Solar Intermittence Implementation in the ACRANEB2 Radiative Transfer Scheme

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Gaseous optical depths normally need to be calculated at every time step in radiative transfer schemes. Because the parameters influencing them change relatively slowly, it is possible to avoid their recalculation, therefore saving computation time, as is commonly exploited in radiative transfer schemes. The only exception is the solar zenith angle, which changes rapidly and affects solar optical thicknesses in a broadband scheme such as ACRANEB2 via spectral saturation. With the introduction of a new version of the ACRANEB scheme the gaseous computations became more expensive (and accurate), necessitating intermittency in both solar and thermal bands to maintain short computation time. We show that it is possible to avoid full recalculation by interpolating optical thicknesses between their extreme values with respect to the solar zenith angle attained during an intermittence period, reducing model computation time by about 5 % without a significant loss of accuracy.

1 Introduction

As the atmospheric gaseous composition and temperature and pressure profile do not change as quickly as the cloud cover, we can speed up radiative computations by calculating gaseous optical thicknesses less frequently than the rest of the variables. In other words, we can introduce an *intermittence* period longer than the model time step during which the gaseous optical thicknesses are not recalculated.

In the thermal part of the spectrum, we can achieve this by simply maintaining constant optical thicknesses during the intermittence period. In the solar spectrum, however, the situation is complicated by the fact that optical thickness depends on the zenith angle. It is therefore necessary to devise a method of accounting for this change without the need to do a full recalculation of optical thicknesses.

2 Theoretical Considerations

In the following text, we assume a broadband model with two bands (solar and thermal), plane-parallel and delta-two stream approximations.

2.1 Monochromatic light

Let us first consider the simple case of monochromatic light passing through a homogeneous atmospheric layer. Radiation passing at cosine of the zenith angle μ is attenuated exponentially by the Beer-Lambert law:

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$$I(z_2) = I(z_1)\exp\left(-\frac{1}{\mu}k\Delta u\right)$$

where k is the mass extinction coefficient, and Δu is the mass of the absorber per unit area. Here, $\frac{1}{\mu}k\Delta u$ is the *optical path* through the layer.

In addition to *optical depth*, we use the concept of *optical thickness*. The *optical thickness* of a layer is commonly defined as the optical path through the layer in the vertical direction ($\mu = 1$), but we note that this is the same as normalizing the actual optical path by μ:

$$\tau := \tau(z_1, z_2; \mu = 1) = k\Delta u = \mu\left(\frac{1}{\mu}k\Delta u\right) = \mu\tau(z_1, z_2; \mu)$$

where $\tau(z_1, z_2; \mu)$ denotes optical path for radiation passing at the (cosine of) angle μ. We use the same symbol τ for optical thickness and optical depth, but stating its meaning explicitly where needed. In the monochromatic case, both definitions are equivalent, but the latter generalizes better to the broadband radiation treatment, where the Beer-Lambert law no longer holds. We will therefore use this latter definition:

$$\tau := \mu\tau(z_1, z_2; \mu)$$

2.2 Downward and upward broadband optical thickness

In a broadband radiative transfer scheme, it is necessary to distinguish downward and upward optical thickness of a layer. This is because the optical thickness depends not only on the properties of the layer (as in monochromatic case), but also the spectral composition of the radiation entering the layer and the length of the path through the layer, which determines the amount of spectral saturation.

The downward solar optical thickness is calculated for parallel radiation coming directly from the Sun at a zenith angle θ and is equal to the optical path through the layer normalized by cosine of the zenith angle (which is proportional to the length of the path).

The upward solar optical thickness, on the contrary, is calculated for diffuse radiation reflected from the surface, which does not have any associated direction in the δ-two stream approximation. In this case, the dependence on the zenith angle is only through its influence on the spectrum of the incoming radiation, which has passed through the atmosphere as parallel radiation at the given zenith angle.

The geometry of the downward case is depicted in Fig. 1.

2.3 Modified cosine of the zenith angle

The actual angle at which radiation passes through an atmospheric layer is not the same as the zenith angle. This is due to the sphericity of the atmosphere, and is particularly true for high zenith angles ($\mu \to 0$).

In order to transparently account for this effect, the ACRANEB2 scheme uses a modified cosine of the zenith angle in place of μ (Masek et al.):

$$\mu' = \frac{1}{\left(\left(\frac{a}{H}\mu\right)^2 + 2\frac{a}{H} + 1\right)^{1/2} - \frac{a}{H}\mu}$$

where a is the radius of the Earth, and H is the approximate height of the atmosphere. The ratio H/a was chosen to be a constant of 0.001324, for which $\mu'(\mu = 0) = 38.88$[3]. This has an additional benefit of preventing $1/\mu$ growing to infinity as $\mu \to 0$ in numerical calculations.

The modified cosine of the zenith angle is the natural coordiate for studying the change of optical thickness with the position of the Sun in the sky.

3 Analysis Using a Single Column Model

In order to empirically investigate dependece of broadband gaseous optical thicknesses on the zenith angle, we can use a single column model to calculate optical thicknesses for varying values of the zenith angle. We used multiple runs of the ACRANEB2 SCM model over a range of μ values from the interval $[0, 1]$.

3.1 Dependece of optical thickness on the zenith angle

The plot in Fig. 2 shows the result for a clear sky atmosphere with 87 layers in standard and log-log coordinates. The dependence is plotted as a function of the modified cosine of the zenith angle (see above). As you can see from the logarithmic plot, the dependence is close to a power function (i.e. is linear in the logarithmic coordinates). This suggest that a linear interpolation between extreme values of the zenith angle in an intermittence period could yield accurate enough results. Similar relatiotionship was observed in cloudy atmosphere and a number of additional cases.

3.2 Linear interpolation of optical thicknesses

As justified by the empirical analysis of optical thickness dependence on the zenith angle, we performed an experiment with the single column model where the log optical thicknesses were linearly interpolated with respect to log of the modified cosine of the zenith angle. The Fig. 3 shows the result for a clear-sky atmosphere, and a choice of solar intermittence interval of $\Delta\theta = 15^\circ$ (1 h on the equator on equinox). The heating rates were compared to the reference (non-interpolated) case. The difference in heating rates was the most significant for high zenith angles (low $\cos(\mu)$), when the change in the zenith angle corresponds to a large change in the cosine of the zenith angle. The difference was within 0.1 K/day (5 %) for all but the top layers, which is an acceptable loss of accuracy compared to the rest of the broadband radiative scheme.

3.3 More cases

We performed the same analysis as above on multiple other cases: a *cloudy atmosphere* with the same temperature and composition profiles, *tropical*, *midlatitude summer* and *winter* atmospheres, and *subarctic summer* and *winter* atmospheres[4]. The cloudy atmosphere did not differ significantly from the clear sky case. The tropical, midlatitude and subarctic cases had error of the heating rate within 0.5 K/day.

[3] It should be noted that the true angle at which radiation passes through a layer depends on the layer height, but here an independent scaling was used. It is also affected by refraction, which is omitted as well.

[4] Plots of all studied cases can be found in the Additional Materials (see the end of this report).

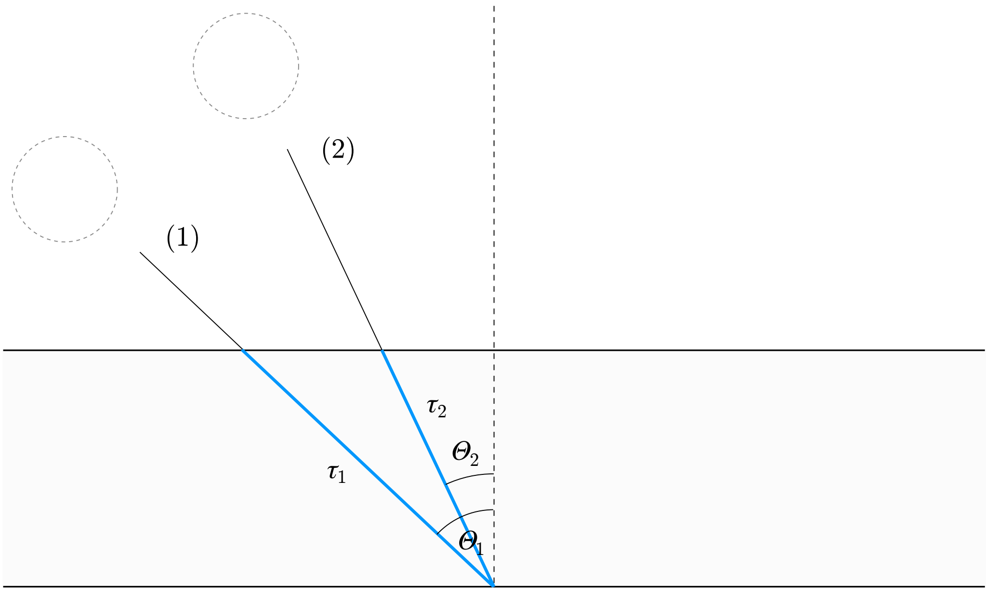


Figure 1 – **Geometry of the solar intermittence problem (downward).** (1) At the beginning of the intermittence period, solar radiation passes through a plane-parallel atmospheric layer at zenith angle θ_1. (2) As the Sun rises to zenith angle θ_2, the broadband optical thickness (as per our definition) of the layer changes from τ_1 to τ_2. Note that $\tau_2 > \tau_1$, as the broadband optical thickness equals to optical path normalized by $\mu = cos(\theta)$, which is proportional to the length of the path.

4 Solar Intermittence Implementetion in a 3D Model

The results from the Single Colomn Model support the application of solar intermittence in a 3-dimensional NWP model. This was implemented in the ACRANEB2 scheme in the ALADIN/ALARO[5] model.

In the 3D model, the radiative transfer scheme calculates radiative transfer independently for each grid point of the model domain.

4.1 Overview of the implementation

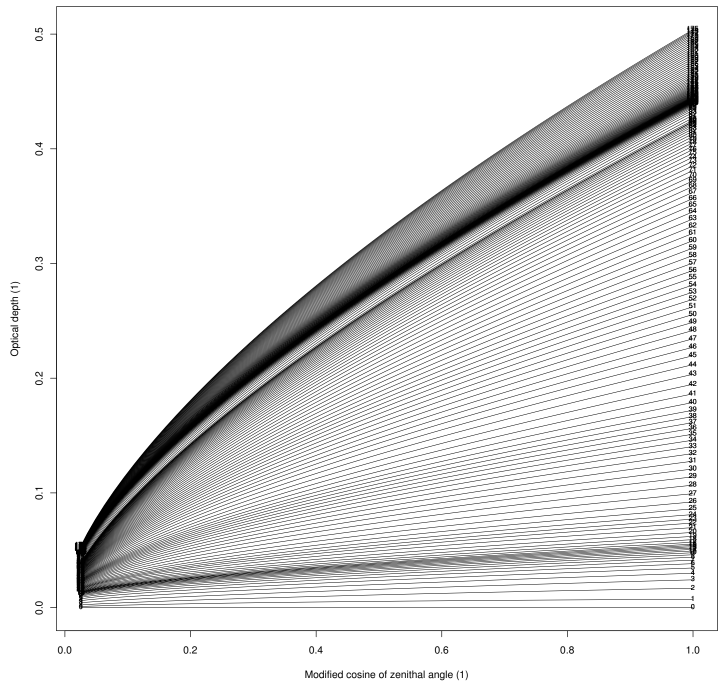
At the beginning of an intermittence period (*full* radiative time step):

1. Calculate the mimimum and maximum values of the zenith angle attained at any time step during the intermittence period. Store the zenith angles (the extreme values as well as the values at all time steps) in global arrays (preserved across time steps).
2. Calculate solar optical thicknesses as usual for the two extreme values the zenith angle. Store (the logarithm of) the optical thicknesses in global arrays.

At every time step *within* the intermittence period (*partial* radiative time step):

1. Retrieve current zenith angle from the global array (ignoring the zenith angle supplied by the model), and continue all computations with this zenith angle.

[5] ALARO cycle 38.



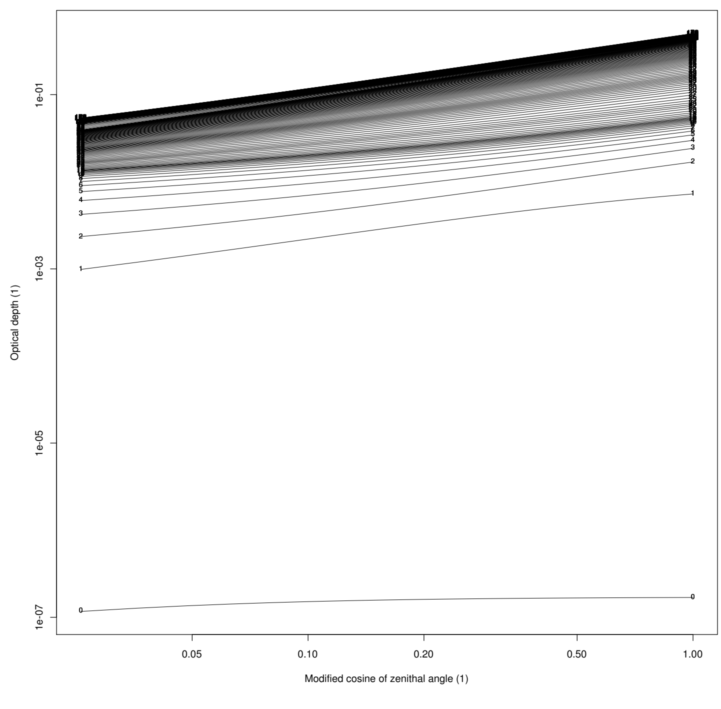


Figure 2 – Optical depth of layers as a function of the (modified) cosine of the zenith angle. Optical depths are plotted in normal (top) and log-log coordinates (bottom). Lines are labeled with layer numbers, where numbers above 87 are upward optical depths. Note that the relationship is almost linear in the log-log coordinates.

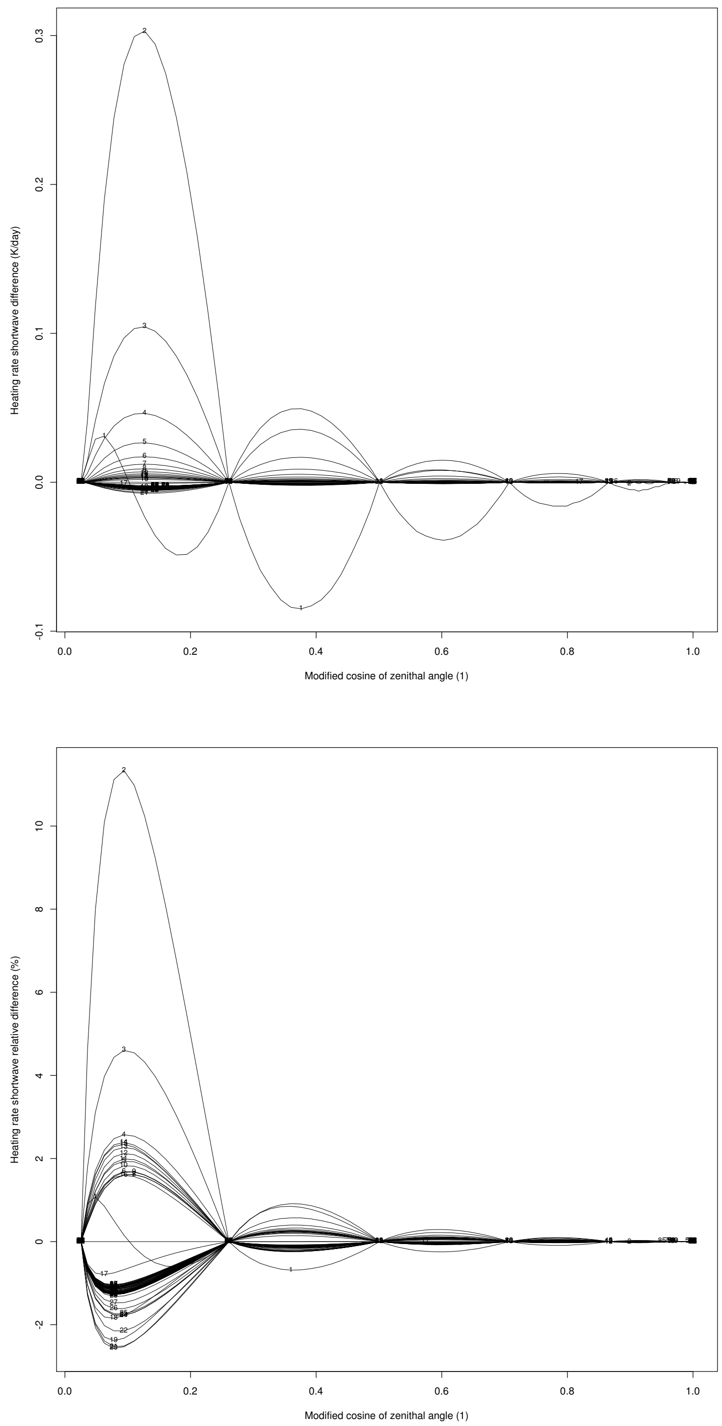


Figure 3 – Heating rate difference between the reference and linearly interpolated optical thicknesses at 15° steps of the zenith angle. Top, absolute difference in heating rate. **Bottom,** relative difference in heating rate in per cent.

2. Calculate optical thicknesses by interpolating between the extreme optical thicknesses as stored in the global arrays.

4.2 Technical considerations

There were a number of additional technical considerations which needed to be taken into account when implementing solar intermittence in a 3D model:

1. **Solar declination.** Solar declination varies during the intermittence period. In our case, the model does no provide the scheme with solar declination for the subsequent time steps, nor a straighforward way of calculating it[6]. In order to simplify implementation, solar declination within intermittency period is kept constant. This is justified since the length of the intermittency period is not expected to be chosen long enough for the variation of solar declination to be important.

2. **Storage requirements.** Solar intermittence requires us to store fields of downward and upward optical thickness at two extreme values of the zenith angle. This results in four 3D global fields of optical thickness and a number of 2D global fields of zenith angles to be kept in the main memory between time steps.

3. **Day/night segmentation.** The ACRANEB2 scheme performs calculations on blocks of grid points in a vectorizable form[7]. The solar computations are only performed on segments of grid points where the Sun is in the sky. This selection has to be extended with grid points where the zenith angle is positive at any time during the intermittence period.

4. **Modularization.** The solar intermittence implementation required more modularization in terms of decoupling the solar and thermal computations of optical thickness.

4.3 Results

In order to determine how the solar intermittence affects accuracy, we looked at the global bias of heating rates, as well as the local error and its statistical distribution.

[TODO: Results.]

We measured performance of the new scheme using a 24-h run of the NWP model on 4 CPUs of a NEC SX-9 supercomputer (100 GFLOPS per CPU). The decrease in total model computation time with 2-h solar intermittence was 5 %, which is in our experience a significant reduction. See Tab. 1 for details.

5 Conclusion

Solar intermittence is a viable approximation in plane-parallel broadband radiative transfer schemes. By avoiding calculation of solar gaseous optical thicknesses at every time step we gain a signification reduction in computation time, while maintaining good accuracy of heating rates.

[6] Without copying a significat amount of code.

[7] In the sense of performing an operation on a sequence of values simultaneously by a single processor (on processors which support such a feature).

Table 1 – **Impact of solar intermittency on the model computation time.** The table lists full NWP model computation time of 6-hour integration, 180-s time step (case 2012-07-01T00:00:00Z) for a number of different configurations. Time is expressed relative to the baseline case. *Note:* Memory increase due to solar intermittency was 2.4 %.

Day/night computation	Solar intermittency	Time (relative)
Yes	No	1.00
No	No	1.02
No	Yes, 0 h	1.08
No	Yes, 1 h	1.04
Yes	Yes, 0 h	1.05
Yes	Yes, 1 h	**0.95**

Linear interpolation of optical thickness on logarithic scale is enough to account for the dependence of optical thickness on the relatively quickly-changing zenith angle for intermittence periods up to 2 hours long (at least).

Additional Materials

All additional materials used in the analysis can be found at https://github.com/peterkuma/solar-intermittence.

The ACRANEB2 single column model and changes to the code cannot be made publicly available as they are proprietary.

References

Masek, J, JF Geleyn, R Brožková, O Giot, and HO Achom. "Single Interval Shortwave Radiation Scheme with Parametrized Optical Saturation and Spectral Overlaps." Article in preparation.