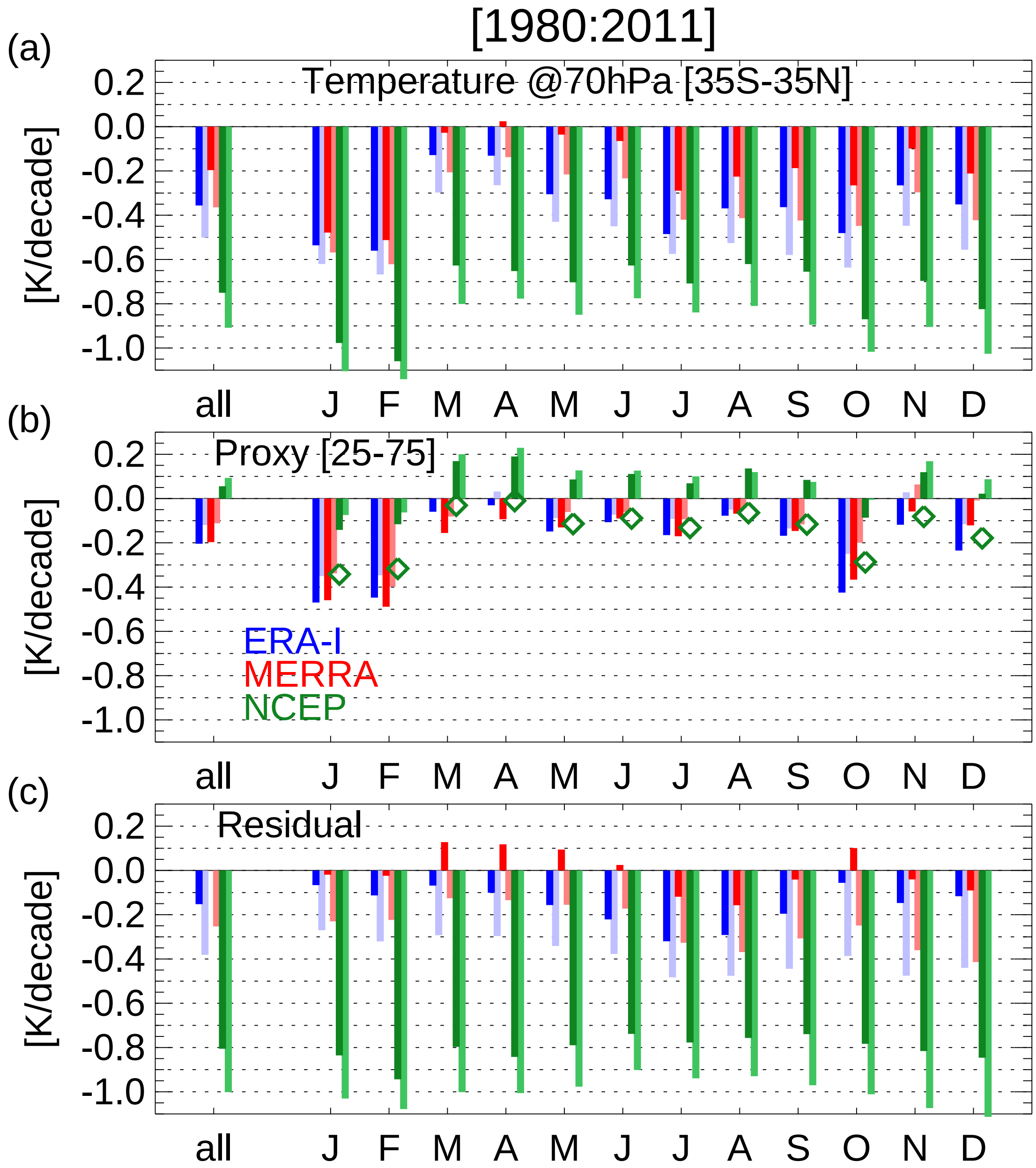
→ The actual aerosol-related ΔT (from Q^{aerosol}) may be much larger than the actual observed ΔT.

The dynamical response in reanalyses



(a) TLS; (b) ERA-Interim 70hPa, (c) MERRA 70hPa, (d) NCEP2, (e) Residuals.

The dynamical temperature proxy



Trends (K/decade) with (light color)/without (dark color) volcanic periods, for ERA-Interim (blue), MERRA (red), NCEP (green).

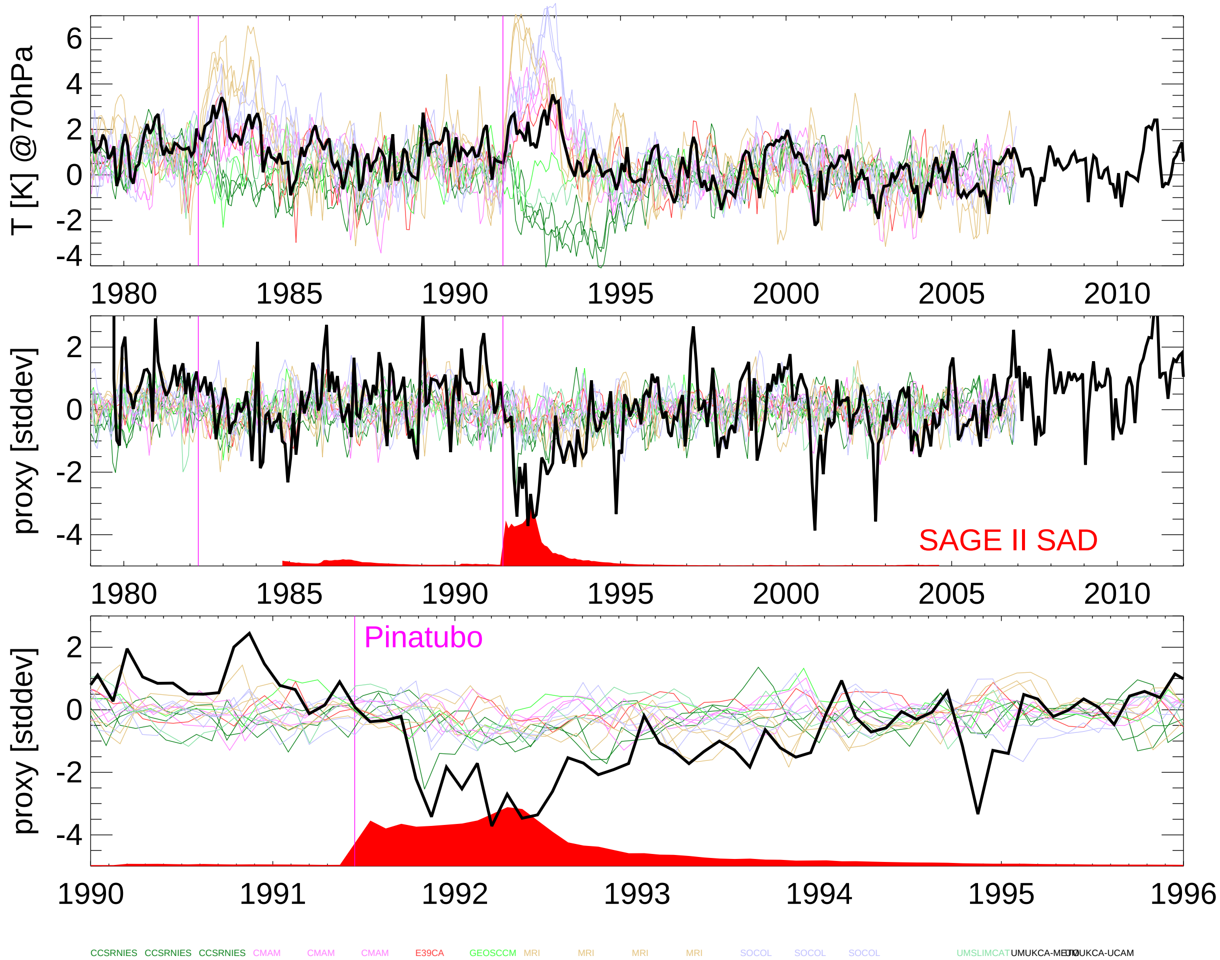
(a) Temperature

(b) v'T'-based proxy

(c) residual.

→ Also trends in proxy are sensitive to volcanic periods.

Model failure II: Dynamical response



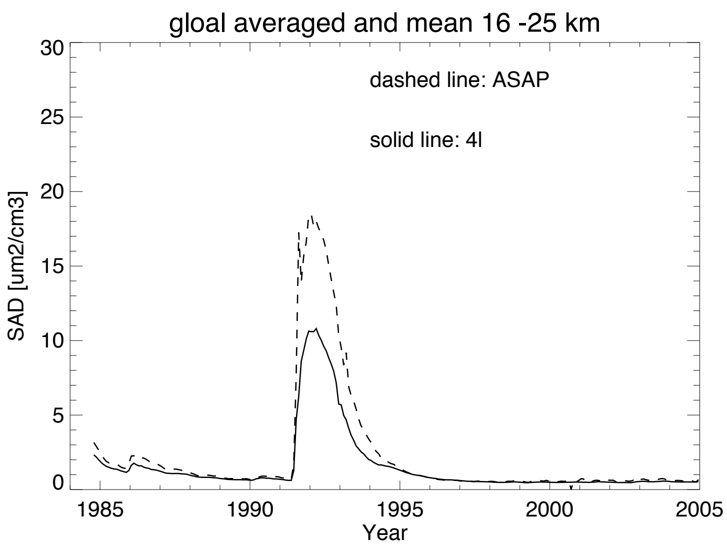
Colors: CCMVal2; Black: ERA-Interim.

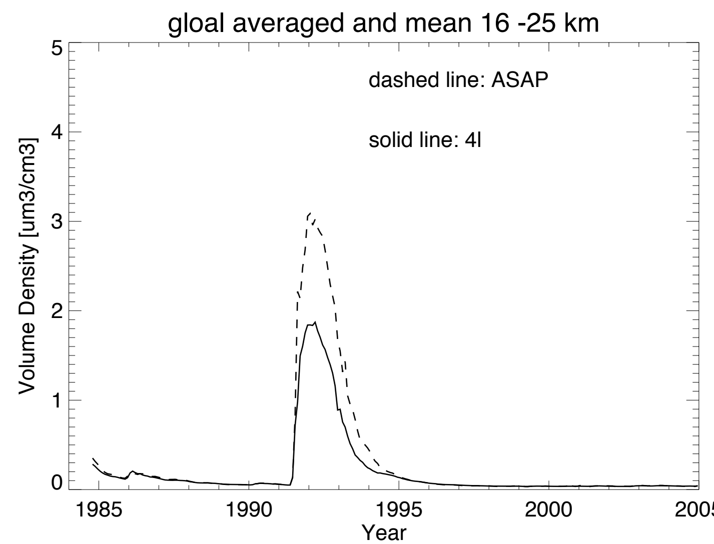
Temperature at 70hPa.

Dynamical proxy at 70 hPa.

→ Models fail to capture dynamical response (4-std deviations of 1994-2011).

Differences in aerosol properties

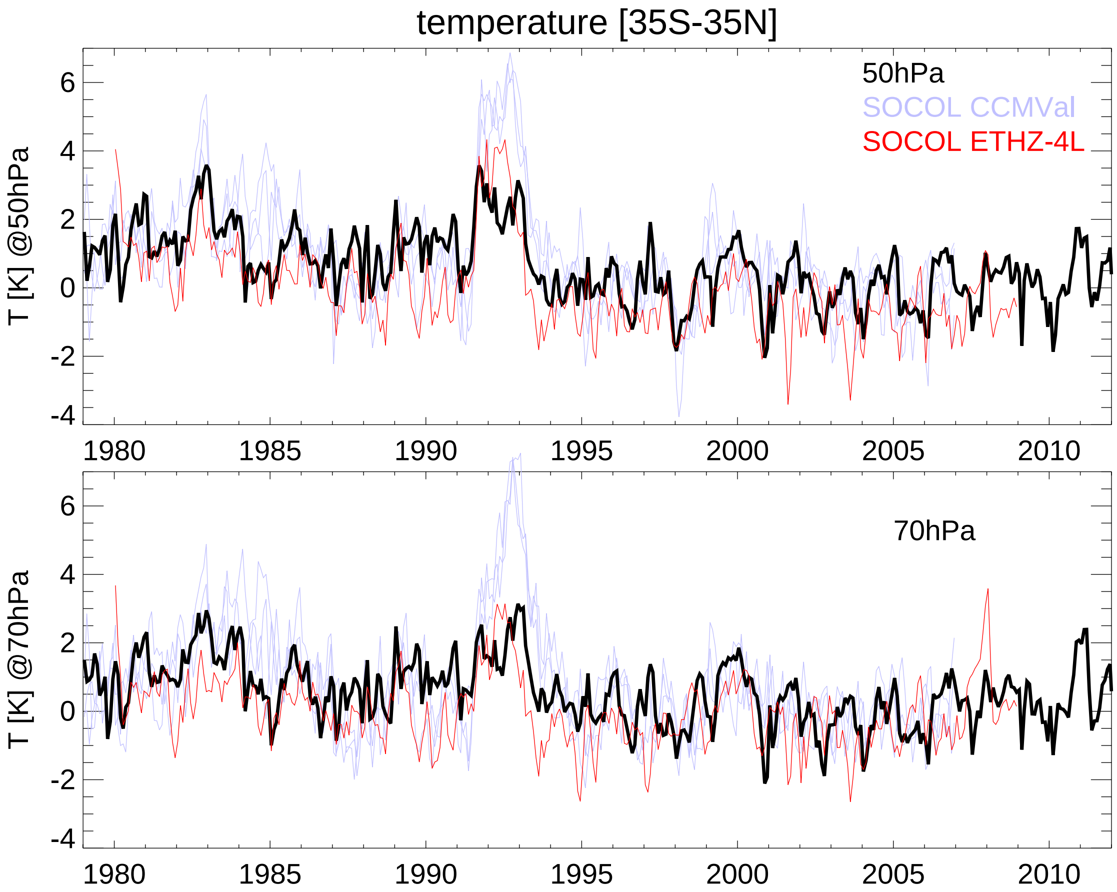




Surface Area Density (left) and Volume Density (right) of aerosol.

Dashed: SPARC ASAP dataset. Solid: New ETHZ 4λ dataset based on SAGEII V7 (see Arfeuille et al. 2013).

Model runs with different aerosol

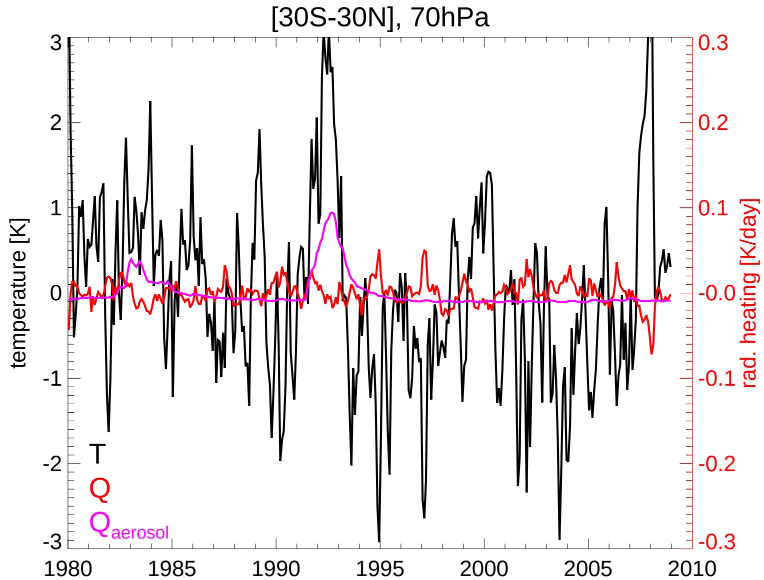


SOCOL runs with ASAP and 4λ aerosol.

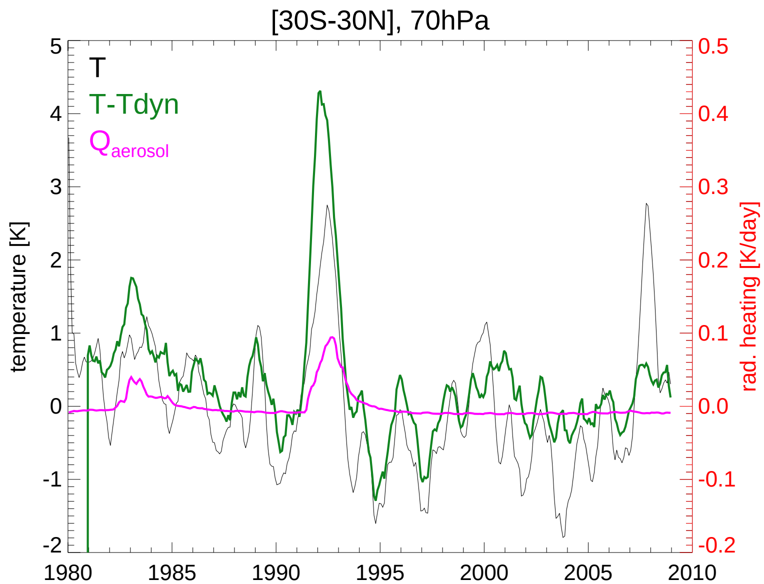
Top: 50hPa.
Bottom: 70hPa.

New model runs agree better for temperature (less warming); consistent with expectation from aerosol properties.

The SOCOL/4λ run

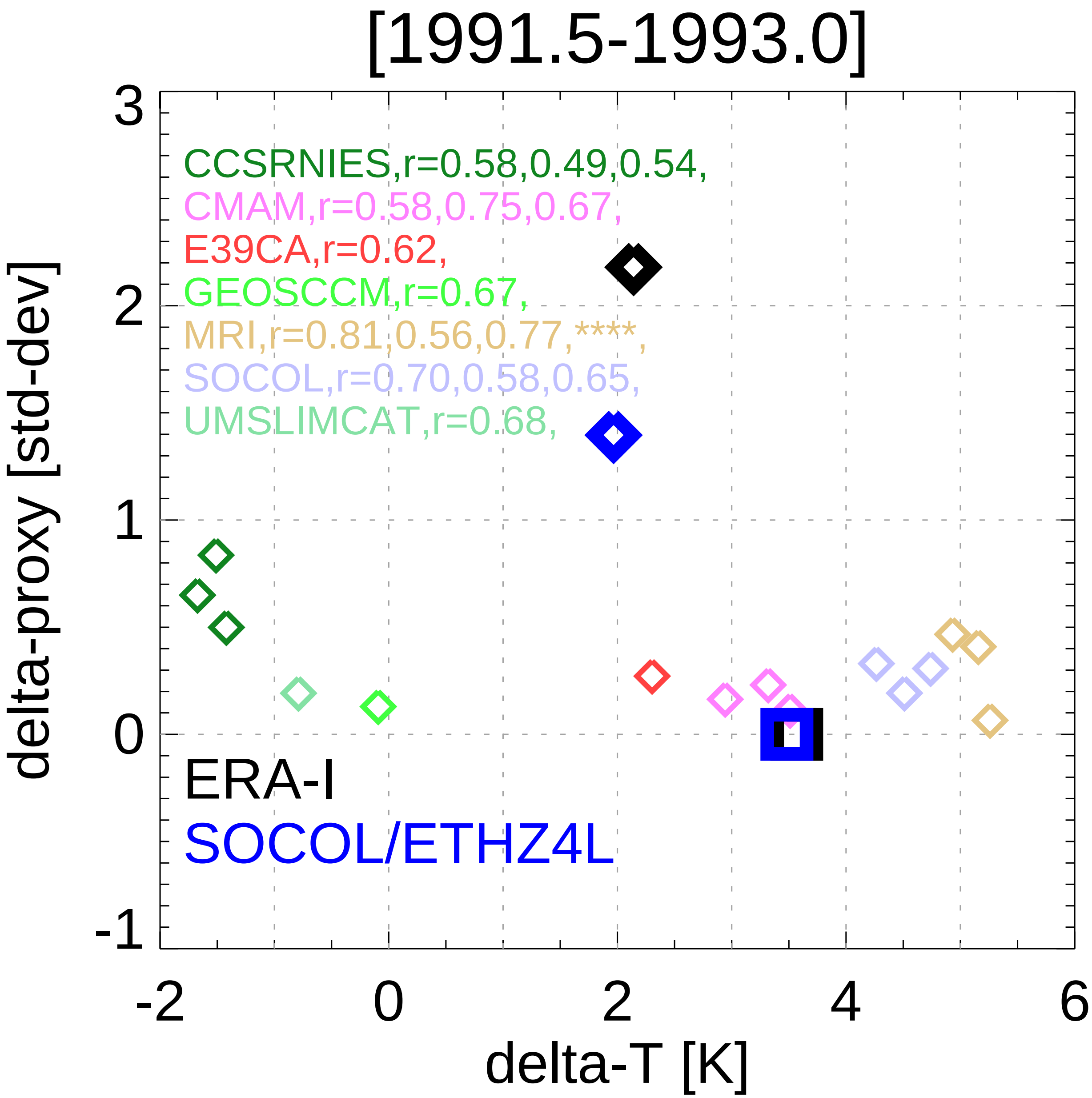


Temperature, radiative heating, and aerosol radiative heating. Recall: $\frac{\partial T}{\partial t} + \frac{T}{\tau} = \frac{T_{\mathrm{E}}^{\mathrm{gas}}}{\tau} + Q^{\mathrm{aerosol}} - K \cdot w^{*}$

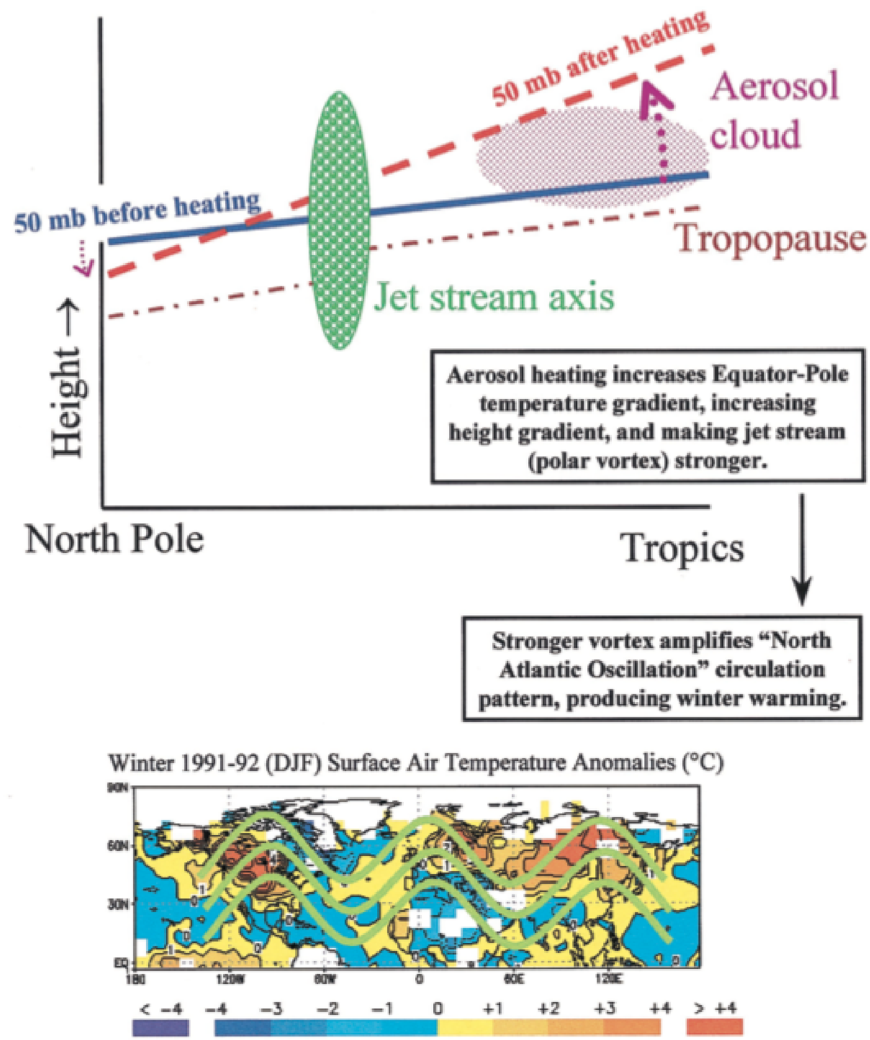


Temperature, aerosol radiative heating, and the difference between temperature and the dynamical (v'T') temperature proxy. → This model runs does show a substantial response in dynamics.

Pinatubo-period temperature and dynamics

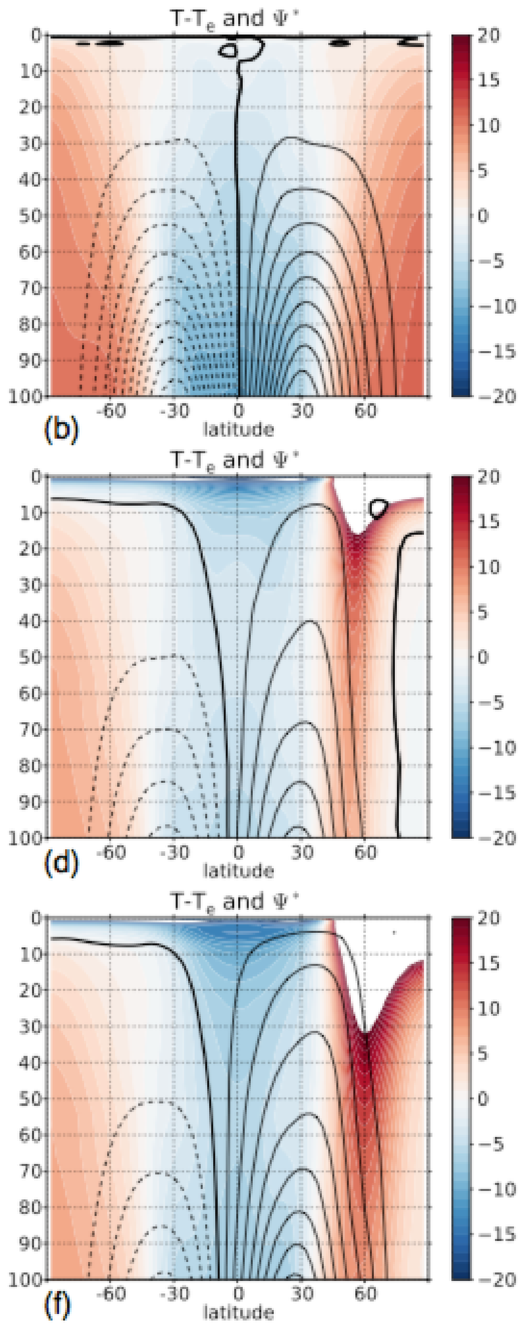


The dynamical response - the cartoon



[Robock, Rev. Geophys., (2000)]

The dynamical response - primitive equation models



Experiment: Use dry GCM with Newtonian cooling, force with Q^{aerosol}. Importance of base state?

Left: 3 dry GCM setups, diabatic heating (color), residual streamfunction (black).

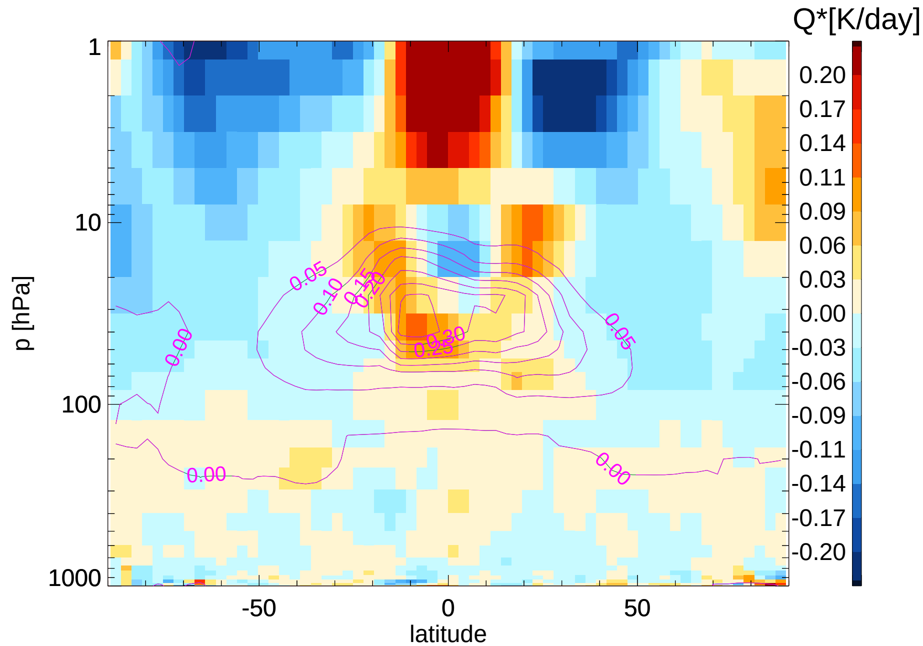
Top: Held-Suarez (1994).

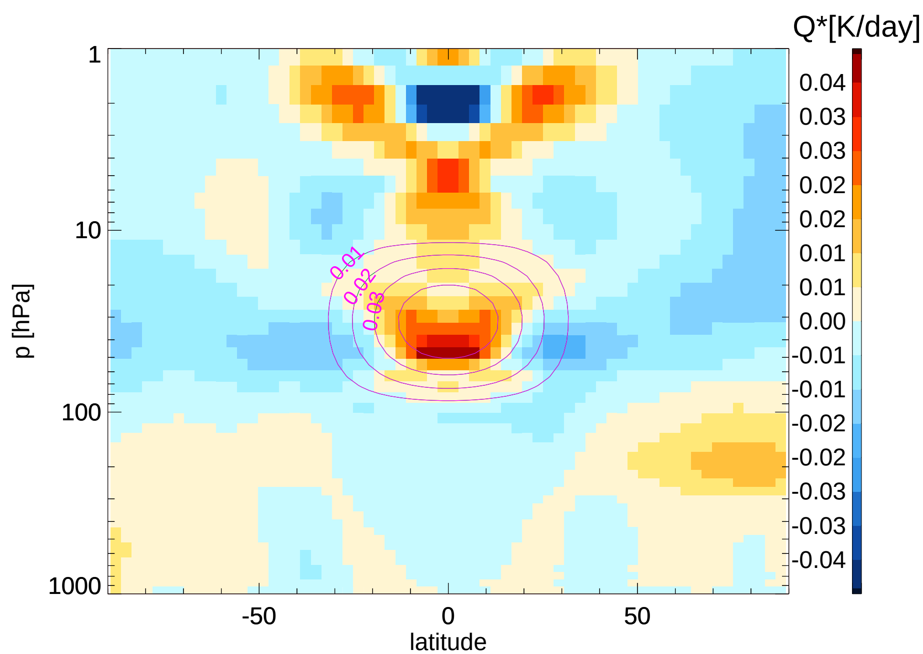
Center: Polvani and Kushner (2002).

Bottom: Gerber and Polvani (2009).

[Jucker/Fueglistaler/Vallis, JAS, in press.]

SOCOL and dry GCM: Q-forcing and Q-response

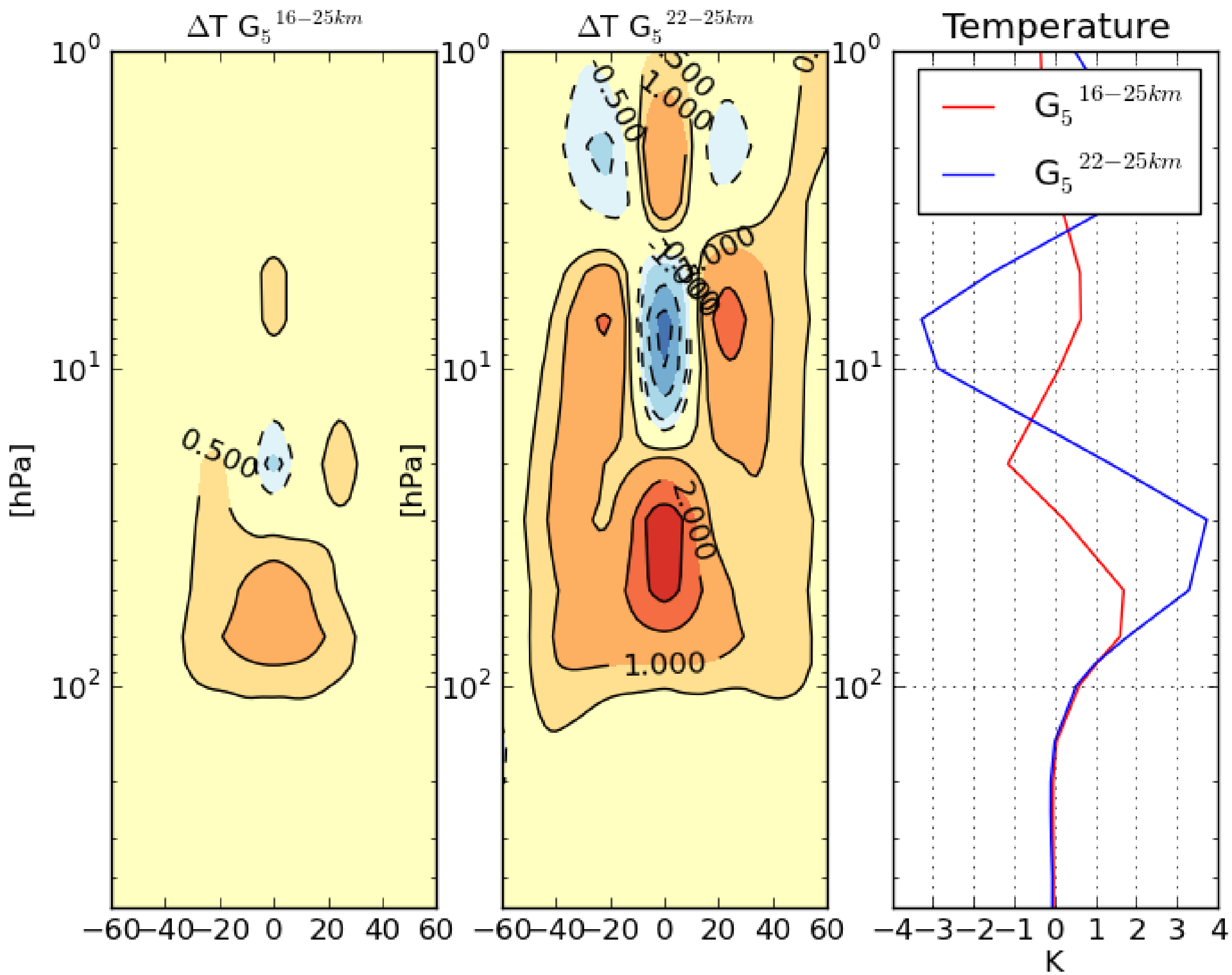




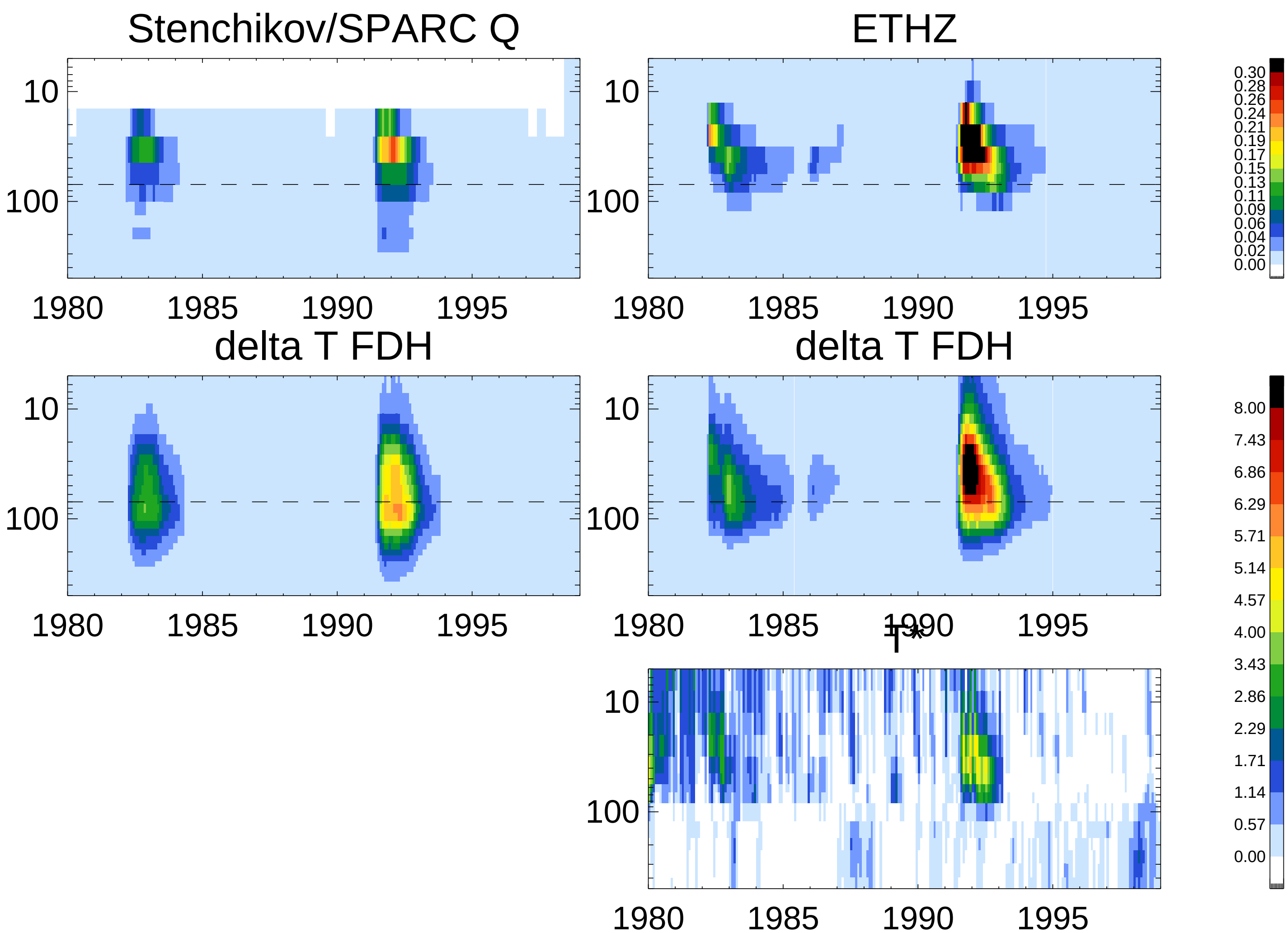
Top: SOCOL/4λ.
Bottom: HS94, idealised forcing.

→ Some similarities, some differences.
→ Both model calculations have a global-scale response that is a strenghtening of the stratospheric residual circulation.
Recall TD-equation discussion:
→ neither T ∼const. nor w^* ∼const.

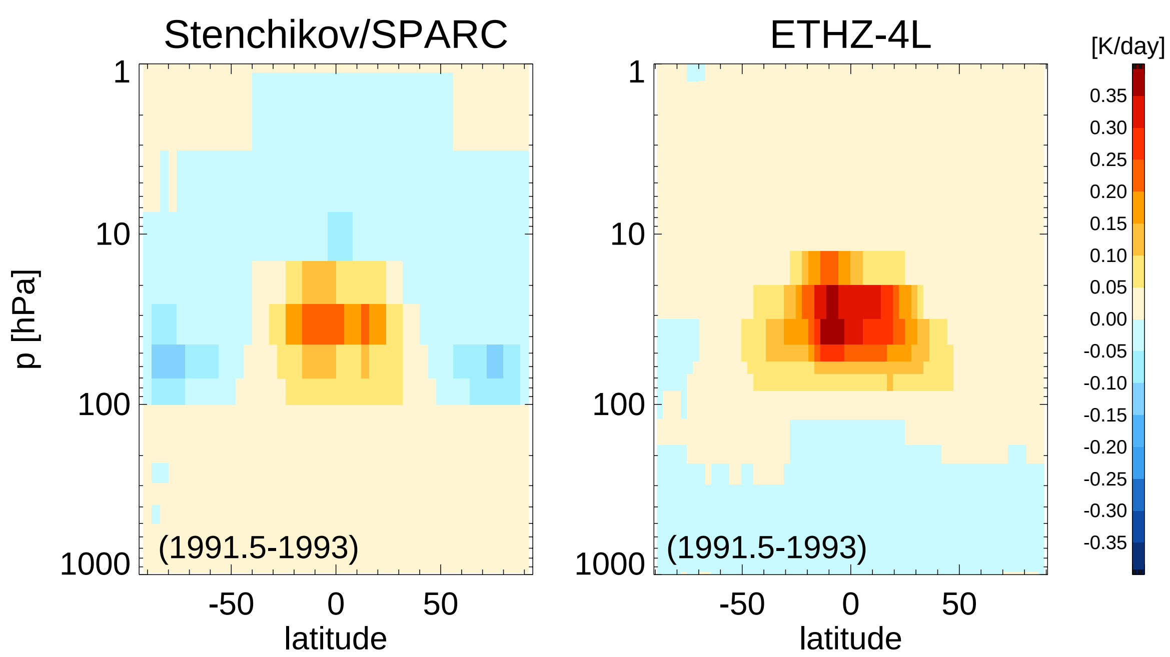
Response in a geo-engineering run, Aquila et al. (see poster)



Comparison of forcings



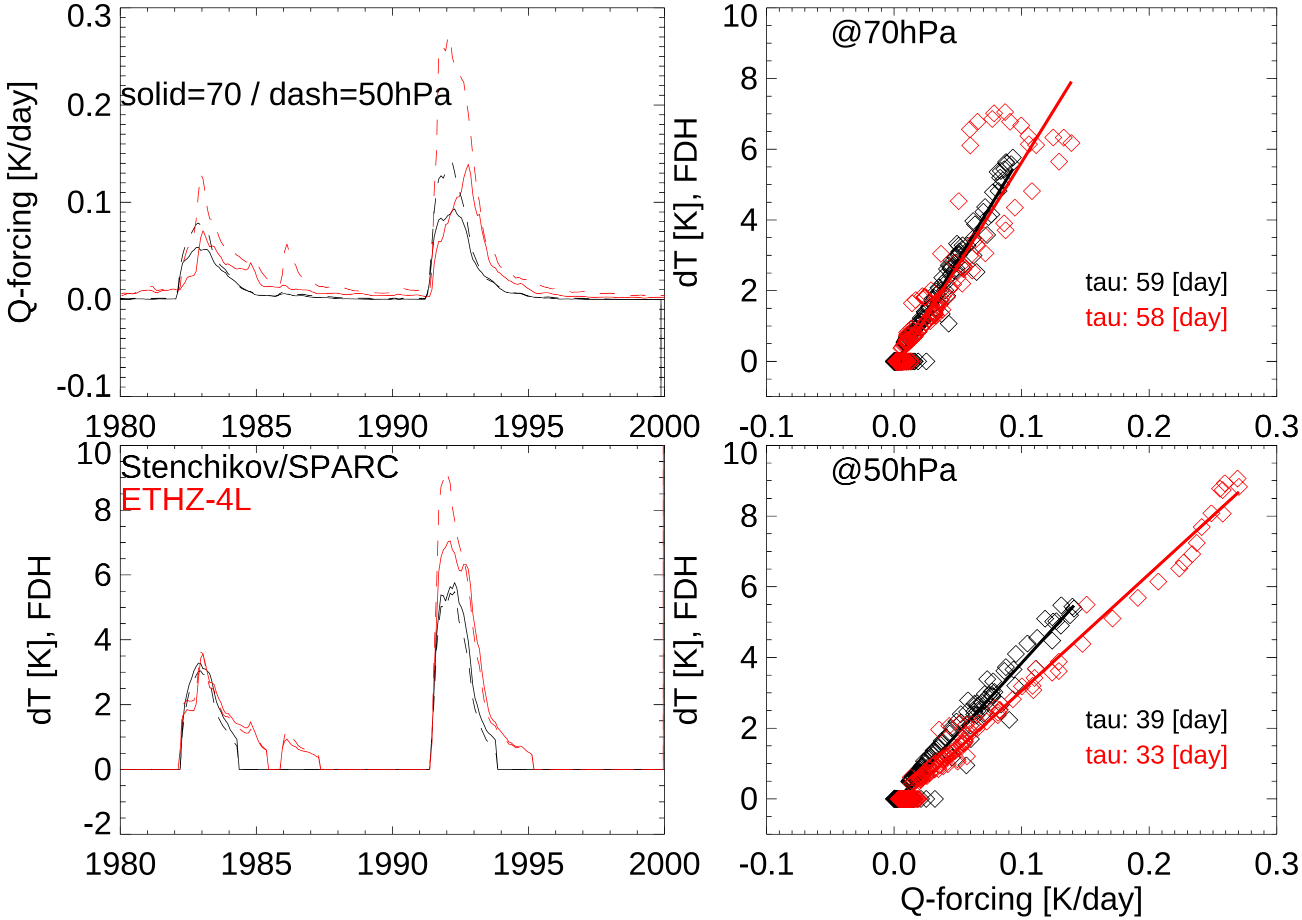
Comparison of forcings: Q^{aerosol}



$\rightarrow$ ETHZ/4λ has a weaker forcing than SPARC/ASAP, but stronger than Stenchikov/SPARC.

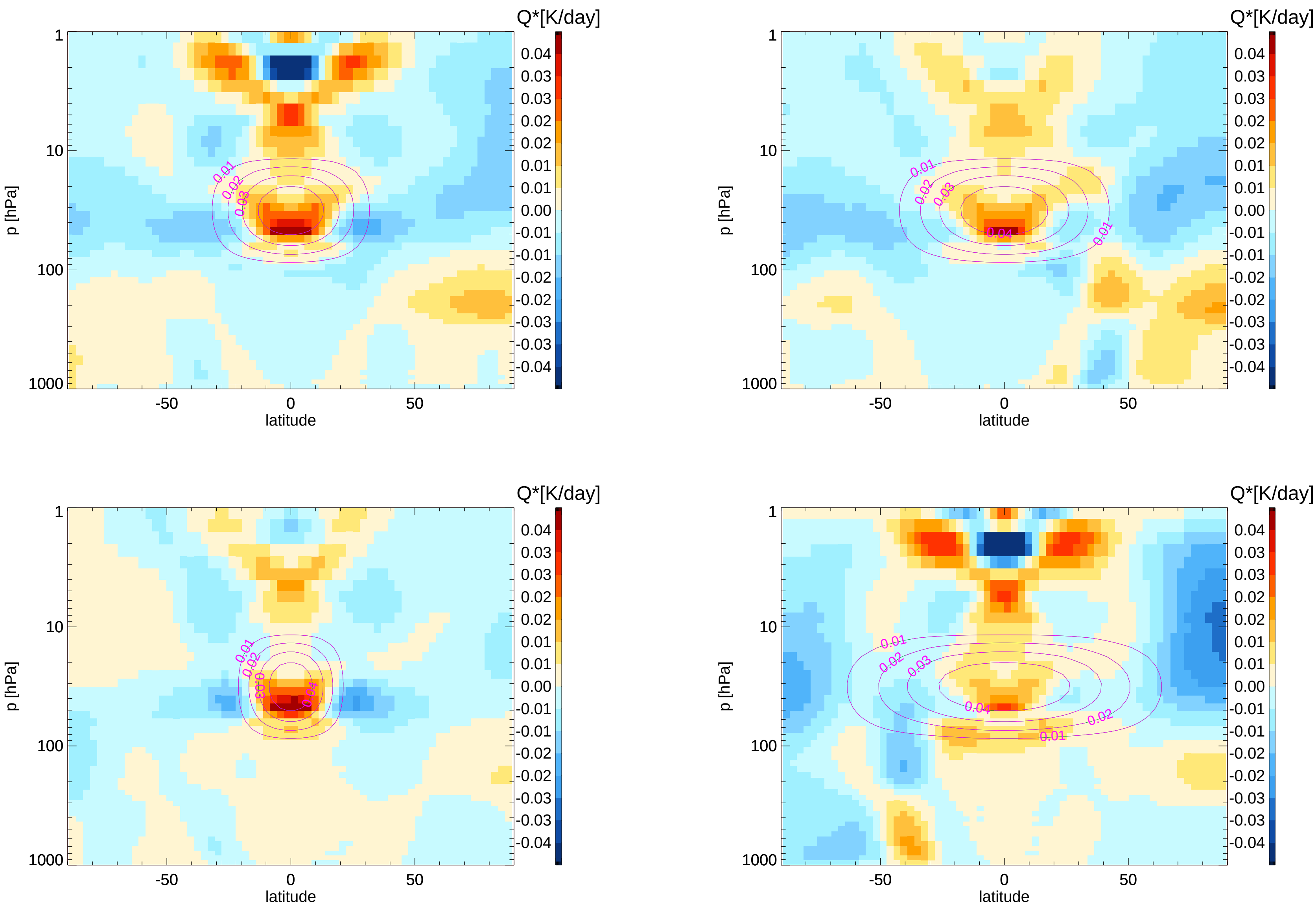
FDH temperature estimate ($Q^{\text{aerosol}} \leftrightarrow T$)

How valid is FDH? Works ok for volcanic forcing, but amplitude is much larger than observed:



As previous figure, but for 70hPa and 50hPa. Scatter plots: linear relation between delta-Q and delta-T for FDH reasonable.

Sensitivity to diabatic forcing



Bottom line:

- Observed temperature change in response to increase in aerosol is highly complex response; not clear how well models get the dynamical response. 'Correct' temperature evolution may be fortuitous.

- No flooding of the stratosphere following Pinatubo - also because of dynamical response.

- Lack of dynamical response: not because of too weak amplitude in forcing. Q: fundamental problem of models, or sensitive to details in Q^{aeorsol}? $\longrightarrow$ Would be helpful to know Q^{aeorsol} rather than aerosol properties.

- Linear trends since 1979: better exclude volcanic periods.

- Vindication of radiative forcing on circulation ... ? Coupling between tracers, radiation, temperature and dynamics very strong; but think:
$Q^{\mathrm{aeorsol}} \longrightarrow \mathrm{d}T/\mathrm{d}t \longrightarrow T \longrightarrow u \longrightarrow$ EP-flux$\longrightarrow w^{*} \longrightarrow \mathrm{d}T$....

Thank you!