Parameterizations of radiation and cloud optical properties

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Introduction

Radiative transfer in the atmosphere is an important physical process in which clouds are the dominant modulators and remain one of the more uncertain quantities in climate models. Therefore, studies to improve the cloud and radiation parameterizations are crucial to the ongoing important and enhancement of a key component of the model physical parameterizations. Such studies have been extensively carried out at the BMRC for a number of years and this work and major results will be presented in this paper.

Radiation parameterizations

Both the climate and NWP versions of models at the Bureau have used the Lacis and Hansen (LH) (1974) code in the shortwave and Fels and Schwarzkopf (FS) (1991) radiation in the longwave for a number of years. However these schemes are over a decade old and have a number of major limitations that have restricted the Bureau model’s capacity for performing certain tasks in climate simulations. The major deficiencies in the shortwave code are: 1) the low spectral resolution that is not good enough for treatment of spectral variation of absorbing gases, clouds and aerosols, and this is particularly true for a gas having a feature of narrow absorbing band, 2) the simple treatment of the rayleigh scattering that leads to an large error in the solar radiation at the surface, 3) ignoring the absorption of the solar radiation by trace gases, especially oxygen which has significant absorption in the solar spectral region, and 4) it is difficult to implement the effect of aerosols. For the longwave FS code, the spectral resolution and accuracy are relatively better, but because the code uses an emissivity approach for dealing with gaseous absorption the scattering effects of aerosol and cloud particles cannot be taken into account in the calculations. The other disadvantage is its low efficiency with respect to the model vertical resolution. The computational burden of such a scheme is proportional to the square of the number of vertical levels.

The above deficiencies are difficult to overcome by simply modifying the existing codes. As a result the Edwards and Slingo radiation package (Edwards and Slingo, 1996) and Genln2 line-by-line radiation code (David, 1991) were implemented and have undergone a series of modifications. The original Genln2 has been modified to make it more flexible and consequently a more useful and powerful tool for development and validation purposes. The treatment of gas absorption, especially overlapping absorption and cloud optical properties, in the Edwards and Slingo code were replaced with a new novel method leading to much better accuracy and improved efficiency compared with the original code (Sun and Rikus, 1999a). As a result of these enhancements the code has been renamed the Sun-Edwards-Slingo (SES) radiation. An important enhancement is the development of an interface system, which uses the correlated k-distribution formulation to link the Genln2 line-by-line and broadband radiation code. This interface allows the broadband code to be easily updated with new spectral information and physical processes and new versions of code to be easily developed.

Using this facility, the SES code was developed several years ago and has been implemented into the Bureau's global model as a replacement for the Fels and Schwarzkopf code. Fig. 1 shows a

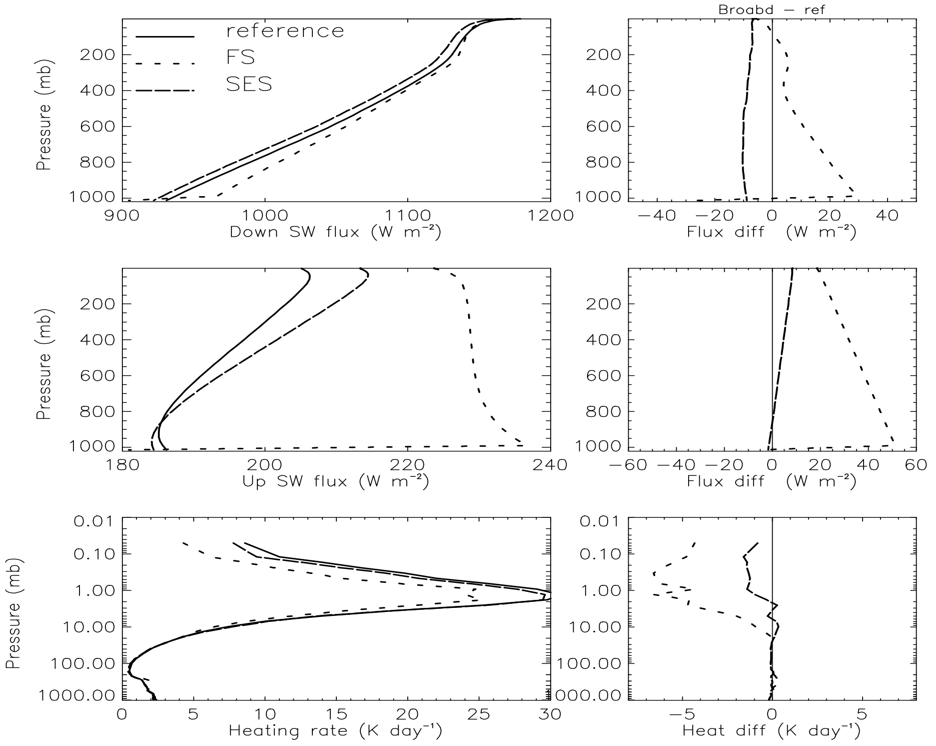

Fig. 1: Comparison of solar radiation determined by three schemes: reference refers to 210 spectral bands SES benchmark code; LH to Lacis and Hansen code and SES to Sun-Edwards-Slingo code. Three major absorbing gases and Rayleigh scattering are included. The calculation assumes a mid-latitude summer atmosphere with a solar zenith angle of 30° and a surface albedo of 0.2.

comparison of the shortwave results between the LH and SES codes relative to reference results which were determined using a high spectral resolution benchmark code (210 spectral bands in SW). It is seen that both downward and upward solar fluxes determined by the LH code depart significantly from the reference results (solid curve) with differences as large as 30 Wm^{-2} for the downward flux and 50 Wm^{-2} for upward flux at the level immediately above the surface. This large difference is due to the simplified treatment of Rayleigh scattering, which is only considered by adjusting the surface albedo and scaling the downward solar flux at the surface in the LH code. This is the reason that the flux profiles from the LH code show discontinuity at the surface because it attempts to correct the flux at the surface to get the surface radiation budget right. The heating rate error from the LH code is also large (about 6 K day^{-1}) as shown in the bottom panels of the figure 1. In contrast, the results determined by the SES code are closer to the reference.

Although the SES code is accurate compared with the reference result, there is still plenty of room for the code to be further improved. The first version of the code doesn't include trace gases and the efficiency is lower with overhead of about 20% relative to FS code. For this reason a second version of SES code is under development. The new version, based on more recent spectroscopic data and incorporating the correlated k-distribution technique, has included 3 extra absorbing species (O_2, CH_4, N_2O) that are considered to be important in the shortwave spectrum and CFC gases that are important in the longwave for climate studies. Since these species feature narrow absorbing spectral bands, the number of spectral bands in the shortwave code has to be increased to resolve these signatures. A minimum 9 spectral bands was found to be adequate for including these species (the first version has 4 bands). Theoretically, the use of the larger number of spectral bands will inevitably increase computational expense. This conflicts with our goal to further improve the model efficiency. To solve this problem a new method was proposed to minimize the number of quadrature points in a spectral integration for each spectral band. The band averaged transmittance is determined with line-by-line model by following integration,

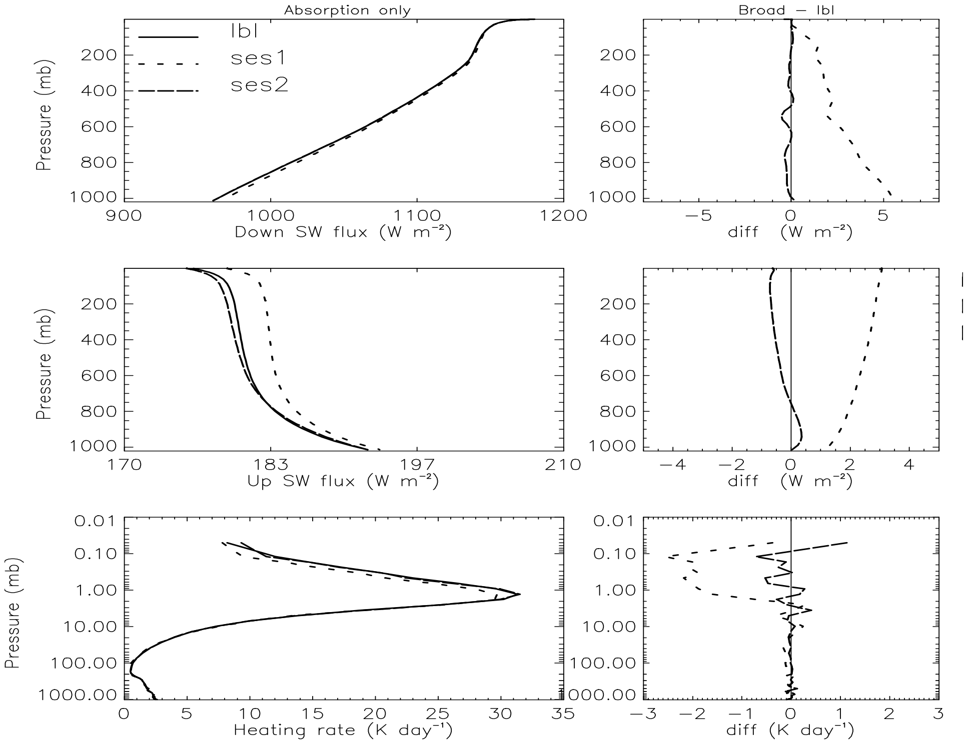

Fig. 2: Comparison of the solar radiative flux and heating rate dut to gaseous absorption only determined by the SES and line-by-line radiation schemes. The legend ses1 refers to the old version and ses2 to the new. The calculations use the mid-latitude summer atmosphere with a solar zenith angle of 30 ° and a surface albedo of 0.2.

$$T = \int_{\Delta \upsilon} \frac{1}{\Delta \upsilon} \exp(-k_{\upsilon} u) d\upsilon , \qquad (1)$$

where T represents a band averaged transmittance, k absorption coefficient, υ wavenumber and u absorber amount. With the aid of the correlated-k method the equation (1) can be simplified to

$$T = \sum_{i=1}^{n} w_i \exp(-k_i u) , \qquad (2)$$

where n is the number of intervals in each band, w_i denotes a weight in each interval and k_i is an representative absorption coefficient in each interval. The same quantity T that needs several million spectral lines when using Eq. (1) can be determined with just n quadrature points in Eq. (2). Clearly the larger n is the more accurate Eq. (2) becomes. The new method starts with 145 quadrature points. Reasonable accuracy for the radiation code can be maintained using such a large number of n and the results are regarded as the *reference*. We then reduce the number of n to 1 ~ 6, depending on the spectral band and number of species included in that band. The weight w_i for each subinterval in a band is carefully specified by closely examining the gaseous absorption spectrum to ensure that the interval width is adequate for these species. The representative absorption coefficients k_i are determined by minimizing the following expression,

$$\varepsilon_i = \sum_{l=1}^{m} (N_l^{ref_i} - N_l^i)^2 , \tag{3}$$

where m represents the number of atmospheric layers, N_l^i denotes the net flux profile for the subinterval i, $N_l^{ref_i}$ is the net flux profile determined using the *reference* for the same interval i. Using this method the flux profile determined with 145 quadrature points is successfully

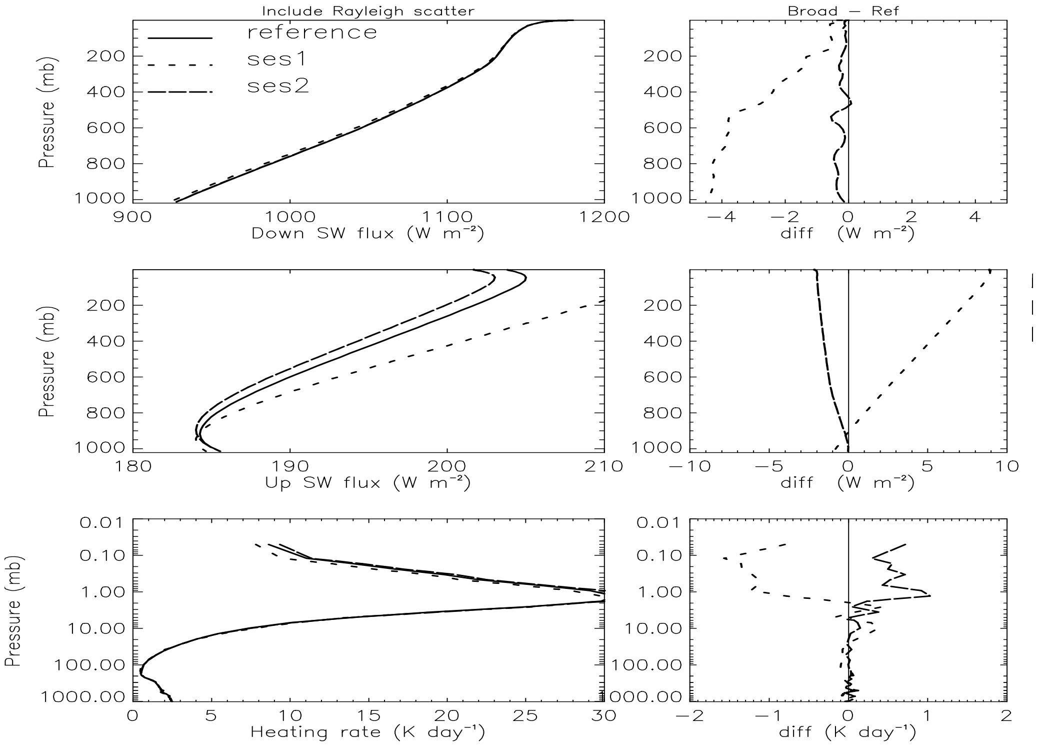

Fig. 3: Same as figure 2 except for including the effect of Rayleigh scattering.

reproduced with a few quadrature points ranging from 1 to 6 so the total number of quadrature points for the 9 band model is only 26 while the early 4 band model uses 38. This means the new version of the code is even more efficient than the old version.

Figure 2 shows a comparison of the results determined by the two version of the SES code and line-by-line for the case of gaseous absorption only. Both the downward and upward solar fluxes at the surface determined by SES1 (first version) are about 3 - 6 W m^{-2} higher than the line-by-line values. This discrepancy is due to the neglect of the absorption by O_2, CH_4, and N_2O. The results from SES2 agree very well with the line-by-line. Neglect of these three species also causes a heating error of about 2K day^{-1} around 1 hPa. Figure 3 shows a comparison for the case in which the Rayleigh scattering is included. The reference for this case is determined using the 210 spectral band version of the SES code. As can be seen when considering Rayleigh scatter the downward flux from the SES1 is underestimated by 4 W m^{-2} and the upward flux is overestimated by about 9 W m^{-2}. This indicates that the Rayleigh effect in SES1 is too strong, leading to more solar flux scattered back to space. Again the results from SES2 agree well with the reference.

Parameterization of cloud optical properties

The cloud optical properties describe the absorption and scattering of radiation by cloud particles including liquid droplets and ice crystals. Before 1995 the Bureau's model employed constant cloud optical properties, i.e. the cloud reflectance and transmittance for three levels of clouds were prescribed. The first cloud optical property scheme described by Lemus et al. (1994) was introduced into the Bureau's NWP model in 1995. This scheme combines Platt's (1997) formula for determining the cloud extinction coefficient and Rockel et al. (1991) for single scattering albedo and asymmetry factor. All three parameters are dependent on cloud water content that is determined by the cloud temperature. In 1996, the CAR (Centre for Atmospheric Research at CSIRO) version of the LH shortwave radiation scheme was implemented into the Bureau's climate model for the purpose of supporting the prognostic cloud scheme developed at CAR. In line with this implementation the CAR version of the Slingo cloud optical property scheme was also used in the climate model. This is a major division in that the Bureau's NWP and climate models use different cloud and cloud optical property schemes.

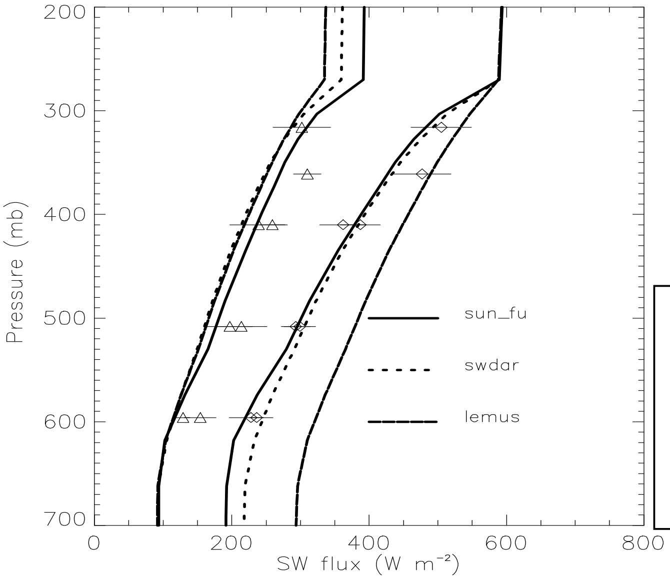

Fig. 4: Comparison between modeled and observed solar fluxes within a frontal cirrus cloud. The modeled results were determined using three cloud optical property schemes.

In addition to these schemes, there have been several developments and implementations in cloud optical property schemes in recent years. Since these were carried out for the SES scheme they are currently used as experimental only. The new development includes a parameterization scheme for effective ice particle size for cirrus clouds and parameterization for cirrus cloud optical properties (Sun and Rikus, 1999b). The scheme for effective ice particle size is based on aircraft observations on the tropics and a theoretical study by McFarquhar and Heymsfield (1997) and produces more realistic effective particle sizes in cirrus clouds. The optical property scheme for cirrus clouds was developed based on detailed studies by Fu (1996) and uses the effective size and ice water content as input to estimate single scattering properties of ice clouds.

Figure 4 shows a comparison of modeled radiative flux within a cirrus cloud using three parameterizations (solid curve is from BMRC scheme named as sun_fu; dotted from CAR named as swdar and dashed from Lemus) with aircraft observations (symbols). It is seen that the modeled results using both the sun_fu and swdar agree quite well except at the cloud top where the sun_fu scheme reflects more solar flux and at the cloud base where the swdar scheme allows more flux transmitted. The lemus scheme overestimates the downward solar flux.

Summary

There has been substantial development in parameterization of radiation and cloud optical properties in recent years at BMRC. This paper only briefly covers some of these with a focus on the more recent development of the new version of the shortwave SES radiation scheme. The new code has a better treatment at gaseous absorption and Rayleigh scattering and therefore leads to a greater accuracy compared with the old version of code. The second important improvement for this code is the further enhancement in its efficiency. The new version of the longwave code is under development and will include trace gases as well as efficiency improvement.

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