Stratospheric water vapour and climate: sensitivity to the radiative properties of water vapour

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1. Introduction

Trends in stratospheric water vapour (SWV) can affect surface climate by causing a direct radiative forcing on the troposphere [1], and by altering stratospheric temperatures [2] which can drive dynamical interactions between the stratosphere and troposphere [3]. These mechanisms are dependent upon the radiative characteristics of water vapour in the stratosphere, which are poorly constrained across different radiation codes [4].

This study investigates the errors in heating rate, radiative forcing and stratospheric temperature that result from perturbations in SWV in a range of radiation codes which vary in complexity from a line-by-line (LBL) code to broad-band codes. The results have important implications for modelling the climate impacts of SWV trends.

2. Properties of water vapour in the stratosphere

- The dominant contribution of water vapour to stratospheric heating rates comes from the water vapour pure rotation bands ($\nu < 400$ cm^{-1}) [5].
- Under stratospheric conditions, these bands consist of thousands of very narrow spectral lines (half-width $< 10^{-4}$ cm^{-1}).
- The low concentration of water vapour in the stratosphere (~few ppmv) means that, although the band centres are optically thick, the stratosphere as a whole is optically thin and only weakly absorbing ($Q < 1$ K day^{-1}).

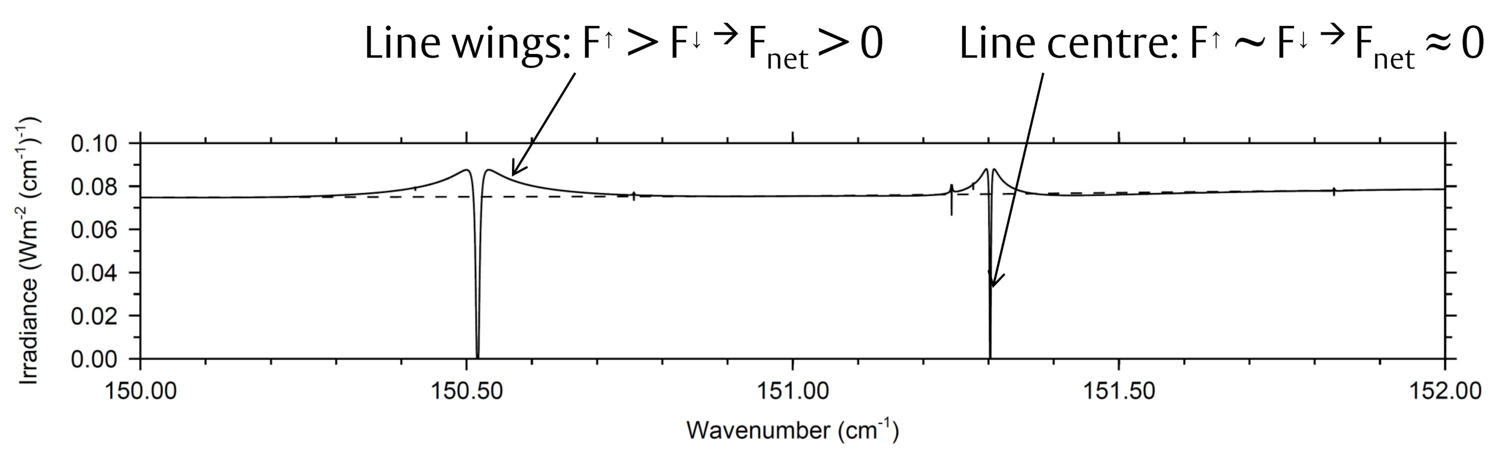


Figure 1: *The net irradiance (W m^{-2} (cm^{-1})$^{-1}$) at 45 km in the spectral interval 150-152 cm^{-1} in a midlatitude summer (MLS) atmosphere with 3 ppmv SWV using the Reference Forward Model (RFM; [6]) LBL code. The solid line shows the calculation with a spectral sampling resolution, $\Delta\nu$, of 0.0001 cm^{-1} and the dashed line shows $\Delta\nu$=1.0 cm^{-1}. If $\Delta\nu$ is too coarse, the structure of the spectral lines is not properly captured.*

3. Method

The radiative impact of uniform perturbations in SWV is considered using both the fixed dynamical heating (FDH) method [7] and two atmospheric GCMs.

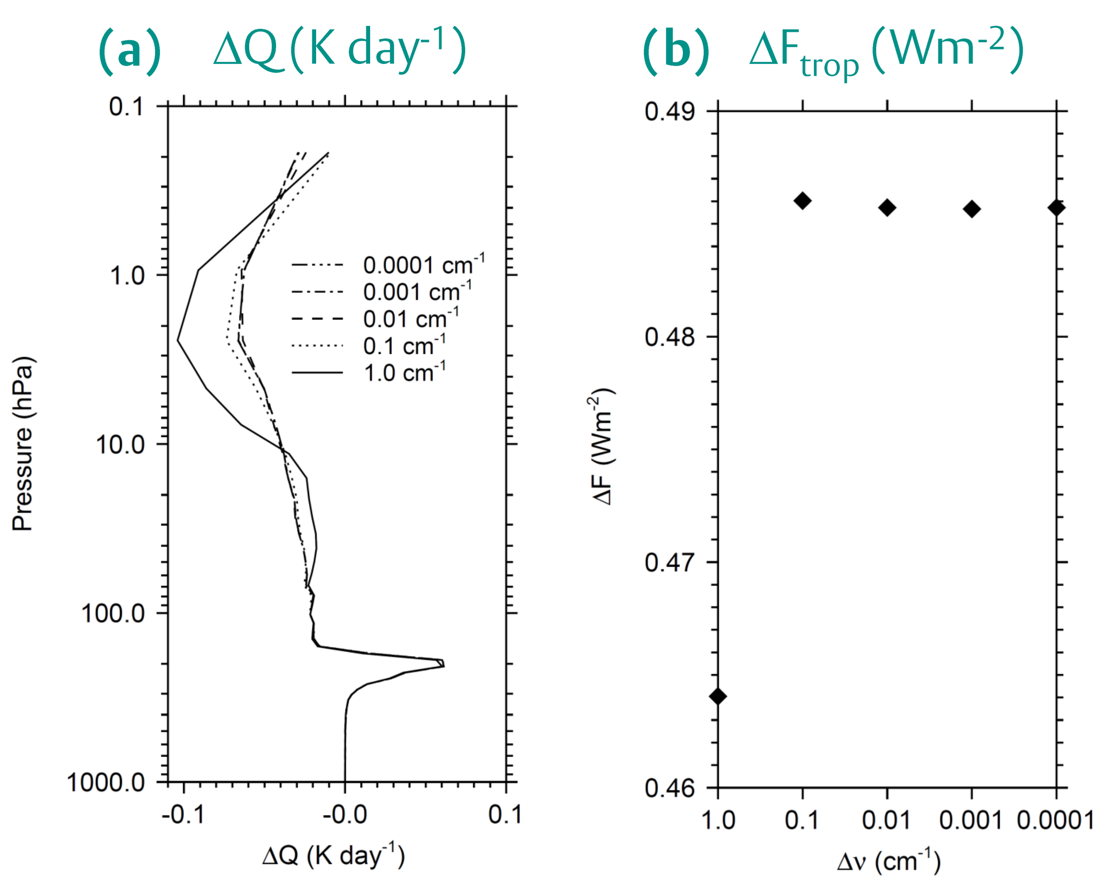
The FDH method: In the presence of a radiative perturbation, the stratosphere is assumed to adjust its temperature to achieve a new equilibrium state under the idealised assumption that the dynamical component of the heating rate remains the same.

The calculations in Sections 4 and 5 all assume a uniform increase in SWV from 3 to 3.7 ppmv in an MLS atmosphere, with the tropopause defined to be at 157.6 hPa.

4. Representation in a line-by-line radiation code

The dependence of the instantaneous change in longwave (LW) heating rate, ΔQ_{LW}, and the instantaneous LW radiative forcing at the tropopause, ΔF_{trop}, on the spectral sampling resolution in a LBL code, $\Delta\nu$, is tested using the RFM [6].

Figure 1: *(a) Vertical profiles of the ΔQ_{LW} (K day^{-1}) due to a uniform increase in SWV from 3 to 3.7 ppmv for different values of the spectral sampling resolution $\Delta\nu$ (cm^{-1}). (b) The instantaneous LW ΔF_{trop} (W m^{-2}) for different values of $\Delta\nu$.*



Key points

- A $\Delta\nu \leq 0.01$cm^{-1} is required to properly simulate ΔQ_{LW} at pressures less than ~10 hPa.
- ΔQ_{LW} is largely insensitive to $\Delta\nu$ at pressures greater than ~70 hPa. This is because the spectral lines are broader at higher pressure.
- A lower resolution of $\Delta\nu \leq 0.1$cm^{-1} is required to simulate ΔF_{trop}. This is because absorption and emission from broader lines in the lower stratosphere dominate the change in irradiance at the tropopause due to the SWV perturbation.

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4. Errors in narrow and broad-band radiation codes

The same SWV perturbation experiment is repeated in the Reading narrow-band model (NBM; [8]), the Edwards and Slingo radiation code (ESRTM; [9]) and the Morcrette code [10], which includes updates for water vapour by Zhong and Haigh (ZHMORC; [11]).

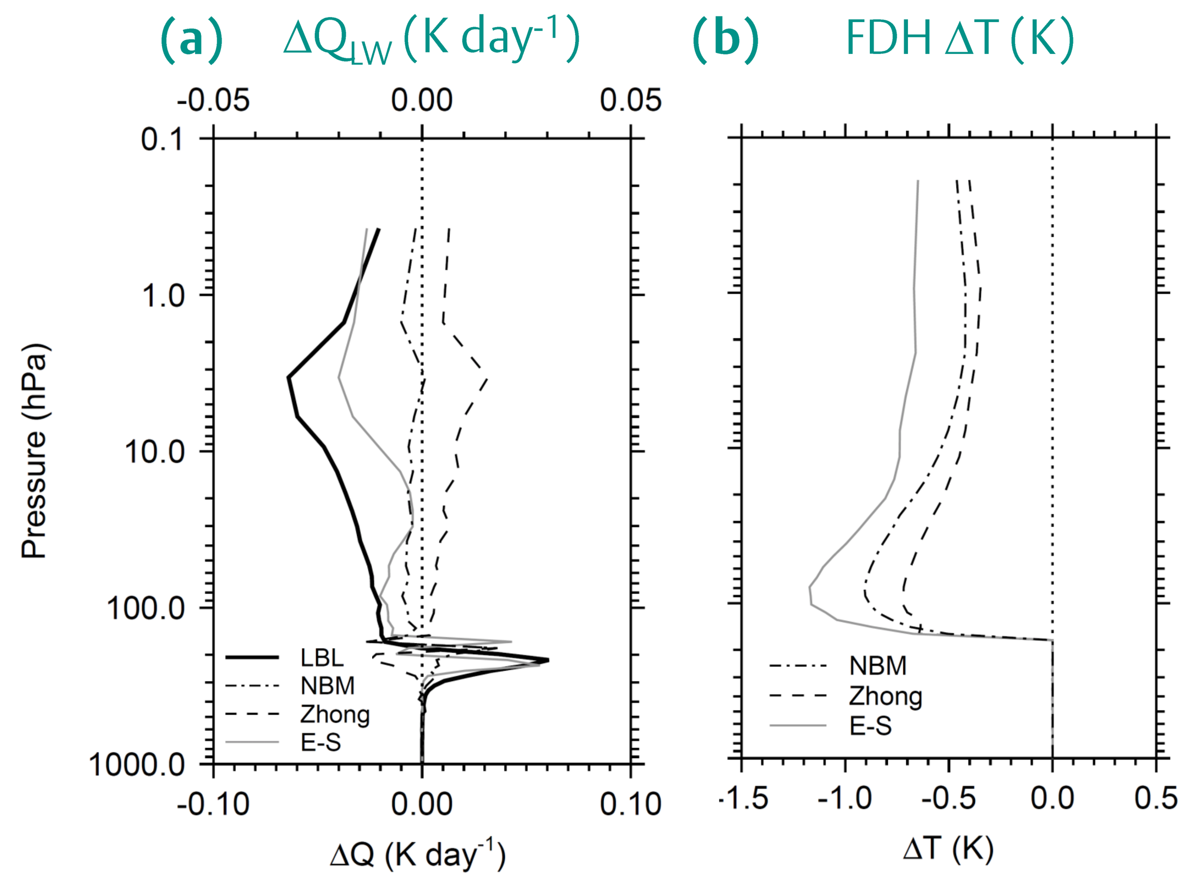

Figure 2: *(a) The ΔQ_{LW} (K day^{-1}) for the 3 to 3.7 ppmv SWV perturbation. The thick black line shows the LBL code using $\Delta\nu$=0.0001cm^{-1}. The band models are plotted as anomalies relative to the LBL calculation using the upper axis. (b) The FDH equilibrium temperature change, ΔT (K), due to the same SWV perturbation in the three band models.*

Model	RFM	NBM	ZHMORC	ESRTM
ΔF_{trop} (W m^{-2})	0.486	+13%	-15%	+32%
ΔF_{adj} (W m^{-2})	---	0.312	-25%	+19%

Key points

- The errors in ΔQ_{LW} are generally smallest in the NBM.
- The ESRTM overestimates ΔQ_{LW} in the lower and upper stratosphere by ~70%.
- The ZHMORC code underestimates ΔQ_{LW} by ~25% throughout the stratosphere.
- There is a factor of two difference in ΔT between the ESRTM and the ZHMORC code.

5. Impact on GCM response to SWV trends

The choice of radiation code will affect the impact of a given SWV trend on climate in a GCM. The response to an increase in SWV from 3 to 6 ppmv is investigated for two atmospheric GCMs: the IGCM [12], which uses the ZHMORC code, and HadGAM1 [13], which uses the ESRTM.

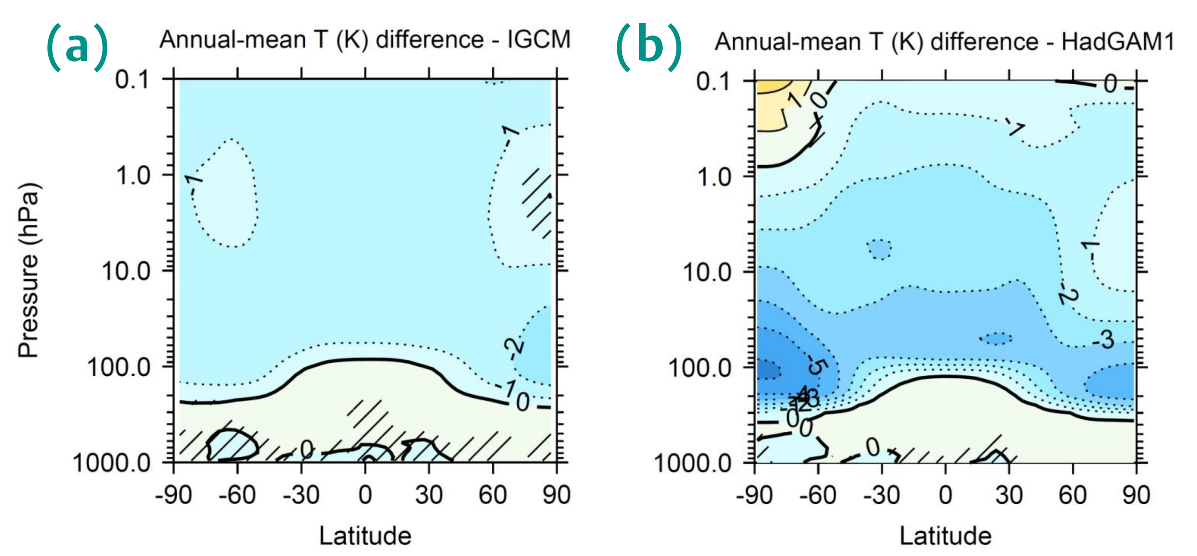

Figure 3: *The annual-mean temperature difference (K) between simulations with uniform 6 and 3 ppmv SWV in (a) the IGCM and (b) HadGAM1. The hatching indicates where the difference is not statistically significant at the 95% confidence level.*

Key points

- The change in stratospheric temperature is generally over a factor of 2 smaller in the IGCM.
- In the polar regions, dynamical feedbacks also play an important role in determining ΔT.

7. Take home points

- The choice of spectral sampling resolution in LBL calculations is particularly important for SWV. It should be quoted in all studies using LBL codes for SWV perturbation experiments.
- Modelling the radiative properties of water vapour in the stratosphere is a considerable challenge for broad-band radiation codes.
- The errors in broad-band codes may cause important differences in the climate response to SWV trends in different GCMs.
- Since broad-band codes incorporate different methods for calculating water vapour transmittance, there is likely to be no generic way of improving them. Attention needs to be paid to how they represent the transmittance at low absorber amounts and at low pressures, to ensure the can properly simulate the impact of changes in SWV.

References

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