Voigt Line Approximation in the ECMWF Radiation Scheme

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ABSTRACT

The vertical extension of a general circulation model generally requires a modification of the model's highly parameterized radiation scheme in order to include approximately the absorption by lines with a Voigt profile. For the European Centre for Medium-Range Weather Forecasts radiation scheme, a modification of the Lorentz line width provides a practical solution for this problem. Thus, the domain of this wideband radiation scheme is extended from the surface up to the mesopause.

1. Introduction

The profile of an absorption line originates from the uncertainty principle (natural broadening), the collisional broadening (due to perturbations to the energy levels of the molecule during a collision), and the Doppler broadening due to the motion of the molecule (Goody and Yung 1989). Only the last two processes are relevant for atmospheric radiation transfer, and the line profile resulting from the convolution of the two previous profiles is the Voigt line profile. In tropospheric general circulation models (GCMs), it is sufficient to consider only the collisional broadening using a Lorentz line shape. However, in a GCM including layers at pressures lower than 10 hPa, it is necessary to account for the Doppler broadening. As part of testing the ECMWF radiation scheme in a GCM including the troposphere, stratosphere, and lower mesosphere, a Voigt line shape approximation was tested in this radiation scheme.

2. Modification of the Lorentz line width

The radiation scheme is based on the European Centre for Medium-Range Weather Forecasts (ECMWF) wideband model (Morcrette 1991). The Voigt line shape is included very simply using the pressure correction method proposed by Fels (1979). In this method, a finite line width (assumed to represent the Doppler half-width of the line) is retained under low pressure conditions where the pure Lorentz line width α_L (proportional to the pressure) would normally become negligible. Practically, this is achieved by a modified Lorentz line shape f_{Lorentz} with a line width α_{Fels} proportional to the pressure corrected by an absorber-dependent residual pressure as in (1) and (2). The residual pressure is an indicator for the height of the transition from Lorentz dominated absorption to Voigt absorption:

$$\alpha_{\text{Fels}}(p, p_{\text{res}}, T) = \alpha_L(p_0, T)\frac{p+p_{\text{res}}}{p_0} = \alpha_L(p, T) + \alpha_L(p_{\text{res}}, T) \quad (1)$$

$$f_{\text{Lorentz}}(\nu - \nu_0) = \frac{\alpha_{\text{Fels}}}{\pi[(\nu-\nu_0)^2 + \alpha_{\text{Fels}}^2]}. \quad (2)$$

3. Cooling rates for atmospheric standard profiles

The residual pressure values are chosen as 30, 60, and 400 Pa for H_2O, CO_2, and O_3 absorption, respectively. The correction values for H_2O and O_3 were applied before by Schwarzkopf and Fels (1991). The plots in Fig. 1 show cooling rates computed for the McClatchey et al. (1971) profiles containing temperature, water vapor, and ozone profiles for typical clear sky conditions occurring in tropical conditions (TRO), midlatitude summer (MLS), and subarctic winter (SAW), respectively. The CO_2 concentration is fixed at 300 ppmv. The vertical grid contains 122 layers with 106 layers between the surface and 0.01 hPa. The dashed and the dotted lines present wideband model (WBM) results. The dashed line was computed without Voigt line correction, that is, it shows the pure Lorentz

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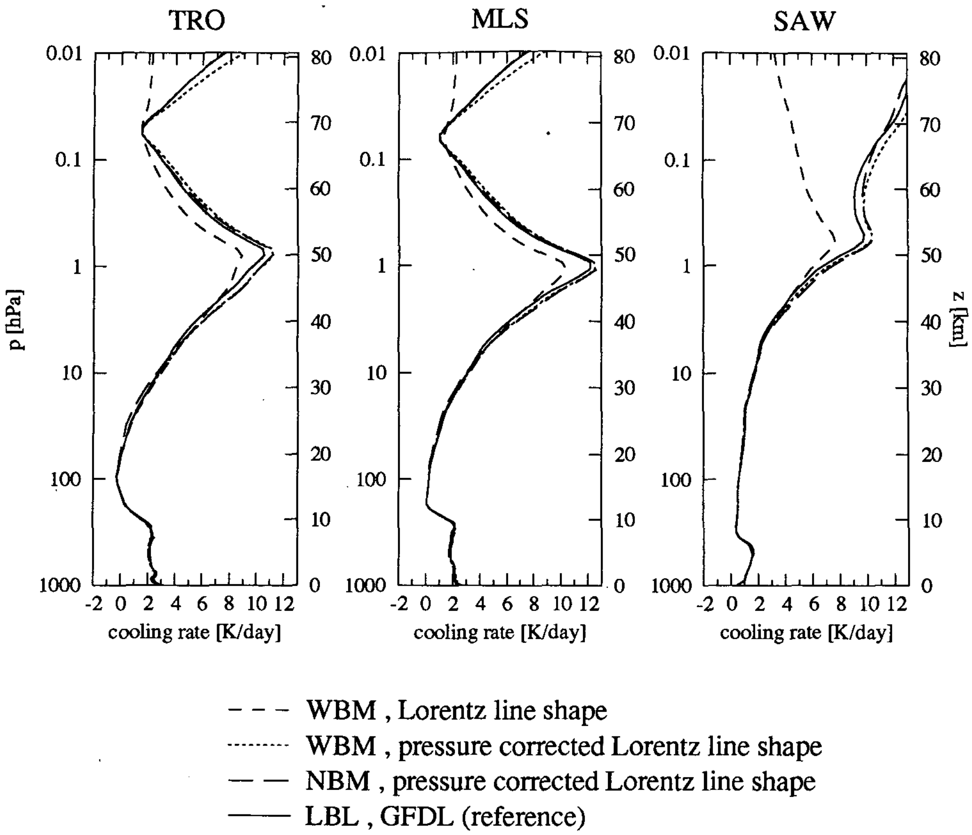

FIG. 1. Clear-sky cooling rates for the combined absorption by carbon dioxide, water vapor, and ozone in a tropical, midlatitude summer, and subarctic winter atmosphere. The NBM and LBL profiles in TRO and MLS are almost identical for 0.1 hPa > p > 0.01 hPa.

contribution. The dotted line was computed in the WBM with the pressure correction method. The long-dashed lines show cooling rates computed in the narrowband model (Morcrette and Fouquart 1985) from which the WBM was derived. The pressure correction method is applied to the narrowband model (NBM) in the same way as in the WBM. The full line is a reference cooling rate computed by Schwarzkopf and Fels (1991) in a line by line model (LBL).

As part of testing the ECMWF radiation scheme in a vertically extended version of the ECHAM GCM including troposphere, stratosphere, and lower mesosphere (Manzini 1993), this Voigt line shape approximation was also tested for a lower vertical resolution of 35 levels from the surface up to 0.1 hPa. Figure 2 displays the cooling rates for McClatchey profiles TRO, MLS, and SAW in 122-layer representation and 35-layer representation as solid and dotted lines, respectively. The high-resolution profile has 47 layers above 1 hPa, 32 layers above 0.1 hPa, and 17 layers above 0.01 hPa, while the low-resolution profile has only 4 layers above 1 hPa and none higher than 0.1 hPa.

4. Discussion and conclusions

The comparison of the cooling rates clearly shows that Lorentz line absorption alone should not be used in a GCM reaching higher than 10 hPa. The pressure-corrected cooling rates given by the WBM and the NBM are very similar to each other up to the mesopause where the cooling rates start to diverge systematically. Below the mesopause the WBM successfully approximates the NBM. Both lines are generally close to the LBL result. The most obvious deviations occur in the upper stratosphere (particularly TRO) and in the SAW mesosphere. In all three cases the deviation is less than 1 K day^{-1}. Fine tuning of the cooling rates is achieved by small modifications of the residual pressures.

The effect of a reduced vertical resolution is generally very small below the 2-hPa level. Above this level one encounters two different types of errors. The type 1 error is caused by the insufficient resolution of the temperature and ozone profile from the stratopause to the upper boundary. This results in an underestimation of the vertical net flux gradient and hence in a under-

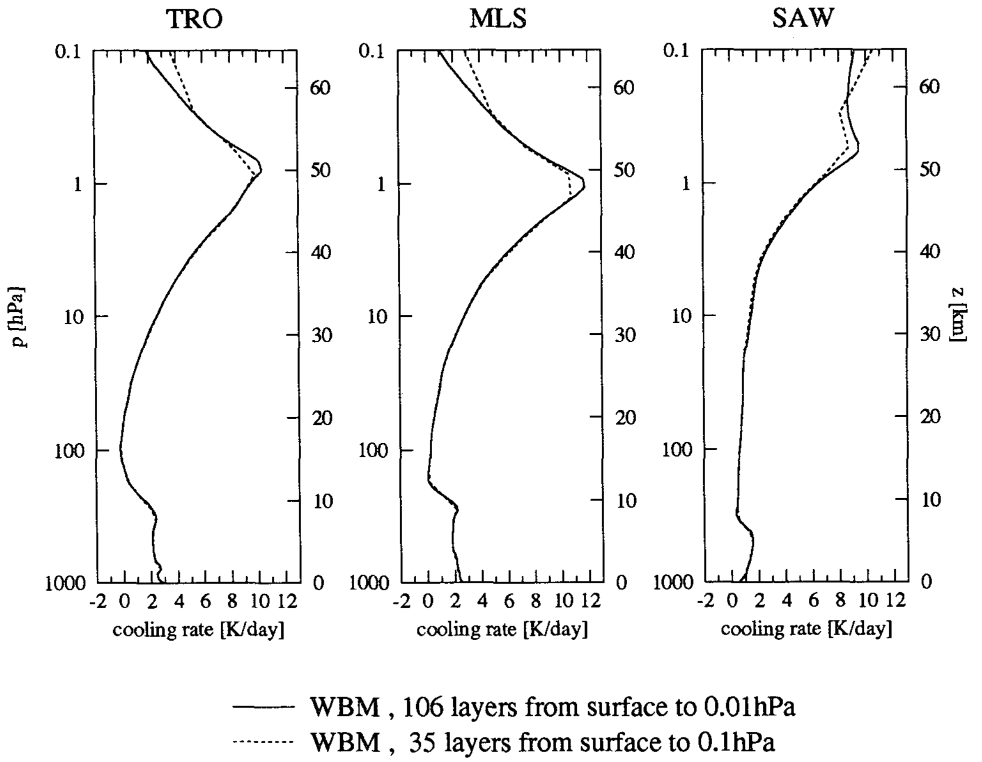

FIG. 2. Comparison of cooling-rate profiles computed on the 35-level grid reaching to 0.1 hPa with the high-resolution cooling-rate profiles having 122 levels, of which 91 levels lie below 0.1 hPa.

estimated cooling rate in the layers neighboring the stratopause. This error occurs clearly visible in all of the profiles TRO, MLS, and SAW. A second type of error occurs in the top layer where the cooling rate is suddenly overestimated as a result of an overestimated downward flux gradient. This error is typical for models that incorporate exact or approximate Voigt line shapes (or any other realistic line shapes) and have a zero LW downward flux assumption at the upper boundary (where $p = 0$) because the cooling rate on the highest level, which is $p = 0.1$ hPa on the 35-level grid, is computed from the flux divergence across this top layer. This flux gradient is necessarily overestimated because it involves the upper boundary LW flux assumption in contrast to the high-resolution computation, where the flux gradient at this level depends only on the fluxes at the interfaces to the upper and lower adjacent layers. However, neither type of errors is due to the pressure correction method itself but both are resolving and discretization problems that would even occur with a full Voigt line formulation within the vertical integration scheme of this radiation code.

In conclusion this comparison shows the effectiveness of the pressure correction method within the framework of the ECMWF wideband model, which can now be used from surface to mesopause. The two problems addressed above are not specific to the applied Voigt line approximation but have a more general nature. The computational costs of the radiation model are essentially the same as for the pure Lorentz line computation.

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