The climatic effects of stratospheric water vapour anomalies

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1. Summary

Water vapour entry into the stratosphere is largely controlled by cold-point temperatures (CPT) in the tropical tropopause region, where ascending air is freeze dried to concentrations of typically a few ppmv. Changes in CPTs bring about changes in the amount of water vapour entering the stratosphere which subsequently alters the radiative balance.

The goal of this study is to quantify the radiative and dynamical impacts of such changes in stratospheric water vapour through a variety of modelling experiments.

2. Stratospheric water vapour anomalies

Changes in stratospheric water vapour (SWV) concentrations can occur through two distinct processes:

- Oxidation of methane in the upper stratosphere.
- Direct mass transport from the troposphere into the stratosphere.

Studies have identified evidence of a long-term positive trend in SWV of ~1%/yr from as far back as the mid-20th century up to the mid-1990’s (Rosenlof et al., 2001). In addition, climatic events which bring about transient changes in tropical tropopause temperatures have been shown to result in SWV anomalies. These include: volcanic eruptions, ENSO events, the quasi-biennial oscillation and changes in the strength of the Brewer-Dobson circulation.

Increases in SWV concentrations have a significant radiative impact which results in a net stratospheric cooling. Due to the changes in the meridional and vertical temperature gradients, this cooling is likely to lead to adjustment of the stratospheric dynamical state. Research has shown changes in the stratospheric circulation can influence the tropospheric large-scale circulation (Polvani and Kushner, 2002). This suggests an improved understanding of the effects of SWV anomalies could be useful for seasonal-decadal forecasts following an injection of water vapour into the stratosphere.

The goal of this study is to quantify the radiative and dynamical impacts of SWV anomalies on both the stratosphere and troposphere. In order to test these hypotheses, this study will utilise both idealised and realistic SWV anomalies in both a fixed dynamical heating (FDH) and general circulation model (GCM).

3. Fixed Dynamical Heating modelling

The FDH approach assumes that at each point the diabatic and dynamical heating components are in balance in the unperturbed system such that:

$$Q(T,\varphi,z)+D(\varphi,z) = 0$$

Using a radiation code the equilibrium diabatic heating, Q(T,φ,z), is computed and thus the dynamical heating, D(φ,z), can be inferred. The system is then perturbed in some way e.g. by adding SWV, which results in an adjusted diabatic heating field Q’(T, φ,z) such that:

$$Q'(T,\varphi,z)+D(\varphi,z) \neq 0$$

The dynamical heating component is assumed to remain fixed in the perturbed state and thus stratospheric temperatures can be adjusted until the system reaches a new balanced state in which:

$$Q(T', \varphi,z)+D(\varphi,z) = 0$$

Tropospheric temperatures remain fixed.

4. Fixed Dynamical Heating experiments

Figure 1(a) shows the FDH temperature response to a homogeneous increase in SWV of 0.7ppmv on a 3ppmv uniform background state. Figure 1(a) shows:

- A net cooling everywhere in the stratosphere.
- A structurally distinct temperature response with peak cooling lobes in the extra-tropical lower stratosphere. This contrasts with the relatively ‘flat’ cooling response for a uniform doubling in atmospheric CO_2 (Fig. 1(b)).

1(a)

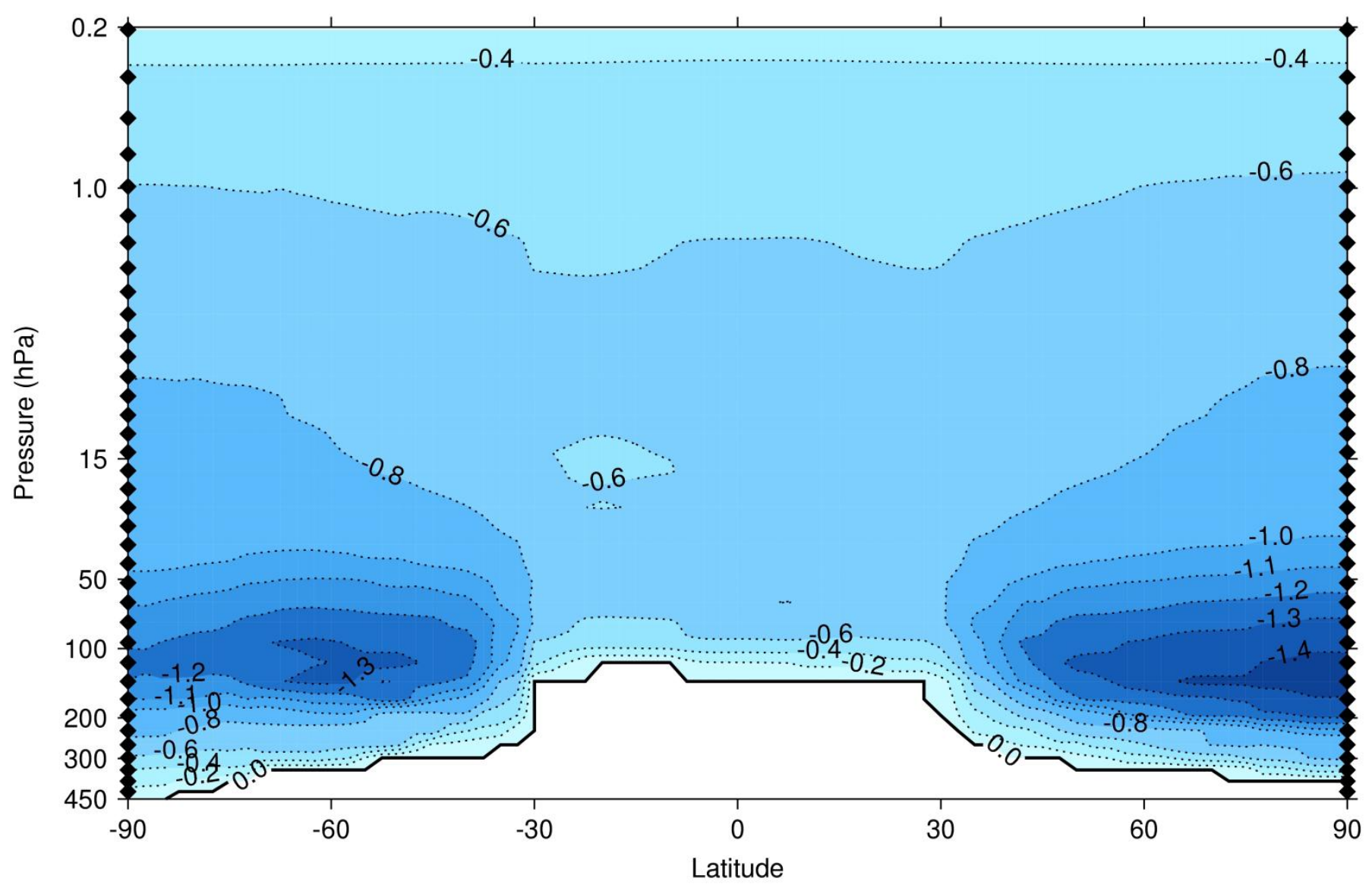


Figure 1: Zonal mean FDH change in temperature (K) for: (a) A homogeneous SWV perturbation of 0.7ppmv on a 3ppmv background state with a climatological cloud field. Contour interval is 0.1K below -1K and 0.2K above -1K. (b) Two times pre-industrial CO_2 levels throughout atmosphere. Contour interval 1K. (c) Same as (a) but with 100% cirrus cloud just below local tropopause. Contour interval same as (a).

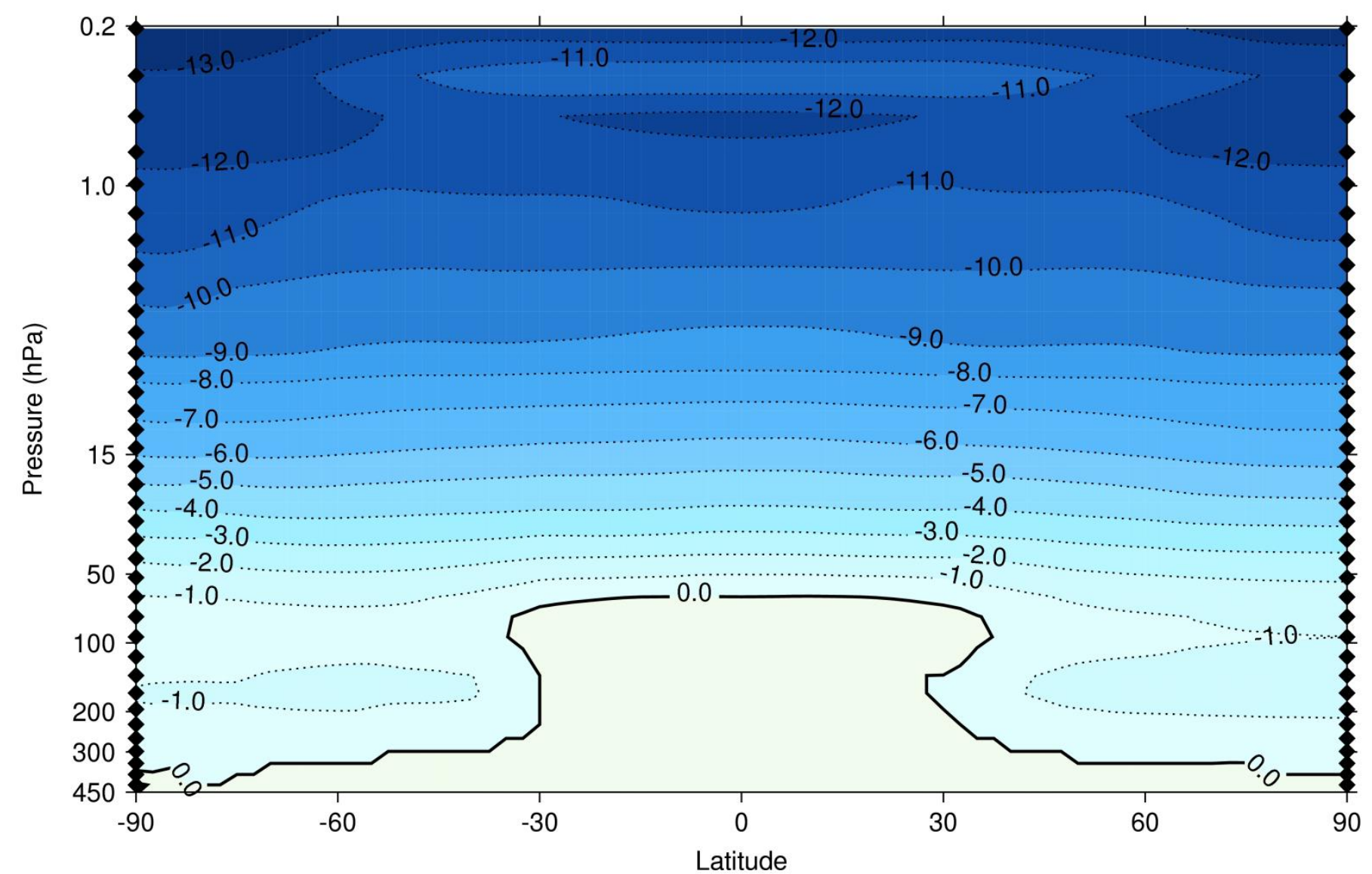
Why does the stratosphere cool when SWV is added?

In simple terms increased SWV leads to:

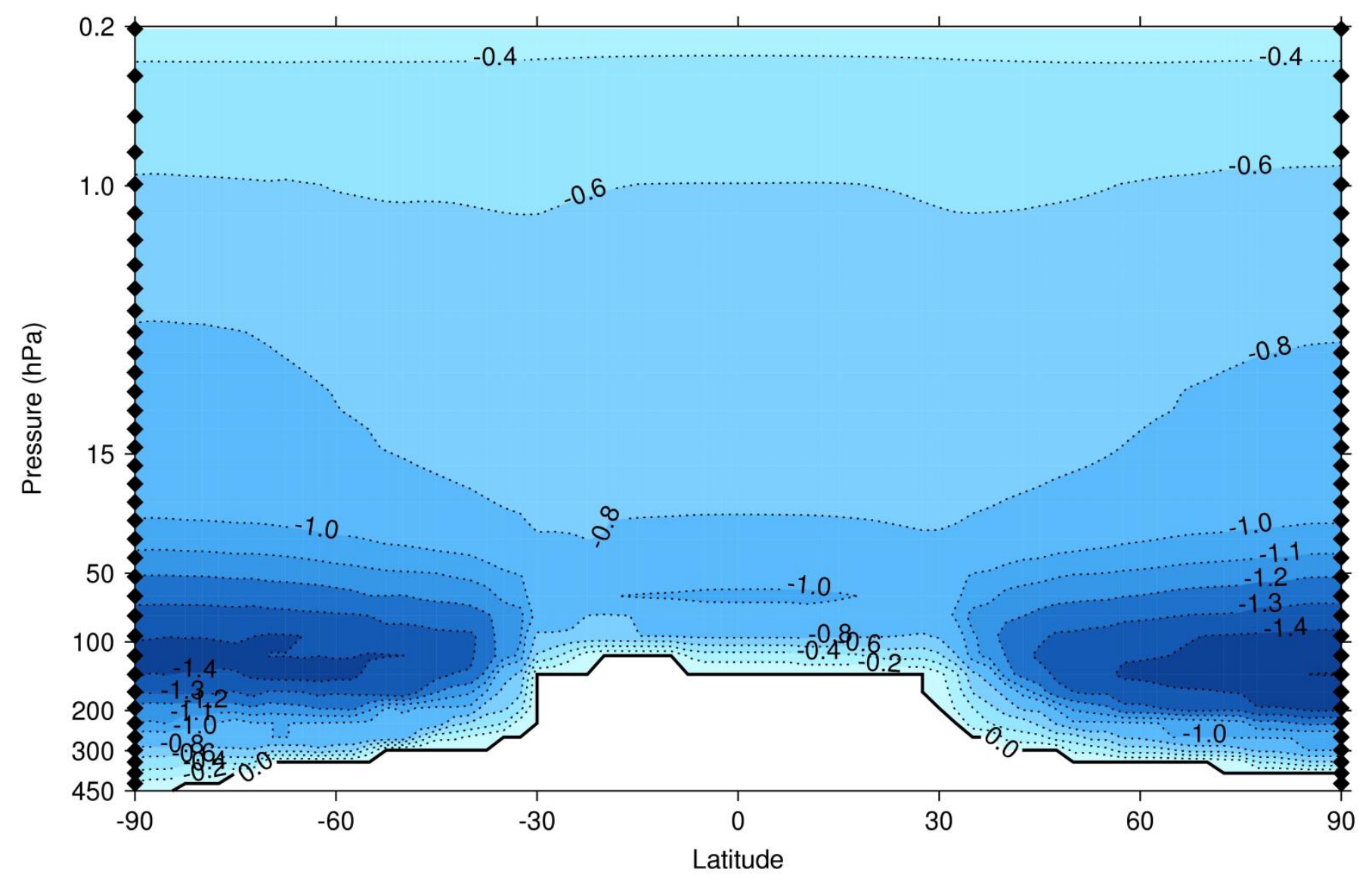
- More absorption of upwelling long-wave (LW) radiation from the troposphere.
- More LW emission to space from layers within stratosphere.
- The net response is a balance between these competing factors.

Can we unpick how the contributions of these effects vary latitudinally to result in the cooling structure in Fig. 1(a)?

1(b)



1(c)



5.Why does the cooling response have such a distinct structure?

One hypothesis is that the amount of outgoing LW radiation (OLR) at the tropopause peaks in the tropics. This means there is less radiation for absorption by SWV at higher latitudes but there will still be more radiation being emitted to space; this may result in the stronger cooling observed.

In order to test this, experiment 1(a) was repeated with a layer of 100% cirrus cloud just below the local tropopause. This dramatically alters the OLR profile at the tropopause, with the biggest reduction in the tropics (Fig. 2). The associated FDH temperature change is shown in Fig. 1(c).

Comparison of Fig. 1(c) with Fig. 1(a) shows that:

- There is some additional cooling in the tropical lower stratosphere as expected from the reduction in upwelling LW radiation.
- However, the peak extra-tropical cooling lobes are still present despite the greatest reduction in OLR being found in the tropics (Fig. 2).
- This suggests that the latitudinal variation in upwelling LW radiation at the tropopause is not the driving factor of the observed structure of the FDH cooling response to increased SWV.

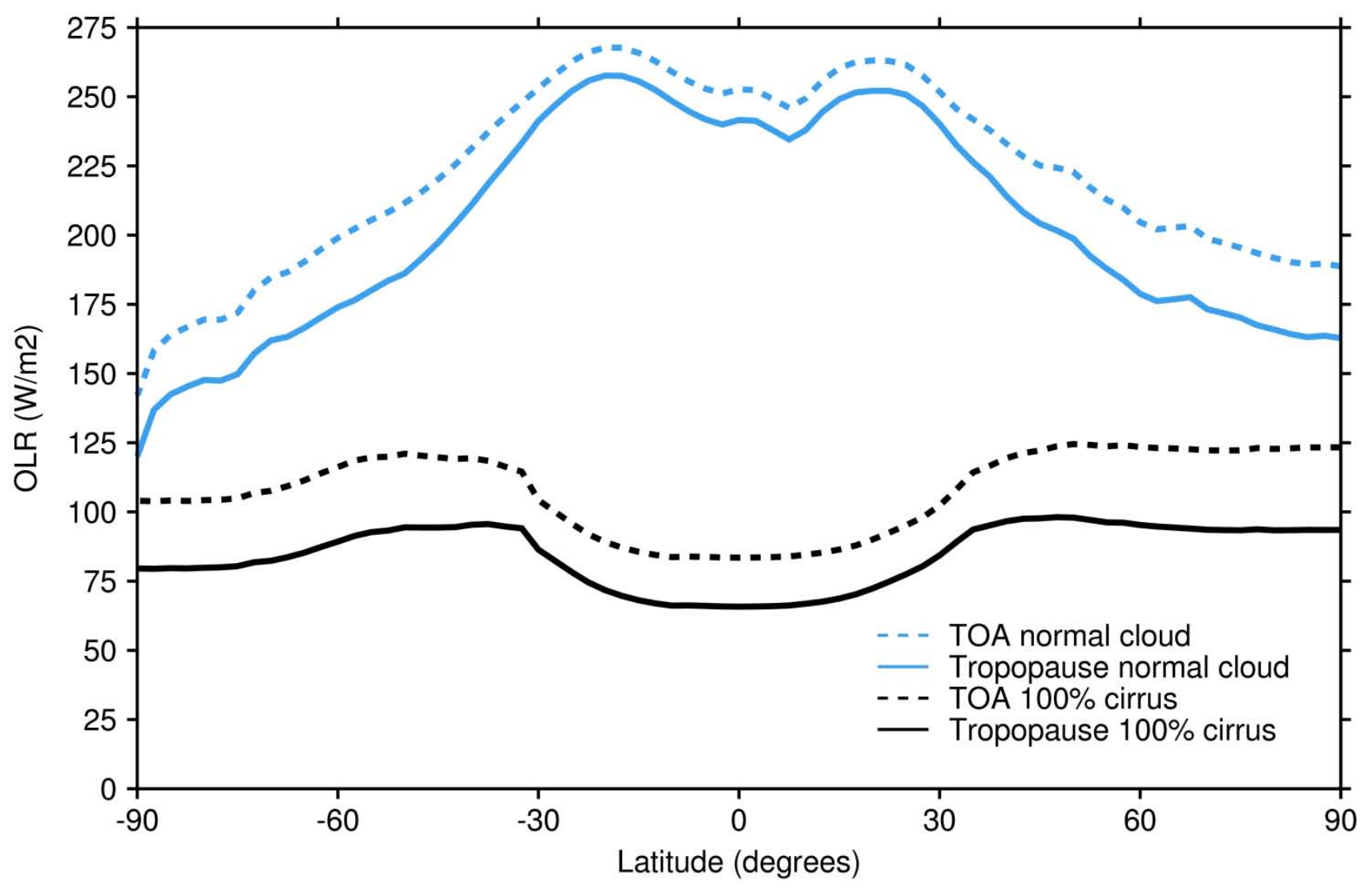


Figure 2: Zonal mean OLR (Wm-2) at the tropopause (dotted lines) and top of atmosphere (TOA) (solid lines) for experiments 1(a) (blue lines) and 1(c) (black lines).

6. Conclusions and further work

- FDH stratospheric cooling due to homogeneous SWV perturbations has a distinct spatial structure.
- The change in meridional T gradient makes SWV anomalies likely to perturb the stratospheric dynamical state.
- The cooling structure persists even when the peak upwelling LW radiation in the tropics is reduced; this suggests it may be intrinsic stratospheric radiative processes which are the primary drivers of the cooling response.
- Subsequent FDH work will analyse the radiative relaxation timescales in the stratosphere to try and further investigate the origin of the cooling structure.
- GCM experiments will be conducted using a version of the Unified Model (UM) with a model top at 0.01hPa and 60 vertical levels in order to ensure the stratosphere is well resolved.
- Homogeneous SWV experiments will be repeated in the GCM so that the fully coupled radiative and dynamical response is seen.
- A pulse SWV anomaly will be input into the tropical lower stratosphere to simulate an anomalous troposphere-stratosphere exchange event in the GCM. The spatial and temporal evolution of the anomaly will then inform more realistic experiments.
- Analysis will be made of the GCM stratospheric and tropospheric circulation changes associated with different idealised and realistic SWV anomalies.

References

Rosenlof, K., et al., Stratospheric water vapor increases over the past half century, GRL, 2001, 28 (7), p. 1195.

Polvani , L. M., and P. J. Kushner, Tropospheric response to stratospheric perturbations in a relatively simple general circulation model, GRL, 2002, 29 (7), p. 1114.