Parameterization of Atmospheric Radiative Transfer. Part II: Selection Rules

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ABSTRACT

This paper describes simple, computationally efficient methods of calculating 2-stream broadband fluxes and heating rates in the shortwave and longwave for multilayered media. The method, herein referred to as selection rules, is used in conjunction with conventional 2-stream solvers to reduce the number of full-up radiative transfer calculations, thus decreasing the computation time.

1. Introduction

One of the main uses of 2-stream models is in applications that require the calculation of fluxes or heating rates. When 2-stream models are solved as two-point boundary value problems, as discussed in Stephens et al. (2001, hereafter Part I), the computation time varies linearly with the number of layers. This is due to the tridiagonal form of the required system of equations. Many applications, however, require a very large number of such calculations. For example, when the Fu and Liou (1992) k-distribution is used in the Colorado State University (CSU) global circulation model (GCM) to specify the optical properties of the atmosphere, 54 radiative transfer calculations are required in the shortwave and another 67 in the infrared per model grid cell, to calculate broadband fluxes and heating rates. Therefore a significant fraction of the GCM run time is spent in the computation of the optical properties and in performing the 2-stream calculations.

Accuracy considerations dictate the number of bands wherein radiative transfer calculations are to be performed. A k-distribution method with a modest number of bands yields acceptable accuracies in the broadband fluxes and heating rates that closely match those obtained by line-by-line calculations (e.g., Part I). While the desire to obtain accurate radiative properties such as fluxes, heating rates, actinic fluxes, and radiances is understandable, very frequently, the uncertainties in the optical properties, introduced by clouds and their unaccounted inhomogeneity, bring to question the need for the extreme accuracy demanded from especially 2-stream plane-parallel computations. In any case, different applications will require different specifications of accuracy, even when plane-parallel assumptions are warranted. Since 2-stream radiative transfer attempts to calculate fluxes that could only be otherwise obtained from much more accurate but computationally expensive 2n-stream models, the motivation to develop efficient methods of calculating 2-stream broadband fluxes follows. A computational acceleration method, herein referred to as selection rules, is described in section 2. The rules that apply to the computation of shortwave broadband fluxes is discussed in section 2a. Section 2b develops selection rules for the calculation of longwave broadband fluxes and heating rates. A description of the numerical experiments is provided in section 3. Sections 4a and 4b discuss the results of applying the selection rule method to the calculation of upwelling and downwelling fluxes and heating rates in the shortwave for the clear and cloudy atmosphere. Section 5 presents a similar discussion, except that the selection rule method is applied to the longwave. In section 6, the selection rules method is applied to the calculation of the outgoing longwave radiation, shortwave upwelling fluxes at the top of the atmosphere, and 24-h zonally averaged heating rates in the shortwave and longwave. Section 7 provides a concluding discussion of the results of this study.

2. Basis of selection rules

In this section, we develop a semiempirical, physically based algorithm to supplement formal, general purpose codes in the rapid computation of broadband 2-stream fluxes. We will demonstrate that such a hybrid approach leads to a controllable accuracy and a computational efficiency that cannot be realized by using general purpose codes alone. This approach is a compromise that trades generality for speed with a possible reduction in accuracy. Selecting the parameters de-
FIG. 1a. Illustrations of comparisons for the clear sky in the shortwave. The upper three plots are the benchmark downwelling fluxes, upwelling fluxes, and heating rates. The heating rates in the lower right hand figure refer to a section of atmosphere between 280 and 320 mb. The optical properties were prescribed by the McClatchey et al. midlatitude summer profile for a 30-layer atmosphere run in single-column mode. The solar zenith angle was $\theta_s = 0^\circ$ and $R_s = 0.0$. The contour plots show how the selection of $\omega_f$ and $\tau_e$ affect the accuracy and time of the computations. Only the absolute differences from the benchmarks are shown.
scribed below that fix the rules is, to some extent, a trial and error process. The selection rule method for the shortwave has already been presented in Gabriel et al. (2000). The basis of the method derives from the observation that the optical properties of the clear sky, as computed by any given $k$-distribution model indicates the prevalence of strong absorption or weak scattering in most of the bands as described in the classification scheme in Part I. The method does not depend on the source function, and addresses the importance of multiple scattering. High-order scattering will be suppressed significantly if the following conditions are met in an $N$ layer medium:

$$
\sum_{i=1}^{N} (\tau_i < \tau_f \cup \omega_i < \omega_f) = N,
$$

where $\omega_i$ and $\tau_i$ are the single-scattering albedo and scattering optical depth of the $i$th layer, respectively. The quantity in parentheses is a logical operation that returns unity if the condition indicated is true for the $i$th layer. Otherwise a zero is returned. Control over the logical condition is exerted by the selectable scattering optical depth and single-scattering albedos thresholds $\tau_f$ and $\omega_f$, respectively. By summing the returned values over all layers, the optical properties can be categorized as follows: if the sum equals the number of layers, then the medium is either everywhere weakly scattering, everywhere strongly absorbing, or both strongly absorbing and weakly scattering. These conditions disfavor full 2-stream calculations to the extent determined by the thresholds. A single violation of the logical condition ensures that a full 2-stream calculation will be performed, although variations on this theme could obviously be accommodated.

**a. Selection rules with applications to solar radiative transfer**

When the surface albedo underlying the atmosphere can be described by a Lambertian reflector, the fluxes reentering the atmosphere are diffuse. In the shortwave, the downwelling solar flux exiting the $i$th layer is simply

$$
F_{\tau=1} = F_1 \exp(-\tau / \mu_s),
$$

where $\mu_s$ is the solar zenith angle and $1 \leq i \leq N$. The upwelling flux is given by the expression

$$
F_{\tau=1} = F_1 \exp(-2 \tau). \tag{2b}
$$

This equation is derived by multiplying the upwelling flux at the $N$th layer, at the base of the atmosphere by the transmission function for each layer (here, represented by the exponential terms not containing $\mu_s$). The transmission function is defined in Part I. It is discussed at length and further simplified by Gabriel et al. (2000). The factor of 2 in the argument of the exponential derives from the transmission function of the constant-hemispherical model. For the delta-Eddington model, the appropriate factor is $3^{1/2}$. The former was used because the reflection from the surface is diffusely isotropic. In this situation, the constant-hemispherical method yields more accurate fluxes than the delta-Eddington method. If the surface reflection is given as $R_s$, then, the diffuse upwelling flux at the surface is

$$
F_{N+1} = R_s F_{N+1}^- \tag{2c}
$$
Fig. 2a. Illustrations of comparisons for the cloudy sky in the shortwave. The upper three plots are the benchmark shortwave downwelling fluxes, upwelling fluxes, and heating rates. The heating rates refer to a section of atmosphere between 280 and 320 mb. The optical properties were prescribed by the CSU GCM for a 30-layer atmosphere run in single-column mode. The solar zenith angle was $u_0 = 50$ and $R_g = 0.0$. The contour plots show how the selection of $v_T$ and $t_T$ affect the accuracy and time of the computations. Only the absolute differences from the benchmarks are shown.
Note that some loss of computational efficiency is incurred due to the requirement of computing two exponentials with different arguments.

b. Selection rules with applications to infrared radiative transfer

In Part I of this series, the 2-stream equations governing longwave fluxes for a single layer were given. The selection rules criteria require that there be either strong absorption or weak scattering. In these limits, the global reflection function approaches zero and Eqs. (14) in Part I decouple. The emerging fluxes evaluated at the boundaries yield

\[ F_{i+1}^- = S_i^- + F_i^- \exp(-2\tau_i) \]  
\[ F_i^+ = S_i^+ + F_{i+1}^- \exp(-2\tau_i). \]

The sources, designated by \( S \) in the above expressions are given by

\[ S_i^- = \left\{ 1 - \frac{1 - \exp(-2\tau_i)}{2\tau_i} \right\} B_i + [-\exp(-2\tau_i)] \]
\[ + \left\{ 1 - \frac{1 - \exp(-2\tau_i)}{2\tau_i} \right\} B_i \quad \text{and} \]
\[ S_i^+ = [-\exp(-2\tau_i)] + \left\{ 1 - \frac{1 - \exp(-2\tau_i)}{2\tau_i} \right\} B_i \]
\[ + \left\{ 1 - \frac{1 - \exp(-2\tau_i)}{2\tau_i} \right\} B_{i+1}. \]

It is seen that the upwelling and downwelling fluxes are computed as initial-value problems. We distinguish between “layer” and “level” quantities. Fluxes are always computed at specified levels. Sources are the result of emission within a layer, and are computed by the Planck function (or other temperature dependent source), specified by \( B_i \). Once the downwelling diffuse flux at level \( z_{N+1} \) in layer \( N \) is determined, the upwelling fluxes follow since the initial condition that specifies the total upwelling flux is known:

\[ F_{N+1}^- = R_s F_{N+1}^- (\tau_0) + B(\text{surf})(1 - \epsilon). \]

In this expression, the surface emissivity \( \epsilon \) (a quantity that varies with wavenumber) is supposed known. The source function \( B(\text{surf}) \) (another wavenumber dependent function) is computable from the surface temperature \( T_{\text{surf}} \) also supposed known. The computation of the upwelling fluxes proceeds in an efficient manner because of the redundant functions occurring in the sources. The fluxes of this decoupled system can be calculated efficiently by iteration.

3. Description of numerical experiments

To test the ideas just described, the broadband fluxes and heating rates were computed using a hybrid 2-stream model consisting of the selection rules method in conjunction with a 2-stream adding model implemented in the CSU GCM. The radiative profiles so obtained (e.g., the vertical variation of upwelling fluxes, downwelling fluxes, and heating rates) were compared against those calculated by the adding method alone. This latter calculation is considered here as the bench-
Fig. 3a. Illustrations of comparisons for the cloudy sky in the longwave. The upper three plots are the benchmark longwave downwelling fluxes, upwelling fluxes, and heating rates. The heating rates refer to a section of atmosphere between 280 and 320 mb. The optical properties were prescribed by the CSU GCM for a 30-layer atmosphere run in single-column mode. The surface albedo was $R_g = 0$. The contour plots show how the selection of $v_T$ and $t_T$ affect the accuracy and time of the computations. Only the absolute differences from the benchmarks are shown.
Fig. 3b. Illustrations of the variation of the overcast-sky longwave, downwelling fluxes, upwelling fluxes, and heating rates as they are affected by selecting $\omega_T = 0.796$ (dotted), $0.6864$ (dashed), $0.5904$ (broken dashed), and $0.5376$ (long dashed) while fixing $\tau_T = 0.1$.

mark, or “truth.” Optical properties were specified by the McClatchey et al. (1971) standard midlatitude summer profile for a 30-layer atmosphere. The results of these comparisons are discussed below.

In section 6, the GCM was run for 25 1-h time steps. The first run created the benchmark outgoing longwave radiation (OLR), the shortwave fluxes at the top of the atmosphere and the shortwave and longwave zonally averaged heating rates. In the second run, these fields were calculated using selection rules with different thresholds selected for the longwave and shortwave calculations. These runs differ from those described in the paragraph above in that multiple cloud layers, each possessing different optical properties may be present in a column (and there are 3168 columns), not just a single isolated cloud.

4. Shortwave results

a. Clear-sky fluxes and heating Rates

The top row of graphs in Fig. 1a illustrates the clear-sky broadband downwelling fluxes, upwelling fluxes and heating rates calculated for the case of overhead sun and $R_s = 0$ using the benchmark. The next row of contour plots was calculated by using the hybrid model to obtain the downwelling fluxes at the surface, the upwelling fluxes at the top of the atmosphere (TOA), and heating rates, using different combinations of $\omega_T$ and $\tau_T$. The radiative profiles obtained from the hybrid model were subtracted from the benchmark results in the top row of plots. To visualize the effects exerted by the aforementioned thresholds on computation time and accuracy, the differences are illustrated at the base and top of the atmosphere for downwelling and upwelling fluxes, respectively. The labels on the contours represent the gain in speed relative to the full-up computation. For example, a selection of $\omega_T = 0.98$ and $\tau_T = 0.01$ translates to a speed increase of 1.95 times over the benchmark.

The heating rates were calculated for a layer in the atmosphere extending from 280 to 320 mb. This region corresponds to where we placed our cloud as described in the section below. This aids in gauging the size of the errors caused by the selection rules when clouds are absent to when they are present. Application of selection rules for the clear sky yields a maximum difference of less than 0.5 K day$^{-1}$ for $\omega_T = 0.98$.

The largest (absolute) errors in the downwelling fluxes were observed to lie near the base of the atmosphere, diminishing with higher altitudes as shown in Fig. 1b. In this figure, the sold line through the origin represents zero error. The departures from the benchmark as a function of $\omega_T$ is shown by the other curves. Since the density of scatterers, increases with depth, the downwelling total flux will increase as the base of the atmosphere is approached because of significant multiple scattering. In the clear sky, Rayleigh scattering is the only mechanism for producing diffuse radiation. When $\omega_T$ is chosen too large (e.g., $\omega_T = 0.999$, multiple scattering is inhibited by the selection rules and as expected, the downwelling and upwelling fluxes are computed inaccurately. Errors in the downwelling diffuse component appear to be cumulative as one traverses the medium downward from its upper boundary.
Similar considerations apply to the upwelling flux, except that the curvature of the error plot is reversed because at the base of the medium, there is no entrant flux. At higher altitudes, the errors, having been propagated from the lower atmosphere tend toward a constant value because the density of scatterers at these high altitudes is small. The heating rate errors are also presented in Fig. 1b.

When the solar zenith angle was increased, in the presence of surface reflections present, the errors in the hybrid model were observed to increase. The longer slant path enhances the multiple scattering, while the surface reflection introduces an entrant flux at the base of the medium. Since selection rules do not account for multiple scattering effects between the lower boundary and the atmosphere, the errors in the upwelling fluxes at higher altitudes increase. We observed that the heating rate errors are of comparable magnitude to the overhead sun case with $R_g = 0$ when the solar zenith angle was at 60° and $R_s = 0.2$.

b. Cloudy-sky fluxes and heating rates

The selection rules method makes use of the extent of absorption and low-order scattering in an atmosphere to determine whether the diffuse flux is to be calculated.
When clouds are present and the selection rules method applies, its effectiveness depends on the location of the clouds. If the clouds are situated within the lower atmosphere, the effect of gaseous absorption is to reduce the amount of direct radiation entering its boundaries in nearly all the subbands. Photons will not only be strongly absorbed by the interstitial gas, but by the cloud particles as well. At higher altitudes similar principles apply; however, the lower concentrations of absorbing gases increase the amount of energy reaching these clouds. Since the scattering optical depth of the cloud is much greater than that of the clear atmosphere, the determining factor that affects the accuracy and computation time is \( \omega_T \).

The top row of graphs in Fig. 2a illustrates the true broadband downwelling fluxes, upwelling fluxes, and heating rates calculated for the case of a single-layer cloud, overhead sun, and \( R_g = 0 \). The cloud is located at 9 km (extending from 280 to 320 mb) with a visible optical depth of 5.5. The contour plots in the next row were calculated by using the hybrid model to obtain the downwelling fluxes at the surface, the upwelling fluxes at TOA, and heating rates. The radiative profiles obtained via the hybrid model were subtracted from the corresponding top row of plots. As in the cloud-free case, the effects exerted by the scattering optical depth threshold \( \tau_T \) and the single-scattering threshold \( \omega_T \) on computation time and accuracy were explored. The differences in the downwelling flux were computed at the surface, differences in the upwelling flux were computed at the top of the atmosphere while the heating rate differences were computed over the cloud layer. The labels on the contours represent the gain in speed relative to the full-up computation.
Numerical experiments show that accurate radiative profiles (e.g., less than 1%), departure from the true fluxes and heating rates can be obtained for $\tau_\tau = 0.1$. Downwelling flux profiles can be calculated with relatively good accuracy while the upwelling fluxes are calculated more poorly, but still better than a relative error 10% for the case $\omega_T = 0.9$. Departures of these fluxes from the benchmark are shown in Fig. 2b. The heating rate corresponding to this threshold is poorly calculated within the cloud, however, exceeding $2 \text{ K day}^{-1}$. A large improvement in accuracy can be obtained by decreasing $\omega_T$ to 0.84. This selection results in an error of 0.1 K day$^{-1}$ with an attendant increase in computing time. Thus, depending on the intended application, a value of $\omega_T$ that calculates one radiative property accurately does not imply that other radiative properties will be calculated with the same accuracy. In the case of heating rates, the errors are magnified because the flux divergence is equal to the difference between the incoming and emerging fluxes in a layer. If the magnitudes of the fluxes are comparable, these differences will accentuate any numerical errors, especially if the layers are thin (see also Tsay et al. 1996).

5. Longwave results

The radiative profiles calculated by the hybrid 2-stream model were in exact agreement with those calculated using the full adding method. Identical results are expected because in the longwave, there is no multiple scattering for the clear sky. Hence the 2-stream equations decouple as a natural consequence of the radiative transfer, making it unnecessary to use the full-up adding solution.
The selection rules method, modified for the longwave, has been applied to the single-layer cloud described in section 4b. The multiple scattering model used in the longwave is the constant-hemispherical 2-stream method introduced in Part I. Although absorption processes dominate in the longwave, multiple scattering by cloud droplets is not negligible (Stephens 1980; Stephens and Tsay 1990). The hybrid model for the longwave fluxes accounts for multiple scattering to the extent determined by the selection of $\tau_T$ and $\omega_T$, exactly as the hybrid model in the shortwave.

The top row of graphs in Fig. 3a illustrate the broadband downwelling fluxes, upwelling fluxes, and heating rates in the longwave calculated by the benchmark. The bottom row of contour plots was calculated by using the hybrid model to obtain the downwelling fluxes at the surface, the upwelling fluxes at TOA, and heating rates as described in section 4b and is presented to show the compromise between speed and accuracy. For the variation in the downwelling fluxes, departures from the benchmark case are illustrated in Fig. 3b. It is seen that the accuracy of the upwelling fluxes is comparable to the accuracy of the shortwave fluxes. In these numerical experiments, the value of $\tau_T$ was fixed to 0.1 as in the shortwave. The relative error in upwelling and downwelling fluxes is less than 10% within the cloud. The associated heating rate errors are about 1.3 K day$^{-1}$ for all choices of $\omega_T$ except for $\omega_T = 0.5376$, where they increase to 0.2 K day$^{-1}$. By comparison to the heating rate errors in the shortwave, the errors here are reduced because the flux magnitudes are reduced due to the prevalence of strong absorption.

If $\omega_T$ is small, then small computational gains are realized, but high accuracy is attained. If $\omega_T$ is too large, then speed will be obtained, but at the expense of the broadband fluxes and flux divergences. Large errors in the flux divergences can be caused by small errors in the diffuse fluxes because the flux divergences are computed as differences between fluxes entering and leaving a layer divided by the layer thickness. Smaller values

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**Fig. 4d.** As in Fig. 4b but with the selection of parameters in Fig. 4c.
of \( \omega_r \) may be required if accurate calculation of the flux divergences is the primary goal. The effect of reducing \( \omega_r \) is to increase the accuracy of the computed internal fluxes. In applications that do not require heating rates such as in surface energy budgets, where only the surface flux is required, larger \( \omega_r \) may be tolerable, if computational speed is important.

6. Applications in a GCM

The selection rules method has been used with the standard 2-stream adding model used previously to calculate the outgoing longwave and shortwave fluxes, and zonally averaged heating and cooling rates in the CSU GCM for 1 day (25 time steps). This hybrid is extremely flexible in that the selection rules method can be tailored to accommodate a large variety of atmospheric situations. For example, the thresholds can be chosen to optimize the computational efficiency for clear and cloudy conditions in the shortwave and in the longwave while achieving a high degree of accuracy. Such options were not explored since they would not contribute further to our understanding of the method. Instead, in the shortwave, we selected \( \omega_r = 0.98 \) and \( \tau_r = 0.01 \) for both the clear sky and cloudy sky. These thresholds would result in factors of 2.047 and 1.286 in computational speed for the clear and overcast sky upwelling fluxes as determined by the profiles shown in section 4a. In the longwave, we selected \( \omega_r = 0.45 \) and \( \tau_r = 0.1 \) for the cloudy sky. The same thresholds were applied to the cloudy sky and would yield a computational gain of 1.229 for the TOA fluxes. It must be noted that these thresholds apply in the overcast case to a single-layer cloud. In the GCM, a variety of clouds will be encountered. Thus, to properly select the thresholds, the GCM would have to be run using the same initial and boundary conditions over some period time. The compromise between speed and accuracy could then be used to select optimal \( \omega_r \) and \( \tau_r \).

To illustrate these ideas, the upper left plot of Fig. 4a shows the OLR calculated using the full-up 2-stream model. The contours represent the magnitude of the OLR. In the upper right plot, the contours represent the differences from the benchmark using the hybrid. It is seen that a typical (relative) error is about \(-1.5\) out of 225 W m\(^{-2}\), or a bias of \(-0.67\%\). The nature of the error is in the form of a bias, not a random error. This is expected since the reduction in the multiple scattering imposed by the selection rule method causes the atmosphere to be cooler than that predicted by the full-up computation.

The lower left plot of Fig. 4a shows results for the shortwave fluxes at the top of the atmosphere. The difference plots show that the errors are somewhat larger, typically \(-0.375\) out of 30 W m\(^{-2}\), or a bias of \(-1.25\%) and with greater spatial variation. The zonally averaged heating rates in the shortwave and longwave and their associated errors are illustrated in the upper and lower plots in Fig. 4b. Note how at the equator the shortwave heating errors (in K day\(^{-1}\)) are greatest. This is most likely attributed to the presence of high clouds such as cirrus. For high-altitude clouds the selection rule method will give larger errors than for lower-level clouds for the reasons suggested in section 4b. In the case of the longwave, there is generally less scattering, so the selection rules method is more accurate. Nevertheless, as with the shortwave fluxes, there is also a bias in the OLR.

The amount of time required to produce the results displayed in Figs. 4a and 4b is best understood in terms of the time required to perform other functions in the CSU GCM. Since the actual time required to run the GCM code will depend on the computer and compiler, the relative times quoted here may be a more useful measure of performance, as they will be less dependent on the computer. With selection rules, the longwave and shortwave calculations are accelerated by factors of 1.32 and 1.48, respectively. However, the overall speedup factor of the GCM is only 1.10 since the largest amount of time is consumed by the calculation of the optical properties from the \( k \)-distribution method. The amount of time required by the latter is the same, regardless of whether selection rules are used. Without selection rules, the calculation of the optical properties consumes 65.4\% of the (cpu) time. With selection rules, this number increases to 72.3\% because the total time to run the model has decreased. These statistics point to a need to accelerate the optical properties parametrization to derive the full benefit of the selection rules method in the CSU GCM.

To illustrate the performance of the hybrid model when an increase in speed is demanded, we direct attention to Figs. 4c and 4d, produced by rerunning the GCM using shortwave thresholds of \( \omega_r = 0.99 \) and \( \tau_r = 0.1 \) for the clear sky and overcast sky. In the longwave, we set \( \omega_r = 0.55 \) and \( \tau_r = 0.1 \). This resulted in accelerating the longwave calculations by a factor of 1.41 and the shortwave by a factor of 1.64. The overall computational gain of the GCM was 1.13. We see in Fig. 4c that the largest error in the OLR is \(-9\) out of 175 W m\(^{-2}\), or a bias of \(-5.14\%). In the shortwave the largest error is \(-5\) out of 90 W m\(^{-2}\), or a bias of \(-5.55\%). The zonally averaged longwave heating rates shown in Fig. 4d are greatest at the equator at the 300-mb level. In the shortwave the zonally averaged heating rates are largest at the equator but peak at the 195-mb pressure level. By comparison to Fig. 4b, we see that the distribution of errors are similar except that the magnitudes are reduced as expected.

7. Summary and conclusions

This paper describes computationally efficient techniques for solving 2-stream broadband fluxes in multi-layered media. The method is based on the idea that if absorption is dominant everywhere inside a medium,
or if the medium is optically thin in all of its layers, then multiple scattering can be inhibited and only the direct beam contribution need be calculated in the shortwave. In the longwave, the 2-stream equations decouple, to an initial value problem. The accuracy is determined by selecting an appropriate $\omega_T$ and $\tau_T$ combination. If a layer is strongly absorbing or weakly scattering, then a counter is incremented. This test is performed for all layers, and if the count is equal to the number of layers, the selection rules are enforced.

In practice the selection rules method has been found to be flexible in that it can be tailored to accommodate a large range of atmospheric situations by selecting different thresholds for $\omega_T$ and $\tau_T$ in the shortwave and longwave. This will improve the accuracy of the computed fluxes and heating rates. The selection rules method has one shortcoming in that it will always produce a bias, not a random error. This means that the spatially averaged fluxes and heating rates will also suffer from this bias. However, by choosing the thresholds appropriately, this bias can be made acceptably small.

Finally, for a given set of thresholds it does not follow that if the fluxes are computed accurately (e.g., have a small relative error) then heating rates will also be computed accurately. This follows from the fact that the latter are proportional to the flux divergences. Thus selection of thresholds is very much dependent on the required accuracy and intended application.

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REFERENCES


