Intercomparison of radiative forcing calculations of stratospheric water vapour and contrails

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Abstract

Seven groups have participated in an intercomparison study of calculations of radiative forcing (RF) due to stratospheric water vapour (SWV) and contrails. A combination of detailed radiative transfer schemes and codes for global-scale calculations have been used, as well as a combination of idealized simulations and more realistic global-scale changes in stratospheric water vapour and contrails. Detailed line-by-line codes agree within about 15\% for longwave (LW) and shortwave (SW) RF, except in one case where the difference is 30\%. Since the LW and SW RF due to contrails and SWV changes are of opposite sign, the differences between the models seen in the individual LW and SW components can be either compensated or strengthened in the net RF, and thus in relative terms uncertainties are much larger for the net RF. Some of the models used for global-scale simulations of changes in SWV and contrails differ substantially in RF from the more detailed radiative transfer schemes. For the global-scale calculations we use a method of weighting the results to calculate a best estimate based on their performance compared to the more detailed radiative transfer schemes in the idealized simulations.

Zusammenfassung


1 Introduction

Human-induced climate change is caused by many radiative forcing mechanisms, due to either their influence on the thermal infrared radiation, on solar radiation, or on a combination of the two (Forster et al., 2007). Radiative transfer codes are generally adopted for estimating the radiative forcing, which introduces an uncertainty. Many intercomparison exercises have been performed to identify and quantify the uncertainty in such calculations (Boucher et al., 1998; Collins...
et al., 2006; Ellingson et al., 1991; Forster et al., 2005; Forster et al., 2001; Gohar et al., 2004; Meerkötter et al., 1999; Shine et al., 1995). For changes in the atmospheric constituents that affect both thermal infrared radiation and solar radiation, their contributions may have the same sign (e.g. changes in ozone in the troposphere) but it is more challenging if their contribution gives rise to radiative forcings of opposite sign. Here we will investigate two radiative forcing mechanisms that have positive longwave (LW) radiative forcing (RF) and negative shortwave (SW) RF for an increase in their abundance in the atmosphere, namely water vapour in the stratosphere and contrails. Since the net radiative forcing is the residual of LW and SW radiative forcings, the uncertainties in the net forcing may be particularly large, especially if the LW and SW components are of a similar magnitude. Changes in stratospheric ozone and mineral dust are examples of other radiative forcing mechanisms that have opposite signs for the LW and SW forcings. The problem is also relevant to the direct aerosol component that has an opposing forcings for the absorbing and scattering SW components (Schulz et al., 2006).

Water vapour emitted by aircraft perturbs background concentrations of water vapour in the atmosphere, and can lead to the formation of contrails (Sausen et al., 2005; Schumann, 2005). It is in the stratosphere where increase in water vapour from aircraft traffic may be significant because the background concentration is low and removal is slow (Gauss et al., 2003). It is likely that stratospheric water vapour (SWV) has increased over recent decades, but the magnitude of the trend and causes for the trend are uncertain (Scherer et al., 2008). Oxidation of methane in the stratosphere and a climate change feedback are the most probable cause for the observed increase in SWV (Hansen et al., 2005). Model simulations indicate that the SWV abundance responds to changes in the upper tropospheric and lower stratospheric temperature, such as can be caused by aerosols from volcanic eruptions and by changes in stratospheric ozone (Joshi and Shine, 2003; Stuber et al., 2001). The current contribution from aircraft to the increase in SWV is likely to be small, but could be significantly larger in the future, especially should there be fleets of high-flying supersonic aircraft (Søvde et al., 2007). There is much uncertainty in the radiative forcing of contrails and SWV from aircraft traffic (Sausen et al., 2005). This is due to many factors such as uncertainties in the amount and spatial distribution of the water vapour emitted and the amount, spatial distribution and properties of contrails formed, and to uncertainties in the radiative transfer calculations themselves.

In this study we concentrate on quantifying the uncertainties introduced by the radiative transfer simulations. We perform idealized calculations for one vertical profile to identify differences just due to the radiation codes themselves. Thereafter, we perform global-scale calculations to explore the impact of factors such as temperature, clouds, and surface albedo in addition to the radiation codes on the RF due to stratospheric water vapour and contrails. The purpose of the intercomparison is to assess the uncertainty in the RF calculations, in particular for the broad-band codes used in the climate model calculations. It is not the purpose of the paper to explain the differences, as this would be a formidable challenge, although in some cases we are able to identify which models are likely to be more reliable.

### 2 Models

A short description of each model together with appropriate references is given in Table 1. The radiative transfer codes are divided into three groups: line-by-line (LBL) models, intermediate complexity models, and broad-band models used for global calculations either for stand-alone RF calculations or as a part of a general circulation model (GCM). Two LBL codes (with different versions of one of the LBL codes for stratospheric water vapour) are included in this study.

There are several possible reasons why radiation codes may disagree. These include the number of spectral bands, the method of calculating multiple scattering, the origin of the data used to model gaseous absorption and the way that absorption data is used in the model. We note in particular that there have been many updates to the near-infrared spectral line data for water vapour in HITRAN in recent years (see e.g. Chagas et al., 2001; Giver et al., 2000; Rothman et al., 2005) which have led to a systematic increase in the calculated absorption. These factors mean that models with higher spectral resolution are not necessarily more reliable, and this especially applies to the differences between intermediate and broadband models, where the transmittance calculation has to be parameterized in some way.

### 3 Intercomparison setup

Calculations with the mid-latitude summer single profile were performed for various solar zenith angles and surface albedos. These calculations acted as a reference. The mid-latitude summer profile with a solar zenith angle of 30 degrees and a surface albedo of 0.2 was selected for the rest of the single column calculations and perturbations to stratospheric water vapour, and contrails were then introduced. The concentration of stratospheric water vapour was fixed at 3.0 ppmv and then at 3.7 ppmv and the RF due to this change was calculated. For contrails, the optical depth was varied between 0.1, 0.3, and 0.52 with no wavelength dependence. We span this range because of uncertainties in the actual contrail optical depth. To ensure that differences in single-scattering properties of contrail particles did not influence the intercomparison, the asymmetry
<table>
<thead>
<tr>
<th>Group</th>
<th>Model</th>
<th>Model descriptions</th>
<th>Reference</th>
<th>Sections in this article</th>
</tr>
</thead>
<tbody>
<tr>
<td>UiO</td>
<td>UIO_LBL</td>
<td>A line-by-line model (GENLN2) coupled to the multi-stream DISORT code. Used for calculations in LW and SW spectrum with 16 streams for both.</td>
<td>(MYHRE and STORDAL, 2001; STAMNES et al., 1988)</td>
<td>4.1.1-4.1.2</td>
</tr>
<tr>
<td></td>
<td>UIO_CCM</td>
<td>Radiation code in the NCAR climate model. The LW calculation uses a broad band absorptivity/emissivity model approach and SW with a delta-Eddington code.</td>
<td>4.1.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>UIO_BBMI</td>
<td>LW calculation with a broad band model. The SW code use the multi-stream DISORT code (with 8 streams) and broad bands for treatment of the gas absorption.</td>
<td>(MYHRE et al., 2007)</td>
<td>4.1.1 &amp; 4.2.1</td>
</tr>
<tr>
<td></td>
<td>UIO_BBMS</td>
<td>The SW and LW codes use the multi-stream DISORT code (with 8-streams) and broad bands for treatment of the gas absorption.</td>
<td>(MYHRE and STORDAL, 2001)</td>
<td>4.1.2 &amp; 4.2.2</td>
</tr>
<tr>
<td>UW</td>
<td>UW_MOD</td>
<td>The Moderate Resolution Transmission (MODTRAN) Code calculates atmospheric transmittance, radiance, and flux. MODTRAN is based on the DISORT solver. The LW and SW calculation uses 8 streams and spectral resolution of 15 cm⁻¹.</td>
<td>(BERK et al., 1998)</td>
<td>4.1.1-4.1.2</td>
</tr>
<tr>
<td></td>
<td>UW_STR</td>
<td>A band model based on the DISORT solver. Used for calculation in SW and LW spectrum with 8 and 2 streams. There are 24 SW and 105 LW bands.</td>
<td>(STAMNES et al., 1988)</td>
<td>4.1.1-4.1.2</td>
</tr>
<tr>
<td></td>
<td>UW_FU</td>
<td>Fu-Liou code developed by FU &amp; LIOU (1992, 1993) includes delta 2/4 streams for SW and LW. There are 6 LW and 12 LW bands.</td>
<td>(FU and LIOU, 1992; FU and LIOU, 1993)</td>
<td>4.1.1-4.1.2 &amp; 4.2.2</td>
</tr>
<tr>
<td>CNRM</td>
<td>ARPEGE-Climate single column model</td>
<td>The SW is divided into 2 bands. Droplet absorption and scattering is treated with a Delta-Eddington approximation. The LW has 6 spectral domains and uses a greybody emissivity formulation. For the contrail cases, the greybody emissivity formulation is replaced by a two-stream approximation in order to accommodate the prescribed optical properties of the contrail.</td>
<td>(MORCRETTE, 1990)</td>
<td>4.1.1, 4.1.2, 4.2.1, &amp; 4.2.2</td>
</tr>
<tr>
<td>DLR</td>
<td>ECHAM4/SLT</td>
<td>Broad band code designed for use in 3D GCM: absorptivity/emissivity approach for LW, 6 bands; SW (2 bands) with delta-Eddington approximation.</td>
<td>(LAND et al., 2002)</td>
<td>4.2.1</td>
</tr>
<tr>
<td></td>
<td>ECHAM4/ATT</td>
<td>Radiation code identical to ECHAM4/SLT, but changed water vapour background due to different water vapour advection treatment (Lagrangian).</td>
<td>(STENKE et al., 2008)</td>
<td>4.2.1</td>
</tr>
<tr>
<td>UoR</td>
<td>UoR_RFMP*</td>
<td>A line-by-line radiative transfer code (Reference Forward Model) developed at the University of Oxford (LW calculations only).</td>
<td>(DUDHIA, 1997)</td>
<td>4.1.1</td>
</tr>
<tr>
<td></td>
<td>UoR_RFMP</td>
<td>UREAD/RFMP coupled to a Discrete Ordinate Code (Calculations for LW and SW)</td>
<td>(STAMNES et al., 1988)</td>
<td>4.1.1, 4.1.2</td>
</tr>
<tr>
<td>UoR</td>
<td>UoR_NBM</td>
<td>LW code is a Malkmus random-band model at 10 cm⁻¹ resolution; SW code is (a) 4 stream discrete ordinate code, with 5 nm resolution in ultraviolet, 10 nm resolution in the visible and (b) a delta-Eddington code with exponential sum fitting in 14 bands in the near-IR.</td>
<td>(CHAGAS et al., 2001; FORSTER and SHINE, 1997)</td>
<td>4.1.1, 4.1.2, 4.2.1</td>
</tr>
<tr>
<td></td>
<td>UoR_FU</td>
<td>As UW/FU – implementation as described in RADEL and SHINE (2008)</td>
<td>(FU and LIOU, 1992; FU and LIOU, 1993)</td>
<td>4.1.2, 4.2.2</td>
</tr>
<tr>
<td>UoR</td>
<td>UoR_E-S</td>
<td>Edwards-Slingo radiation code, offline version of the two-stream radiation code used in the UK Met Office Unified Model, uses delta-Eddington approximation in the solar region and a diffusivity factor of 1.66 in the thermal region, the spectral resolution is variable: we use six and eight spectral bands in the SW and LW regions respectively.</td>
<td>(EDWARDS and SLINGO, 1996)</td>
<td>4.1.1, 4.2.1</td>
</tr>
<tr>
<td>UoL</td>
<td>UoL_E-S</td>
<td>Edwards and Slingo radiation code. 4 stream discrete ordinate scattering code. 9 band longwave, 6 band solar scheme as used in the HadGEM climate model. Recently identified corrections to Rayleigh scattering have been made.</td>
<td>(EDWARDS and SLINGO, 1996)</td>
<td>4.1.1; 4.1.2; 4.2.1; 4.2.2</td>
</tr>
</tbody>
</table>
factor was specified to be wavelength independent (0.8) and the single scattering albedo was 1.0 in the solar spectrum and 0.6 in the terrestrial spectrum. These are typical values for contrail optical properties (Strauss et al., 1997). Simulations were performed for a 100% contrail cover, with the contrails between 10 and 11 km height. Instantaneous LW, SW, and net RF are reported at the tropopause (179 hPa).

Global calculations for the change in stratospheric water vapour from 3.0 to 3.7 ppmv and for change due to emissions by sub and supersonic aircrafts were performed. In these simulations SWV is fixed to these abundances and no feedback from the temperature change from SWV is taken into account. The aviation water vapour increase has been derived from water vapour emissions for 2050 generated by the SCENIC project (Søvde et al., 2007). Radiative forcing (instantaneous as well as with stratospheric adjustment) at the tropopause is reported. For the intercomparison of the effect of contrails on the global scale, a 1% homogeneous cover with a contrail top at 11 km was used. The contrails had an optical depth of 0.3, and the other optical properties were similar to the single profile exercise. Radiative forcing at the top of the atmosphere is reported. Each modelling group used their own data for temperature, clouds, water vapour in the troposphere, surface albedo, and tropopause altitude for the global-scale calculations.

### Table 2: LW, SW, and net RF for global SWV changes (in Wm$^{-2}$). LW and net RF shown for both instantaneous and stratospheric temperature adjusted RF.

<table>
<thead>
<tr>
<th></th>
<th>SWV 3.0 – 3.7 ppmv</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>LW inst</td>
<td>LW adj</td>
<td>SW</td>
<td>Net inst</td>
<td>Net adj</td>
</tr>
<tr>
<td>UiO_BBM</td>
<td>0.41</td>
<td>0.29</td>
<td>-0.058</td>
<td>0.35</td>
<td>0.23</td>
</tr>
<tr>
<td>UoR_NBM</td>
<td>0.40</td>
<td>0.27</td>
<td>-0.020</td>
<td>0.38</td>
<td>0.25</td>
</tr>
<tr>
<td>UoR_E-S</td>
<td>0.52</td>
<td>0.29</td>
<td>-0.030</td>
<td>0.49</td>
<td>0.26</td>
</tr>
<tr>
<td>ECHAM4/ATT</td>
<td>0.41</td>
<td>0.25</td>
<td>-0.051</td>
<td>0.35</td>
<td>0.20</td>
</tr>
<tr>
<td>ECHAM4/SLT</td>
<td>0.25</td>
<td>0.19</td>
<td>-0.034</td>
<td>0.22</td>
<td>0.16</td>
</tr>
<tr>
<td>UW_FU</td>
<td>0.37</td>
<td></td>
<td>-0.052</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>CNRM_ARPEGE</td>
<td>0.31</td>
<td></td>
<td>-0.055</td>
<td>0.26</td>
<td></td>
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<tr>
<td>UoL_E-S</td>
<td>0.49</td>
<td>0.40</td>
<td>-0.021</td>
<td>0.49</td>
<td>0.38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Aircraft 2050</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LW inst</td>
<td>LW adj</td>
<td>SW</td>
<td>Net inst</td>
<td>Net adj</td>
</tr>
<tr>
<td>UiO_BBM</td>
<td>0.058</td>
<td>0.062</td>
<td>-0.011</td>
<td>0.047</td>
<td>0.050</td>
</tr>
<tr>
<td>UoR_NBM</td>
<td>0.081</td>
<td>0.052</td>
<td>-0.005</td>
<td>0.076</td>
<td>0.047</td>
</tr>
<tr>
<td>ECHAM4/ATT</td>
<td>0.056</td>
<td>0.043</td>
<td>-0.008</td>
<td>0.047</td>
<td>0.035</td>
</tr>
<tr>
<td>ECHAM4/SLT</td>
<td>0.044</td>
<td>0.035</td>
<td>-0.007</td>
<td>0.037</td>
<td>0.028</td>
</tr>
<tr>
<td>UW_FU</td>
<td>0.059</td>
<td></td>
<td>-0.009</td>
<td>0.049</td>
<td></td>
</tr>
<tr>
<td>CNRM_ARPEGE</td>
<td>0.044</td>
<td></td>
<td>-0.009</td>
<td>0.035</td>
<td></td>
</tr>
</tbody>
</table>

### 4 Results

#### 4.1 Single profile cases

##### 4.1.1 Stratospheric water vapour

The results for the change in SWV from 3.0 to 3.7 ppmv are presented in Figure 1. For the net RF, the difference among the models is more than a factor of two, but the separate LW and SW RF also differ by this same factor. Differences between the net RF for the LBL models are small, but that is due to a compensation of larger differences for the LW and SW RF, particularly the latter. The method of integration to irradiances has little influence on the results for the two versions of the UoRLBL codes. The stronger short-wave forcing in the UoRLBL is likely to be due to the use of more recent spectral line data (HITRAN-2001) compared to the UiOLLBL calculations (HITRAN-1992) (see section 2). To investigate the implementation of radiative transfer schemes, three types of codes are used at two different groups. The Streamer codes give identical results, and the two groups using the Fu-Liou code have identical LW results and with SW results being only slightly different. The E-S code has been implemented at UoR and UoL with identical LW RF, but with SW RF that differs by more than 50%. This is due to differences in the absorption data in a different version of the E-S code. Three of the intermediate complex models give a weak SW RF (at least a factor of two weaker than the LBL codes) and thus a high net RF. The differences
for the differences. In general the deviations are larger for the broad-band models compared to the intermediate complexity models (in particular for LW) indicating a need for further investigation of the parameterizations for shortwave absorption and their dependence on the source of absorption data.

### 4.1.2 Contrails

The second part of the intercomparison concerned the addition of contrails to the single-profile cases. The properties of the contrails were described in section 3. Figure 2 shows the RF due to contrails for the different models and at three different solar zenith angles (30, 60, and 75 degrees) upon which the RF is known to depend substantially (Meerkötter et al., 1999; Myhre and Stordal, 2001; Stüber et al., 2006). All results shown are for a 100 % contrail cover and for a contrail optical depth of 0.3.

The differences in the LW and SW components between the models are much smaller for the contrail RF than they were for the RF due to SWV. The differences are a maximum of 35 % for both LW and SW RF if the CNRM_ARPEGE code is excluded. The magnitude of the SW RF for contrails is, for some solar zenith angles, more comparable to the LW RF than is the case for SWV. Therefore, the relative difference in the net RF between models can be large, despite rather small differences in SW and LW RF. Differences for the LBL codes are about 15 % for LW (smaller for SW) and the difference for the net RF is enhanced, since the deviations for LW and SW RF go in the same direction for the two codes. The sign for the net RF is still the same for the two LBL codes for the three solar zenith angles, more comparable to the LW RF than is the case for SWV. Therefore, the relative difference in the net RF between models can be large, despite rather small differences in SW and LW RF. Differences for the LBL codes are about 15 % for LW (smaller for SW) and the difference for the net RF is enhanced, since the deviations for LW and SW RF go in the same direction for the two codes. The sign for the net RF is still the same for the two LBL codes for the three solar zenith angles.

### 4.2 Global calculations

#### 4.2.1 Stratospheric water vapour

Figure 3 shows global and annual mean LW, SW, and net RF resulting from a change in SWV from 3.0 ppmv to 3.7 ppmv, and Figure 4 shows global and annual mean LW, SW, and net RF of estimated change in SWV from sub and supersonic aircraft in 2050 (Søvde et al., 2007). The results shown in the figures include stratospheric temperature adjustment. Table 2 summarizes RF for instantaneous and adjusted RF. The agreement in Figure 3
Figure 2: Longwave (light-grey, left), shortwave (grey, lower left), and net (black, lower right) RF at the top of the atmosphere due to contrails with optical depth 0.3. Shortwave and net RF are shown for solar zenith angles of 30 degrees, 60 degrees, and 75 degrees (see text for further details).
Figure 3: Global and annual mean longwave (light-grey), shortwave (grey), and net (black) RF for a global change in stratospheric water vapour from 3.0 to 3.7 ppmv. Stratospheric temperature adjustment is included in the simulations.

Figure 4: Global and annual mean longwave (light-grey), shortwave (grey), and net (black) RF for a global change in stratospheric water vapour from sub and super sonic aircrafts estimated for 2050 in the SCENIC project (Søvde et al., 2007). Stratospheric temperature adjustment is included in the simulations.

is better than in Figure 1. The difference is more than 50% in the net RF, but this is less than in Figure 1, even though additional factors, such as spatial variability in meteorological fields of temperature, humidity, clouds as well as stratospheric temperature adjustment, have been introduced.

In Table 2, the strong reduction in the RF (LW and net) as a result of stratospheric temperature adjustment for the homogeneous SWV change from 3.0 to 3.7 ppmv can be seen in all six models that calculate both instantaneous and adjusted RF. The strongest reduction occurs in the UoR_E-S and the weakest in the ECHAM/SLT and UoL_E-S. The strong effect of stratospheric temperature adjustment in the UoR_E-S explains the much better agreement in Figure 3 than in Figure 1 for the E-S model. The UoL_E-S has a weaker effect of the stratospheric temperature adjustment than the UoR_E-S. The former model has a tropopause level at 100 hPa in the tropics and 250 hPa at mid and high latitudes. However, the stratospheric temperature adjustment is included at altitudes above 250 hPa at all latitudes and this could be a source for the difference in the effect of stratospheric temperature adjustment. It can also be seen in Table 2 that UW_FU and CNRM have a weaker instantaneous RF than most of the other models.

ECHAM4/SLT and ECHAM4/ATT both indicate derivatives of the well-established ECHAM4 climate model, with increased vertical resolution in the upper troposphere/lower stratosphere region (Land et al., 2002). In ECHAM4/ATT the operational semi-Lagrangian transport (SLT) scheme for water vapour and cloud water has been replaced by the Lagrangian advection scheme ATTLA (Reithmeier and Sausen, 2002). Using Lagrangian transport significantly reduces a distinct wet and cold bias in the extratropical lowermost stratosphere (Stenke et al., 2008) with a number of beneficial side effects such as a lowering of the extratropical tropopause (which is located at a too high altitude in ECHAM/SLT). The impact of the difference between ECHAM4/SLT and ECHAM4/ATT is shown.
in Table 2 to be significant and almost as large as the range between the other models, even though the radiation scheme is identical in both model versions. In the rest of the analysis we use the ECHAM/ATT model.

The deviations in net RF for SWV change estimated for 2050 in Figure 4 are significant, but still smaller than shown for the single profile cases. This is partly due to a compensation of the LW and SW RF, as well as the different effects of the stratospheric temperature adjustment. For a homogeneous SWV increase, cooling will occur in the entire stratosphere; however, for water vapour changes that reach their maximum at altitudes higher than the tropopause, heating may occur just above the tropopause (Myhre et al., 2007). Whereas UoR_NBM and ECHAM4/ATT have a strong reduction in the RF due to the effect of the stratospheric temperature adjustment, the UiO_BBM has a weak increase. The much weaker SW RF for UoR_NBM is also consistent with the results shown in Figure 1 and 3.

The SW RF results for SWV show larger differences than the LW RF. This is partly because stratospheric temperature adjustment reduces the difference in the LW calculations but also that some of the models with the weakest LW RF have not calculated the full RF. However, it seems that factors such as background humidity, temperature and clouds do not introduce an additional large uncertainty in the calculation of RF due to SWV.

### 4.2.2 Contrails

Global and annual mean RF for a 1% homogeneous contrail cover is shown in Figure 5 for clear and all-sky conditions. For UiO_BBM, UoR_FU, and UW_FU the difference between the clear and all-sky RF is small, as shown in earlier studies (Myhre and Stordal, 2001; Rädel and Shine, 2008; Stuber and Forster, 2007). The agreement between the five models is slightly better for the all-sky conditions than for the clear-sky conditions, because UoL_E-S has a large impact of clouds on the LW RF and that UoL_E-S and CNRM_ARPEGE have a weak impact of clouds on the SW RF. Differences between some of the models are of similar magnitude for the clear sky condition as in Figure 2, but slightly amplified for the global simulations (e.g. UW_FU versus UiO_BBM). CNRM_ARPEGE and UoL_E-S have substantially stronger LW RF for the clear-sky conditions, and for the former model this is consistent with the findings in Figure 2. The relatively large clear sky LW RF from UoL_E-S compared to results in Figure 2 could be due to several factors among them temperatures and water vapour.

Figure 6 shows the geographical distribution of the annual mean all-sky RF for a 1% homogeneous contrail cover (global mean shown in lower panel of Figure 5). Despite differences in the magnitude, the spatial pattern from the five models has many similarities with maximum values in sub-tropical regions and particularly over the Sahara. The latter is due to a maximum LW RF and weak SW RF because of the high reflectivity over the Saharan region. It should be mentioned here that contrail formation in some of the regions with maximum RF is not so likely at 10–11 km due to the dry conditions. Weak RF is simulated near the equator due to large cloud cover, in particular for UiO_BBM with even negative values in a narrow region. There is also a consistent pattern between the models with rather low values at high latitudes (even negative in CNRM_ARPEGE).

To convert the idealized experiment with a homogeneous contrail cover over to a more realistic case, the contrail cover as estimated in Rädel and Shine (2008) is adopted. The UiO_BBM, UoR_FU, UW_FU, and CNRM_ARPEGE net RFs for a realistic contrail cover (and contrail optical depth of 0.3) are 9.3, 10, and 12, and 15 mWm$^{-2}$, respectively. This is a slightly smaller difference than shown in Figure 5 because the estimated contrail cover is small where the differences in Figure 5 are the largest (i.e. in the tropics).

### 5 Interpretation of results

The single profile calculation can be used in a ranking of the results and for an evaluation of a best estimate for the global calculations. For the single profile cases we have the benchmark LBL calculations available; despite the fact that there remain uncertainties in the LBL codes, they still must be regarded as the most reliable. The LBL model formulation and their complexity are much closer to first principles than schemes used for global calculations. We treat therefore LBL as more accurate, but acknowledge that there is an uncertainty associated with the LBL as well. However, because of their heavy computational requirements, it is impractical to use them for global calculations. To generate a “best estimate” for the global calculations from the models contributing to the intercomparisons, a number of options are available. These include (a) simply choosing the global results from the intermediate or broad-band model that are closest to the LBL code for the single profile cases, (b) taking a simple arithmetic average of all the model results or (c) finding an appropriate weighting to combine the model results. We regard option (a) as too restrictive, as just because a model agrees with the LBL results for one profile should not be taken to imply it does so for all cases. However option (b) neglects all information from the single profile comparisons, and the degree to which the model agrees with the reference results. Therefore we adopt option (c), but also compare it with the results from option (b).

For option (c) we use a weighting adopted by Murphy et al., 2004 and the following formula:

\[ V_i = e^{-(0.5\sigma(RF_i - RF_0)^2/\sigma^2)} \]

where $\Delta RF_i$ is the absolute difference in RF between model $i$ and the reference (mean of LBL results), and $\sigma$
is the standard deviation of the results of the single profile calculations. Results from identical models have not been double counted in the calculation of the standard deviation.

The weighting $V_i$ for each model is calculated separately for SW and LW and thereafter applied for calculation of a best estimate for SW and LW by simply multiplying the percentage weighting of each model with the RF. This method has been applied to the global SWV changes with weighting factors 36.7%, 41.9%, 5.4%, 10.5%, and 5.4% for LW and 41.5%, 4.4%, 11.6%, 3.6%, and 38.9% for SW for UiO_BBM, UoR_NBM, UoR_E-S, ECHAM4, and UoL_E-S, respectively. The resulting best estimate is 0.284, –0.039, and 0.245 Wm$^{-2}$ for LW, SW, and net RF of SWV change from 3.0 to 3.7 ppmv. A simple average of the results (option b above) gives 0.300, –0.038, and 0.262 Wm$^{-2}$ for LW, SW, and net RF. Thus the weighting has a small impact on the SW RF, but gives a weaker LW RF since the models with very high LW RF have a large deviation from the LBL models.

The SW single profile calculations of contrails revealed strong solar zenith angle dependence, as did the deviations from the LBL results. To calculate the SW weighting we have averaged the results for the three solar zenith angle results. The resulting weighting factors for LW are 12.6%, 20.8%, 20.8%, 28.4%, and 17.4%, respectively, for UiO_BBM, UoR FU, UW FU, CNRM_ARPEGE, and UoL E-S. The SW weighting factors for the same models are 24.9%, 26.1%, 24.7%, 2.7%, and 21.6%. Including these factors in the calculations of 1 % contrail cover results in 0.260, –0.097, and 0.163 Wm$^{-2}$, respectively for LW, SW, and net RF. The corresponding numbers for a simple average is 0.250, –0.107, and 0.143 Wm$^{-2}$. A similar deviation for LW and SW RF for the two methods adds up to a twice as
large deviation for the net RF of 0.020 Wm$^{-2}$.

The uncertainties in terms of standard deviations among the models considered in the above analysis show similar ranges in global calculation as in the single profile cases for SWV changes, indicating that the uncertainties associated with input parameters do not exceed the uncertainties in the use of the radiation codes. For contrails, the standard deviations among the models are slightly higher for global calculations than the single profile calculations, but smaller than for SWV changes.

6 Summary

With varying complexity in radiative transfer schemes, we have explored the uncertainties in the RF of changes in stratospheric water vapour and contrails. Seven groups have been involved in this intercomparison study as part of the EU project QUANTIFY. Our main findings are:

- Changes in SWV lead to larger differences in RF than contrails.
- Results from several of the models for global calculations of changes in SWV differ substantially from detailed radiative transfer schemes both for LW and SW radiation.
- Simulations of global changes in SWV differ by about a factor of 2 between the models, but cancellations of differences may indicate that uncertainties are larger.
- Although the SW RF has a magnitude much more comparable to the LW RF for contrails than it does for SWV changes, the sign of the net RF due to contrails for various solar zenith angles is similar among most of the models.

Figure 6: Geographical distribution of the annual mean all sky net radiative forcing at the top of the atmosphere for a homogeneous 1% contrail cover, UIO_BBM a), UoR_FU b), UW_FU c), CNRM d), UoL_E-S e).
The net RF due to global changes in contrails agree within a factor of two for a homogeneous contrail cover; the agreement is even better for a realistic contrail cover.

The pattern of geographical distribution of the RF for a homogeneous contrail cover is consistent between five models, but the magnitude is significantly different.

Differences in the global distributions of input fields of temperature, humidity, clouds, and surface albedo do not introduce a substantial uncertainty compared to the uncertainty in the radiative transfer schemes in the RF for contrails and change in stratospheric water vapour. In the case of stratospheric water vapour, the choice of external parameters (like tropopause height) may require more attention, if they have a direct influence on the estimated perturbation itself.

Weighting the results based on their performance against detailed radiative transfer schemes does not lead to an average that differs substantially from a simple average, but is to be preferred since the best estimate is less influenced by outliers compared to detailed schemes.

The results, and in particular the deviations between the benchmark line-by-line models and the simpler models, indicate aspects of the simpler models that appear to be in need of attention, if their radiative forcing calculations are to be improved. This is particularly the case for absorption data for water vapour. In the solar spectrum the absorption data have been significantly updated in recent years and the absorption data in the models should be accordingly updated. In the LW spectrum the parameterization of absorption by water vapour in the stratosphere should be investigated further.

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