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Key Points:
- Infrequent radiation calls in models can lead to stratospheric temperature errors of 3–5 K
- They also cause erroneous patterns in time mean solar fluxes around a latitude circle
- Fix by averaging cosine of solar zenith angle over the daylit part of the radiation time step

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Effect of solar zenith angle specification in models on mean shortwave fluxes and stratospheric temperatures

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Abstract Many weather and climate models call their radiation schemes only every 3 h, which we show can lead to a stratospheric temperature overestimate of 3–5 K and wavenumber 8 fluctuations in top-of-atmosphere (TOA) net shortwave flux around the tropics of amplitude 1.6 W m^{-2}. Solving this problem while retaining a 3h radiation time step requires careful treatment of the cosine of the solar zenith angle, μ_0, which appears twice in the calculation of shortwave fluxes, scaling the following: (1) TOA incident flux and (2) the path length of the direct solar beam through the atmosphere. If μ_0 is calculated as the average over the radiation time step, rather than at the central time, then the fluctuations are removed, but the stratosphere is still too warm by 2–3 K. It is only if the second μ_0 is averaged only over the sunlit part of the radiation time step that the temperature bias is removed.

1. Introduction

To limit computational cost, global circulation models used for both weather and climate forecasts are often configured with the radiation scheme called only every 3 h. At the time of writing, the European Centre for Medium-Range Weather Forecasts (ECMWF) makes radiation calls every 1 h in its high-resolution deterministic forecast but only every 3 h in its ensemble system, seasonal forecasts, and reanalysis. Climate models with a 3h radiation time step include ACCESS [*Bi et al.*, 2013], EC-Earth [*Hazeleger et al.*, 2011], GFDL [*Anderson et al.*, 2004], HadGEM3 [*Walters et al.*, 2014] and INM-CM4 [*Zhou et al.*, 2015]. This has been found to lead to errors in the diurnal cycle of temperature [*Yang and Slingo*, 2001; *Hogan and Bozzo*, 2015] and to change the climate sensitivity of the model [*Morcrette*, 2000]. It is hardly surprising that this is problematic in the shortwave since eight radiation calls in 24 h implies typically only four for which the sun is above the horizon, and four discrete angles are clearly a poor approximation to the path of the sun through the sky.

The cosine of the solar zenith angle is used twice in the calculation of solar fluxes, best illustrated by considering the following expression for the direct solar monochromatic flux into a horizontal surface at a height z in the atmosphere:

$$S^{\downarrow}_{\rm dir} = S_0 \mu_0 \exp\left[-\tau(z)/\mu_{0m}\right], \tag{1}$$

where S_0 is the solar irradiance at top of atmosphere (TOA) and $\tau(z)$ is the zenith optical depth of the atmosphere from height z up to TOA (after delta-Eddington scaling). Both μ_0 and μ_{0m} represent the cosine of the solar zenith angle, but different symbols are used to emphasize the different ways that this variable is used.

The fact that μ_0 scales the entire profile of shortwave fluxes (and therefore heating rates) means that it is straightforward to account for poor temporal sampling. *Morcrette* [2000] described the method currently used in the ECMWF model and others [e.g., *Yang and Slingo*, 2001] as follows: when the shortwave radiation scheme is called at the beginning of a *radiation* time step, the TOA incoming solar flux into a horizontal plane is set to unity in order that the computed net shortwave flux profile is normalized. Then at every intervening *model* time step, the actual net flux profile (and associated heating rate profile) is computed by multiplying the normalized flux profile by $S_0\mu_0$, where μ_0 is computed at a time halfway into the model time step. This approach is illustrated by the schematic in Figure 1 and hereafter is referred to as the Morcrette method. *Zhou et al.* [2015] stressed the importance of using the average value of μ_0 across the time interval rather than the centered time value; this explained their finding that the incoming solar radiation in 8 out of the 28 climate models they examined had erroneous fluctuations in the annual mean as a function of longitude around the equator. For example, the EC-Earth model (based on the ECMWF weather model in 2006) had wavenumber 24 fluctuations of amplitude around 1 W m^{-2}. They attributed this to the radiation scheme having been called

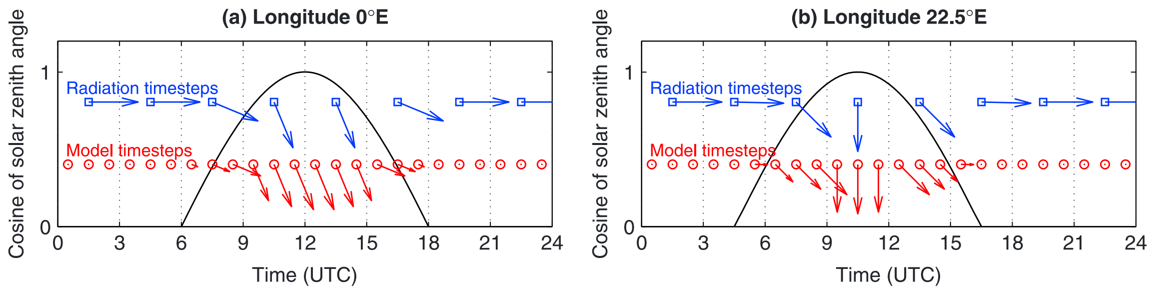

Figure 1. Schematic illustrating the *Morcrette* [2000] method for treating solar zenith angle when the radiation scheme is called every 3 h. The black lines show the true diurnal cycle of μ_0 at two points on the equator, where the longitude is (a) 0° and (b) 22.5°. Both points are at an equinox so that the sun passes exactly overhead once per day. The radiation scheme is called at the start of each 3 h interval using the solar zenith angle at the center of that interval, indicated by the angle of the blue arrows. The fluxes are normalized, indicated by the length of all the blue arrows being the same. In this example the model time step is 1 h, and every model time step that fluxes from the most recent call to the radiation scheme is multiplied by the value of μ_0 at the center of the time step. This is indicated by the change in length of the red arrows, although note that their angle is not changed from the angle used in the radiation scheme (indicated by μ_{0m} in the text).

once per hour, but in fact it was called every 3 h. In section 2 we show that the use of the Morcrette method means that the amplitude and wave number of these fluctuations is due to the *model* time step, and therefore they are far smaller for the short time steps of weather forecast models.

The nonlinear dependence on μ_{0m} in (1) makes it much more tricky to make a correction between calls to the radiation scheme. *Manners et al.* [2009] reported instantaneous errors in surface net shortwave flux in excess of 50 W m^{-2} due to this problem in a model with a 3h radiation time step and proposed a scheme that reduced these errors by a factor of 5. However, their scheme only affects surface fluxes but not atmospheric absorption. In section 3 of this paper we demonstrate that even when the methods of *Morcrette* [2000] and *Manners et al.* [2009] are implemented, radiation calls only every 3 h result in substantial biases in stratospheric temperature that are only slightly diminished if μ_{0m} is averaged across the radiation time step. We explain the reason for this and propose a simple solution.

2. Incoming Solar Radiation

To reproduce the fluctuations found by *Zhou et al.* [2015], Figure 2 depicts the 1 year mean of the incoming solar flux around the equator from free-running 13 month T255 (around 75 km) resolution atmosphere-only model simulations (ECMWF model cycle 41R2) with the radiation scheme called every 3 h. The simulations were started on 1 August 2000, and the annual mean was computed starting on 1 September. With a 1 h model time step, the wavenumber 24 of amplitude around 1 W m^{-2} is very similar to that reported by *Zhou et al.* [2015] for EC-Earth, which also uses a 1h model time step [*Hazeleger et al.*, 2011]. *Zhou et al.* [2015] attributed this pattern to the radiation scheme being called every 1 h in EC-Earth when in fact it was called only every 3 h. The benefit of the Morcrette method to rescale the fluxes every model time step is that the wavelength of the fluctuations is tied to the model time step, not the radiation time step. This is confirmed by the blue

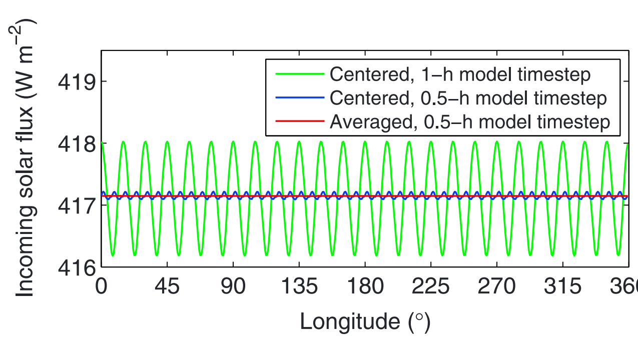

Figure 2. Annual average incoming solar flux at the top of atmosphere above the equator. The calculations are from T255 simulations in three configurations: with (i) a 1 h model time step, (ii) a 30 min model time step, and (iii) a 30 min model time step but with μ_0 computed as an average over the model time step. All three versions call the radiation scheme only every 3 h.

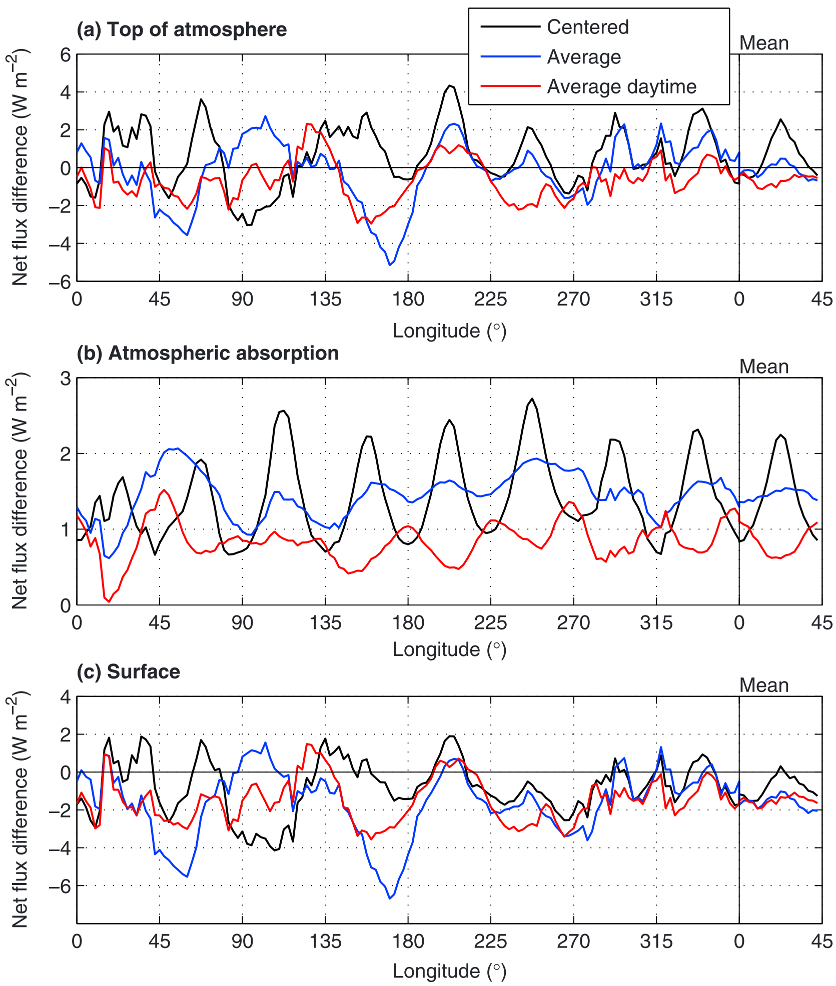

Figure 3. Difference in annual mean net shortwave fluxes between simulations with the radiation scheme called every 3 h and every model time step (30 min) for a ±15° latitude band around the equator. The (a) TOA and (c) surface values and (b) the difference between the two, i.e., the radiation absorbed by the atmosphere. The bias and standard deviation of each of the lines are provided in Table 1. The rightmost part of each panel shows the average of each 45° in longitude, thereby producing a best estimate of the shape of the wave number8 fluctuations in each simulation. The "Centered" line represents the control model configuration in which the cosine of the solar zenith angle used by the radiation scheme, μ_{0m}, is computed at the central time of the radiation time step. "Average" computes μ_{0m} as the simple average over the radiation time step, while "Average daytime" computes μ_{0m} as the average over only the sunlit part of the radiation time step.

line showing the pattern when the model time step is reduced to 30 min, while still only calling the radiation scheme every 3 h. This time the fluctuations have a wave number 48 pattern and are of much lower amplitude. The high-resolution deterministic model configuration at ECMWF currently uses a 10 min model time step, for which these fluctuations are imperceptibly small.

Despite the fact that fluctuations of this magnitude will not impact weather forecasts, the use of an averaged μ_0 across the model time step has now been implemented in the ECMWF model following the suggestion of *Zhou et al.* [2015]. The red lines in Figure 2 confirm that this removes the erroneous fluctuations and is applicable for any model time step. It should be noted that this result is completely independent of whether μ_{0m} is averaged or not, which is considered in the next section.

3. Net Fluxes and Atmospheric Heating Rates

The treatment of both μ_0 and μ_{0m} affects the distribution of net shortwave fluxes throughout the atmosphere, and therefore heating rates and temperature. Since fluctuations in these quantities are most evident in the tropics, Figure 3 depicts the errors in TOA net shortwave flux (S_n^{TOA}), surface net shortwave flux (S_n^{surf}), and

Table 1. Biases in Net Shortwave Flux (W m^{-2}) Associated With Calling the Radiation Scheme Every 3 h, Estimated by Comparing to Simulations Calling the Radiation Scheme Every Model Time Step[a]

	Centered	Average	Average Daytime
Global TOA bias	0.50	0.14	−0.43
Tropical TOA bias	0.61 (1.60)	−0.16 (1.67)	−0.65 (1.12)
Global absorption bias	1.07	1.13	0.67
Tropical absorption bias	1.41 (0.54)	1.45 (0.30)	0.84 (0.26)
Global surface bias	−0.57	−0.98	−1.11
Tropical surface bias	−0.79 (1.44)	−1.61 (1.81)	−1.49 (1.18)

[a]"Absorption" is the atmospheric shortwave absorption, computed simply as the difference between the TOA and surface net flux. The experiments in each of the three columns correspond to those shown in Figure 3 and described in section 3. The rows marked "Tropical" are for a ±15° latitude band around the equator and provide also in parentheses the standard deviation of each of the lines in Figure 3.

atmospheric shortwave absorption ($S_n^{\mathrm{TOA}} - S_n^{\mathrm{surf}}$) for a ±15° latitude band around the equator. Net flux is defined as the downwelling minus the upwelling flux. These are annual means from four-member ensembles of T255 simulations averaged from September 2000 to August 2001 inclusive. Each simulation uses a model time step of 30 min and a radiation time step of 3 h, and each implements the scheme of *Manners et al.* [2009] to reduce errors in surface net fluxes. To isolate the errors due to infrequent calls of the radiation scheme, the fluxes from a reference simulation with the radiation scheme called every model time step have been subtracted. This reference simulation uses μ_0 and μ_{0m} computed at the center of the model and radiation time step, respectively, but there is very little change if they are instead averaged over the relevant time step. The statistics of the lines in Figure 3 are provided in Table 1.

The black lines in Figure 3 show the control simulation in which both μ_0 and μ_{0m} are computed at a time centered on the model and radiation time steps, respectively. Despite longitudinal patterns associated with changes in cloudiness, it is clear that there is a wavenumber 8 pattern in all panels, contrasting with the wavenumber 48 pattern found in the incoming solar radiation in Figure 2. Therefore, this pattern must be associated with the discrete times used in the calculation of μ_{0m} every 3 h rather than the discrete times used in the calculation of μ_0 every 30 min. *Stenchikov et al.* [1998] came to the same conclusion when they found wavenumber 12 fluctuations in mean fluxes in a model that called its radiation scheme every 2 h. Figure 1 illustrates schematically the very different treatment of solar zenith angle at locations separated in longitude by 22.5°, corresponding to the distance between the peaks and troughs in the wavenumber 8 pattern.

The rightmost part of each panel of Figure 3 characterizes the mean shape of the wavenumber 8 pattern. The amplitude of the pattern is 1.6 W m^{-2} at TOA, 0.9 W m^{-2} at the surface, and 0.7 W m^{-2} in atmospheric absorption. Also of concern is the 1.4 W m^{-2} overestimate in atmospheric absorption, which Table 1 shows is 1.1 W m^{-2} as a global mean. While this bias is only a small fraction of the 78 W m^{-2} global mean atmospheric absorption in the reference simulation, Figure 4a shows that this excess absorption occurs largely in the stratosphere and leads to a temperature overestimate peaking at 3.4 K in the Tropics at 10 hPa, as well as even larger errors over the summer pole.

The first thing to try in order to fix this bias is to average μ_0 and μ_{0m} across the model and radiation time steps, respectively: the resulting net flux errors are shown by the green lines in Figure 3. It can be seen that the wavenumber 8 fluctuations are considerably reduced in amplitude at all heights, but the overestimate in mean atmospheric absorption is still present. Figure 4b shows that a stratospheric temperature overestimate is still present but with reduced amplitude: in the tropics the largest error is 2.3 K.

To understand why stratospheric heating is overestimated both when μ_{0m} is computed at the center of the radiation time step and when μ_{0m} is averaged across the radiation time step, it is necessary to consider in more detail how μ_{0m} is actually treated in the model. In fact, μ_{0m} is not used directly in the radiation scheme but

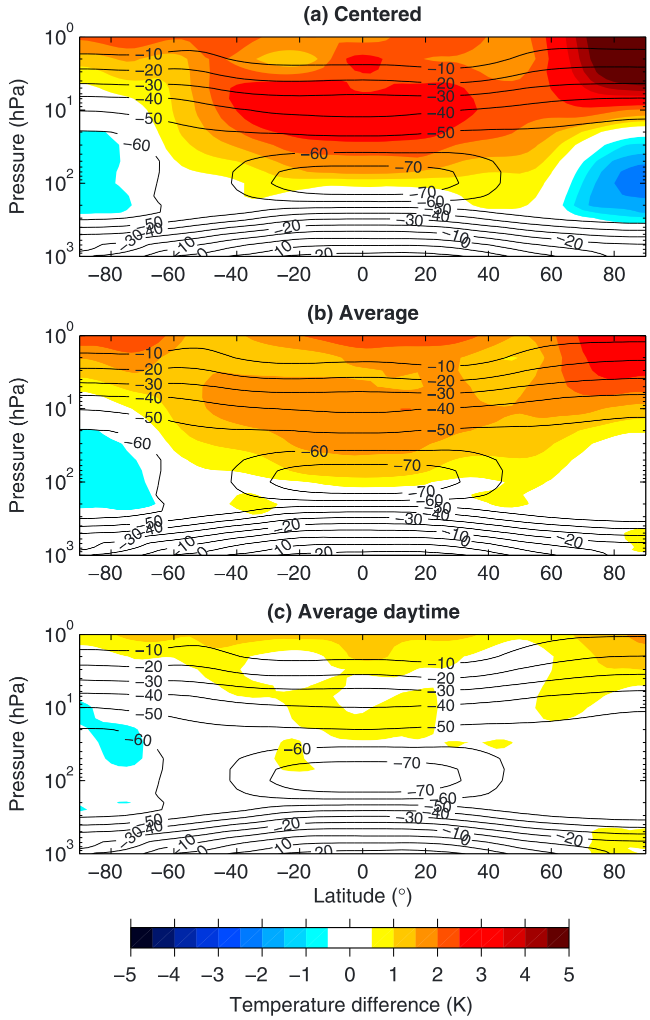

Figure 4. The black contours show the annual mean temperature for model simulations with the radiation scheme called every 3 h, where the three panels correspond to the three model configurations described in the caption of Figure 3. The colors show the differences between these temperature fields and a reference simulation in which the radiation scheme was called every model time step (30 min).

rather a modified version, μ'_{0m}, that accounts approximately for the effects of Earth curvature [*Paltridge and Platt*, 1976]:

$$\mu'_{0m} = \frac{H}{\sqrt{\mu_{0m}^2 + H(H+2)} - \mu_{0m}}, \tag{2}$$

where $H = 0.001277$ is the assumed ratio of the atmospheric equivalent height and the radius of the Earth. Similar schemes are used in other models [e.g., *Fomichev et al.*, 2004]. This function has the property of $\mu'_{0m} \simeq \mu_{0m}$ when the sun is well above the horizon, but as $\mu_{0m} \rightarrow 0$, μ'_{0m} approaches a value of 0.025 corresponding to a solar zenith angle of 88.6°. In practice this means that even at night when $\mu_{0m} = 0$, the shortwave radiation scheme is called with a value of $\mu'_{0m} = 0.025$. In most cases the resulting flux profiles are then multiplied by $\mu_0 = 0$ every model time step to compute shortwave heating rates, which are then zero. However, near dawn and dusk the sun may be below the horizon at the center of the radiation time step (which in the Centered case in Figures 3 and 4 leads to the radiation scheme being called with $\mu'_{0m} = 0.025$), but toward the beginning or end of the radiation time step the resulting fluxes can be multiplied by a value of μ_0 significantly larger than 0.025. This occurs in Figure 1b for model time steps centered on 0530 and 1530 UTC. Physically, this means that the value of μ'_{0m} used in the radiation scheme (i.e., the value of μ_{0m} in equation 1) is unrealistically small for the part of the radiation time step that the sun is actually above the horizon, so the direct solar beam enters the atmosphere at too shallow an angle and is therefore absorbed too much by the upper layers of the atmosphere. This explains the temperature overestimate in Figure 4a. If μ_{0m} is taken to be the average value across the model time step, the inclusion of zeros in this average leads to μ_{0m} still being too low, since the times the sun is below the horizon do not contribute to fluxes or heating rates.

A simple approximate solution to this problem is to compute μ_{0m} as the average over only the fraction of the radiation time step when the sun is above the horizon. Appendix A describes how this is done analytically. Note that μ_0 is still computed as the full average over a model time step, even when the sun is below the horizon. The results are shown by the red Average Daytime lines in Figure 3. It can be seen that as with the simple average μ_{0m}, the wavenumber 8 oscillations in the surface and TOA net fluxes have largely been removed, but this time the bias in atmospheric absorption (Figure 3b) has been substantially reduced. Figure 4c shows that through much of the stratosphere the temperature bias (compared to running the radiation scheme every time step) is less than 0.5 K. Note that there is still a small bias in global mean atmospheric absorption of 0.7 W m^{-2}, but the steeper sun angle at dawn and dusk means that much of this is in the troposphere where the higher air density causes a given error in absorption to be associated with a much smaller temperature error.

In both the Average and Average Daytime configurations shown in Figures 3 and 4, Earth curvature correction is applied after the averaging is performed to yield the value of μ'_{0m} used in the radiation scheme. An alternative approach would be to do the averaging after accounting for Earth curvature. Unfortunately this cannot be done analytically, but we have tested this approach numerically using four-point Gaussian quadrature to compute an average value of μ'_{0m} in the daytime part of the radiation time step. The flux errors are very similar to those of Average Daytime, while the stratospheric temperature errors are slightly worse over the poles (not shown). Thus, it appears that the extra computational expense of using numerical integration is not justified, so we recommend the use of an analytic average of the cosine of the solar zenith angle over the daytime part of the radiation time step, followed by Earth curvature correction.

4. Conclusions

In this paper we have examined the biases that occur due to discrete sampling of solar zenith angle in models whose radiation schemes are called only every 3 h and how these errors can be mitigated. We find that it is important to treat separately the two uses of the cosine of this angle, which we denote as μ_0 and μ_{0m} in (1). In the case of μ_0, which scales the TOA incoming solar radiation, calculating μ_0 at the center of the radiation time step leads to fluctuations in the time-mean incoming solar radiation around a latitude circle [*Zhou et al.*, 2015]. If the *Morcrette* [2000] method is used to rescale solar flux profiles every model time step (with a value of μ_0 for the center of the model time step), then the wavelength and amplitude of these fluctuations is much reduced and is negligible for the time steps of global weather forecast models. Nonetheless, it is straightforward to remove these fluctuations completely, no matter the model time step, by using a value of μ_0 averaged across the model time step.

We have also found that a radiation time step of 3 h leads to wavenumber 8 fluctuations in time-mean net TOA and surface fluxes, and a stratospheric temperature bias of greater than 3 K. These errors are not diminished by reducing the model time step because they are due to the discrete sampling of μ_{0m} rather than μ_0. Averaging μ_{0m} over the radiation time step reduces the erroneous fluctuations, but a significant stratospheric temperature bias still remains. Physically, this is because the direct solar beam tends to enter the atmosphere at too shallow an angle near dawn and dusk, leading to excessive absorption at higher altitudes. This problem disappears if the radiation scheme is called every 1 h or shorter, but we have found that the problem can also be largely removed while retaining a 3h radiation time step by instead using a value of μ_{0m} that is averaged over just the sunlit part of the radiation time step. We would expect comparable errors to be present in other models with a 3h radiation time step, although some differences in behavior may arise with models that do not use the *Morcrette* [2000] or *Manners et al.* [2009] methods to adjust solar fluxes or that have a different way to treat Earth curvature effects [e.g., *Dahlback and Stamnes*, 1991].

Appendix A: Computing the Average Daytime Cosine of Solar Zenith Angle

The cosine of the solar zenith angle may be computed from

$$\mu_0 = \sin\delta \sin\phi + \cos\delta \cos\phi \cos h, \tag{A1}$$

where δ is the solar declination angle, ϕ is latitude, and the hour angle in the local solar time is $h = T + \lambda + \pi$, where T is the solar time expressed in radians (i.e., $T = 2\pi$ corresponds to 24h) and λ is longitude. When the sun is below the horizon, μ_0 is taken to be 0.

We wish to compute $\overline{\mu_{0m}}$, the average cosine of the solar zenith angle for the sunlit part of the time interval T_1 to T_2. The Sunrise Equation states that

$$\cos h_0 = -\tan\delta\tan\phi, \tag{A2}$$

where h_0 is the hour angle at sunrise (if the negative value is taken) or sunset (if the positive value is taken). The times T_1 and T_2 are converted to hour angles h_1 and h_2 and compared to the values at sunrise and sunset to obtain the time interval h_{min} to h_{max} when the sun is above the horizon. The average is found by integrating (A1) with respect to h in this interval to obtain

$$\overline{\mu_{0m}} = \sin\delta\sin\phi + \frac{\cos\delta\cos\phi\left(\sin h_{\text{max}} - \sin h_{\text{min}}\right)}{h_{\text{max}} - h_{\text{min}}}. \tag{A3}$$

Note that in order for the result to be analytic, (A3) is used before applying the Earth curvature correction given by (2).

Acknowledgments
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