The temperature response to stratospheric water vapor changes

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1. Introduction

A uniform increase in stratospheric water vapor (SWV) causes stratospheric cooling which is largest in the lower stratosphere, decreases with increasing height and is enhanced in the extra-tropics by a factor of two compared to the tropics [1]. The cooling has a different structure to that from an increase in CO_2, which shows cooling that increases with height and is maximum at the stratopause [2]. The cooling that results from such a change in SWV, in particular the enhancement of cooling in the extra-tropics, may influence the stratospheric circulation [3].

This study [4] investigates the underlying factors that determine the structure of the temperature response to a uniform change in SWV using a fixed dynamical heating (FDH) model.

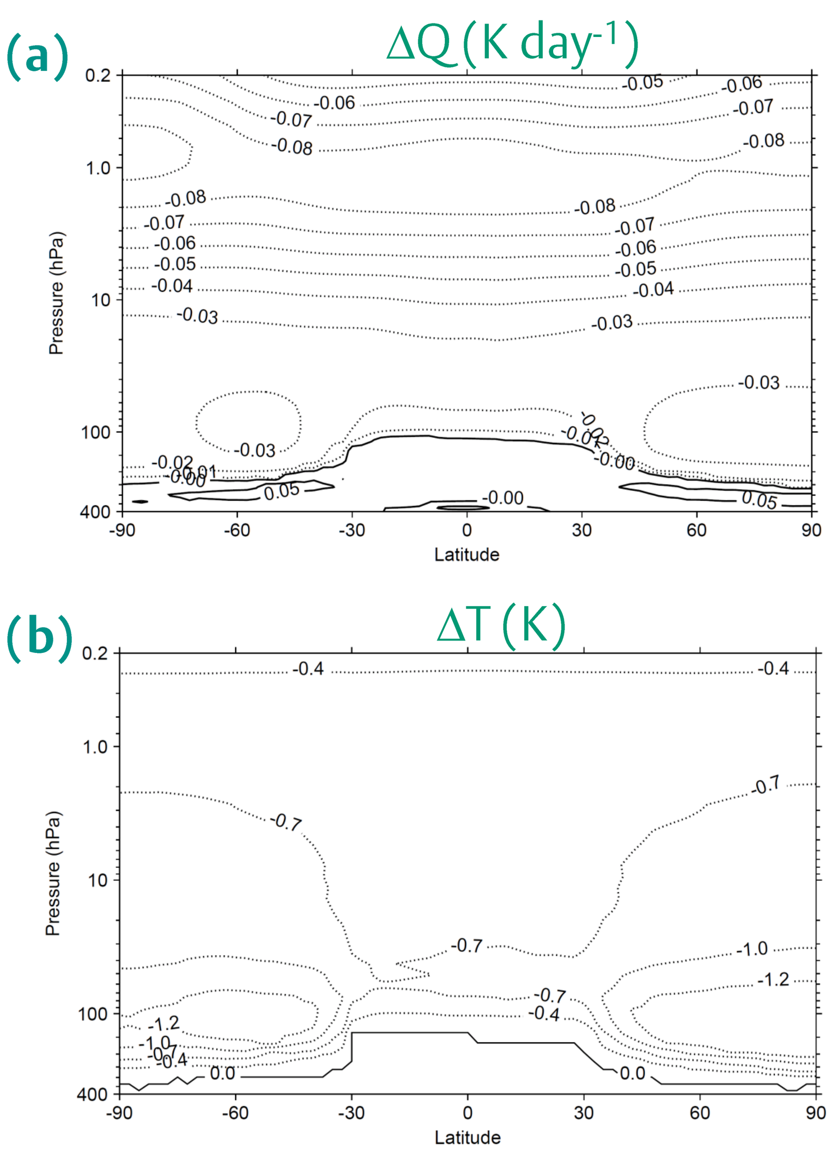
2. Method

Model: Edwards-Slingo radiative transfer model [5] with monthly-mean input fields taken from an N48 60-level (~84 km) HadGAM1 control simulation. A uniform SWV base state is assumed.

Fixed dynamical heating method [2]: At a given temperature T the diabatic and dynamical components of the stratospheric heating rate, Q and D, are assumed to be in a quasi-steady state. A uniform SWV perturbation is added to the system; this results in a different diabatic heating rate Q′. Temperatures are adjusted in the stratosphere until a state T′ is found for which the heating rate equilibrium is re-established. We define the instantaneous change in heating rate due to the SWV perturbation as $\Delta Q = Q' - Q$ and the FDH temperature change as $\Delta T = T' - T$.

3. Uniform 3 to 3.7ppmv SWV control experiment

Figure 1: Annual-mean calculations of (a) ΔQ (K day^{-1}) and (b) the FDH ΔT (K) for a uniform increase in SWV from 3 to 3.7 ppmv.



Key points

- There is a cooling tendency everywhere except in the lowermost stratosphere.
- The magnitude of ΔQ is largest at the stratopause and decreases by a factor of four between the upper and lower stratosphere.
- At 100 hPa, the magnitude of ΔQ is 50% greater in the extra-tropics than in the tropics.

Key points

- There is a cooling everywhere in the stratosphere.
- The largest cooling is in the lower stratosphere; the cooling decreases in magnitude with increasing height.
- The magnitude of ΔT is a factor of two larger in the extra-tropics compared to the tropics.

4. How do different gases contribute to the cooling?

The initial ΔQ comes from changes in absorption and emission by H_2O. However, the response to equilibrate the heating rate perturbation comes from several gases acting together. To understand the contribution different gases make to the cooling, the 3 to 3.7 ppmv SWV experiment is repeated for atmospheres containing different combinations of **uniformly** mixed gases.

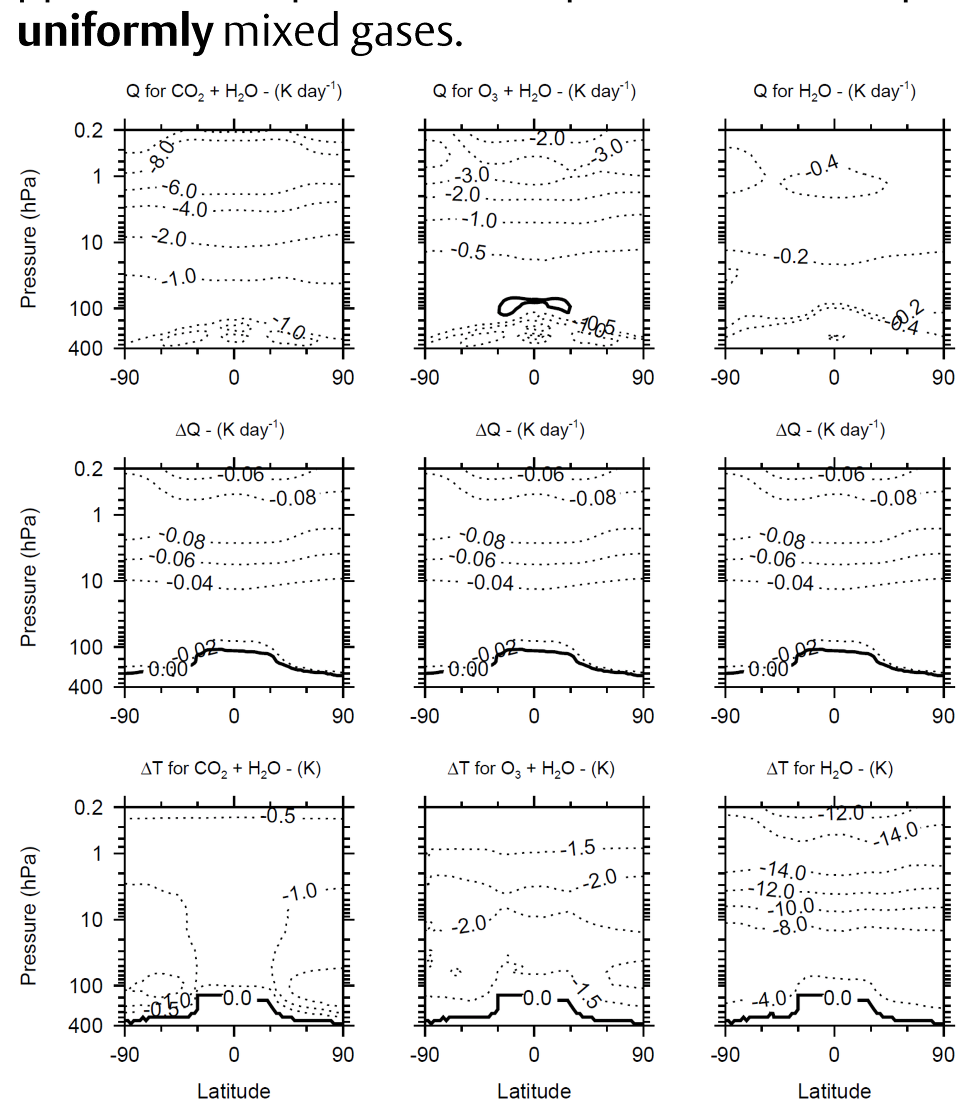


Figure 2: Annual-mean calculations for atmospheres containing from left to right: $CO_2 + H_2O$, ozone + H_2O and H_2O only. Top: Background long-wave heating rate Q (K day^{-1}). Middle: Instantaneous change in heating rate ΔQ (K day^{-1}) for a uniform 3 to 3.7 ppmv change in SWV. Bottom: FDH temperature change ΔT (K).

Key points

- When only CO_2 and H_2O are present, ΔT looks similar to the control experiment in Figure 1(b).
- In this case the cooling is small in the upper stratosphere, where CO_2 can readily cool to space, and larger in the lower stratosphere, where the overlying opacity for CO_2 is high.
- When only ozone + H_2O are present, ΔT is largest in the mid stratosphere at ~10 hPa.
- When only H_2O is present, the cooling is largest at the stratopause.
- For an atmosphere containing only H_2O, the structure of ΔT is dominated by the structure of ΔQ. This is because unlike CO_2 the ability of H_2O to offset a heating rate perturbation does not vary greatly in different parts of the stratosphere.

5. How does the background concentration of SWV affect the structure of the cooling?

The magnitude and structure of ΔQ is dependent on the opacity of the overlying water column since cooling-to-space is the dominant contribution to the long-wave heating rate in the stratosphere. To demonstrate the impact of a change in the H_2O column opacity on ΔQ and ΔT, the same uniform 0.7 ppmv SWV increase was applied to different background SWV concentrations varying from 3 to 100 ppmv.

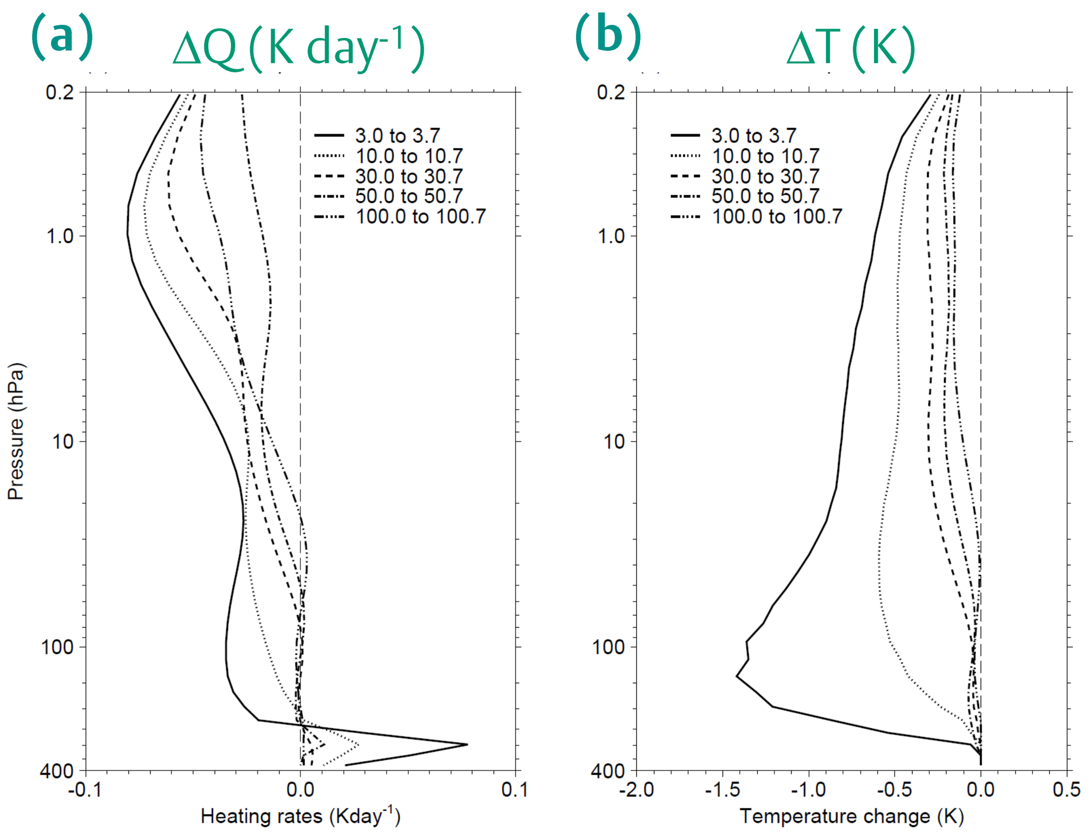


Figure 3: Vertical profiles at 70N of (a) ΔQ (K day^{-1}) and (b) ΔT (K) for a uniform 0.7 ppmv SWV perturbation applied to different uniform background SWV concentrations.

Key points

- As the background SWV concentration increases, the magnitude of ΔQ decreases at most levels except in the lowermost stratosphere.
- The magnitude of ΔT also decreases at most levels as the background SWV concentration is increased. The altitude of the maximum cooling increases.
- For background SWV concentrations ≥30 ppmv, the structure of ΔQ and ΔT resemble those from an increase in CO_2, with the largest ΔT near the stratopause.

6. Why is the cooling enhanced in the extra-tropics?

The magnitude of ΔT is a factor of two larger in the extra-tropics. The height of the tropopause is lower in the extra-tropics; this could affect the radiative balance of the stratosphere and thus impact ΔT. The control experiment is repeated, but with stratospheric temperatures adjusted to the same height as the tropical tropopause at all latitudes. The SWV perturbation is the same as in the control experiment; ΔQ is identical to Figure 1(a).

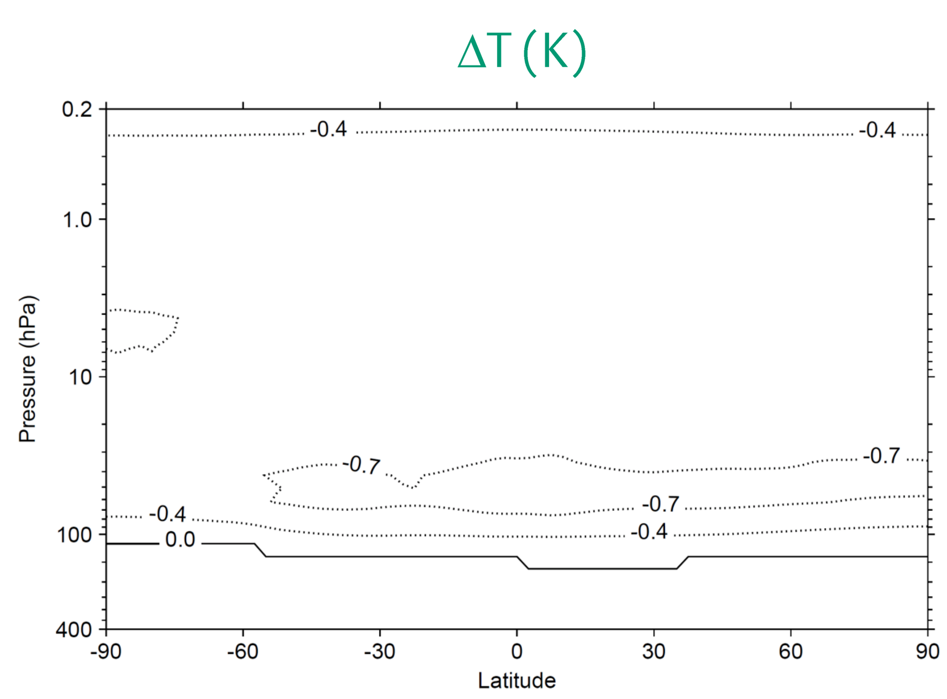


Figure 4: Annual-mean FDH ΔT (K) for a uniform 3 to 3.7ppmv SWV change with stratospheric temperatures adjusted only to the level of the tropical tropopause at all latitudes.

Key points

- The lobed structure of ΔT has disappeared.
- This means that the lobed structure of ΔQ seen in Figure 1(a), has little impact on the latitudinal structure of ΔT.
- As a layer of the stratosphere cools, it emits less radiation to neighbouring layers, causing those layers to cool. This effect enhances the cooling above that expected from the cooling-to-space term in ΔQ. The enhancement to the cooling is greater the lower the height of the tropopause; this effect is responsible for the lobed structure of ΔT in Figure 1(b).

7. Take home points

- A uniform increase in SWV causes stratospheric cooling which is largest in the lower stratosphere, decreases with increasing height and is a factor of two larger in the extra-tropics.
- The dominant gas which drives the cooling response in the mid and upper stratosphere is CO_2. In the lower stratosphere, ozone and water vapor have a more important role because the CO_2 bands are highly opaque at these levels.
- The low concentration of SWV is critical for determining that the cooling from a SWV perturbation is largest in the lower stratosphere. At higher background SWV concentrations, the water vapour bands become more opaque and the structure of the heating rate perturbation and cooling resemble those from an increase in CO_2.
- The latitudinal gradient in the height of the tropopause is responsible for the lobed structure of the cooling that results from a uniform SWV perturbation.

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