Generalizing Cloud Overlap Treatment to Include Solar Zenith Angle Effects on Cloud Geometry

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ABSTRACT

Shortwave radiative transfer depends on the cloud field geometry as viewed from the direction of the sun. To date, the radiation schemes of large-scale models only consider a zenith view of the cloud field, and the apparent change in the cloud geometry with decreasing solar zenith angle is neglected. A simple extension to an existing cloud overlap scheme is suggested to account for this for the first time. It is based on the assumption that at low sun angles, the overlap between cloud elements is random for an unscattered photon. Using cloud scenes derived from radar retrievals at two European sites, it is shown that the increase of the apparent cloud cover with a descending sun is reproduced very well with the new scheme. Associated with this, there is a marked reduction in the mean radiative biases averaged across all solar zenith angles with respect to benchmark calculations. The scheme is implemented into the ECMWF global forecast model using imposed sea surface temperatures, and while the impact on the radiative statistics is significant, the feedback on the large-scale dynamics is minimal.

1. Introduction

It is now almost traditional to commence articles related to clouds by recalling just how complicated a phenomenon they are and how uncertain their representation (parameterization) is in global and regional models. Much of our present lack of confidence stems not only from the representation of cloud microphysical properties, but also of their geometry.

Mesoscale or global models [referred to hereafter as general circulation models (GCMs)] represent complicated fractal cloud structures with just a handful of parameters that describe the essence of their geometrical qualities. Despite varying vertical resolutions, most still assume cloud fills the model grid box entirely in the vertical direction (Brooks et al. 2005), and the representation of cloud geometry is constrained to the horizontal coverage at each height, possibly supplemented by an estimate of the subcloud horizontal water variability.

The models must additionally specify how clouds at different heights overlap. This treatment of overlap is important for nonlocal cloud processes such as precipitation evaporation (Jakob and Klein 1999) and radiation transfer (Morcrette and Jakob 2000; Chen et al. 2000; Barker and Räisänen 2005). In particular, shortwave (SW) radiative transfer is further complicated by the fact that the effective total cloud cover (TCC) as appreciated by an unscattered photon ultimately depends on the solar zenith angle (SZA). At low sun angles, photons have a reduced chance of passing through clear-sky gaps between clouds. The rules that govern the cloud overlap should take this directional effect into account and reproduce the total cloud cover as seen by the direct photon beam.

To assess errors made in SW radiative processes, a benchmark calculation is required. Given a high-resolution, well-resolved, 3D cloud scene, this is provided by a 3D radiative code, such as a Monte Carlo calculation, which accounts for both the exact cloud geometry and photon 3D scattering. Processing the scene to provide the GCM inputs of cloud cover and mean cloud water, the GCM calculation will diverge from the 3D benchmark because of neglect of photon scattering.
directionality including sun position and off-zenith scattering, the inaccurate representation of horizontal and vertical subcloud variability, and the vertical cloud overlap.

A useful intermediate calculation is the independent column approach [ICA; from Cahalan et al. (1994a), who refer to the method as the independent pixel approximation], where a separate radiative transfer calculation is conducted for each column in the high-resolution scene. Photon interaction between the columns is disallowed, and as in a GCM calculation, the SZA enters the calculation only through the decrease in the top-of-atmosphere (TOA) incoming SW radiation and the increase in optical depth in each cloud layer due to the increased pathlength. If the cloud has no horizontal variability, then the GCM will only diverge from the ICA because of inaccurate assessment of the vertical overlap.

To add the SZA-related effect to the ICA, Várnai and Davies (1999) suggested a tilted ICA (termed TICA) calculation, where the cloud field is appropriately rotated according to the sun angle. Compared to the full 3D benchmark for scenes of deep convection, TICA corrects over half the error of the ICA at low sun angles (Di Giuseppe and Tompkins 2005). In other words, accounting for the total cloud cover increase at low sun angles is as important as considering 3D photon scattering. Including this SZA-related effect is thus a first surmountable step to tackle, contributing toward the ultimate goal of representing 3D solar radiative transfer effects in large-scale models.

The fundamental problem in including the SZA impact on effective cloud cover in GCMs is that the position of the clouds within the grid box is unknown. However, a way forward is provided by returning to the concept of the vertical cloud overlap rules. These rules are, in fact, not expected to reproduce each individual cloud scene perfectly, but describe statistically the cloud overlap properties that are true when averaged over many cloud scenes. Likewise, the solar zenith angle–related increase can be described by generalizing the cloud overlap rules to statistically represent the average impact on the effective cloud cover as the sun angle changes.

This paper thus introduces a new parameterization for the solar zenith angle effect on effective cloud geometry by implementing a generalization in existing cloud overlap rules used in SW radiative transfer schemes. The model is tested and evaluated using cloud scenes retrieved from ground-based radar. The simplicity of the parameterization implies that it can be applied easily to any global model radiative transfer model code and could also be combined with more complicated schemes that attempt to represent subcloud variability (Pincus et al. 2003). Here the impact of the scheme using two widely used shortwave radiation codes is demonstrated in 3D integrations using the European Centre for Medium-Range Weather Forecasts (ECMWF) forecast model.

2. Parameterizing solar zenith angle effects

The maximum-random (MAX-RAN) overlap scheme assumes that clouds in adjacent vertical levels are likely to form part of the same vertical cloud element and are maximally overlapped, while clouds separated by a clear layer are assumed to be spatially decorrelated and thus randomly overlapped (e.g., Geleyn and Hollingsworth 1979; Tian and Curry 1989). The latter assumption appears to be well justified in the analysis of radar data (Hogan and Illingworth 2000; Mace and Benson-Troth 2002). This scheme is operational in the ECWMF model as of August 2006.

Hogan and Illingworth (2000) examined cloud overlap using retrieval data from the Chilbolton radar in the United Kingdom. They noted that vertically coherent cloud entities will decorrelate in height in the presence of wind shear (see also Lin and Mapes 2004; Pincus et al. 2005b) and that the MAX assumption could thus underestimate cloud fraction in deep cloud systems. A length scale $L$ was derived from the radar data, which described the rate at which a continuous cloud block decorrelates exponentially in the vertical. Defining $\alpha = \exp(-\Delta z/L)$, where $\Delta z$ is the distance between two cloud layers (or the grid resolution in a GCM), they suggested an exponential-random scheme (EXP-RAN) where the cloud cover $C$ between any two layers ($i$ and $j$, respectively) is given by $C_{i,j}^{\text{EXP-RAN}} = \alpha C_{i,j}^{\text{MAX-RAN}} + (1 - \alpha) C_{i,j}^{\text{RAN}}$.

The new parameterization represents the solar zenith effect on apparent cloud geometry by introducing a simple extension to the EXP-RAN scheme. Assuming that the decorrelation length scale can be derived accurately for the sun overhead case, which will be denoted $L_0$, an adjustment factor $K$ is sought for $L_0$ to account for a declining sun angle, such that the decorrelation length scale is given by $L = KL_0$.

To derive $K$ it is assumed that as the sun descends to the horizon, the overlap between cloud elements becomes increasingly random, that is, the vertical decorrelation length scale (and therefore $K$) should tend toward zero. As the sun descends, it is increasingly the horizontal overlap between individual cloud elements that determines the apparent cloud cover and the associated photon interactions. Averaged over many cloud scenes, the horizontal overlap is likely to be random,
despite the fact that cloud systems can be strongly linearly organized in the presence of vertical wind shear, since the solar direction and the organization of clouds are uncorrelated.

While the random overlap assumption suffers from a severe vertical resolution dependency if used for adjacent cloud layers (e.g., Bergman and Rasch 2002; Stephens et al. 2004) due to its assumption that the cloud decorrelation length scale relates directly to the model vertical grid spacing, this is not the case for the revised scheme outlined because of its use of the fixed decorrelation length scale as in the EXP-RAN scheme.

Given this limit for $K$ at low sun angles, the rate at which the limit of random overlap is achieved as the sun descends, in other words the form for $K$, still needs to be determined. There is no analytical solution possible since this will ultimately depend on the nature of the organization in each individual cloud scene. Here, three simple parameterization forms will be tested:

$$K = \begin{cases} 
1 - \frac{2\theta_0}{\pi} & \text{parameterization 1} \\
\cos(\theta_0) & \text{parameterization 2} \\
e^{-\frac{\theta_0}{\tan \theta_0}} & \text{parameterization 3}
\end{cases}$$

where $\theta_0$ is the SZA. The first two parameterizations link decorrelation length scale decrease linearly to, or with cosine of, the solar zenith angle, respectively. The third parameterization is based on Hogan and Illingworth (2003), with their wind shear parameter replaced by $\tan \theta_0$. Here, on the order of 100 cloud scenes will be used to determine the best form. However, data from the spaceborne radar of CloudSat (Stephens et al. 2002) will provide an improved empirical relation.

The extended scheme is referred to as EXP-SZA-RAN throughout.

3. Validation against TICA

The new parameterization is derived and evaluated in comparison to benchmark TICA calculations for a large number of cloud scenes. For this task, the SW radiation code of the 2001 operational ECMWF forecast model CY23R4 and the 40-yr ECMWF Re-Analysis (ERA-40) system (Uppala et al. 2005) are used (Morcrette 1991) without the effective zenith angle parameterization [Eqs. (6a) and (6b) of Morcrette and Fouquart 1986], which gave unphysical behavior at low sun angles.

These scenes are derived from radar data from two European sites at Chilbolton, UK, and Palaiseau, Paris, France. The retrieval methodology is detailed in the appendix. For the EXP-RAN overlap parameter, a value of the decorrelation length scale $L_0$ is required. The adopted value of $L_0 = 4.0$ km minimizes the mean true total cloud cover bias to less than 0.5% over the Chilbolton dataset. This minimization is deemed acceptable since the aim here is to parameterize the change in apparent cloud cover as a function of the solar zenith angle, not $L_0$ itself.

The Chilbolton dataset is used to determine the best parameterization form from Eq. (1). The total cloud cover and its error are shown in Figs. 1a,b for the Chilbolton site scenes. The error is calculated with respect to the actual SZA-adjusted cloud cover of the high-resolution cloud scene used in the reference TICA benchmark radiation calculation.

The standard schemes produce a total cloud cover ranging from 43% for the maximum overlap assumption to 73% for the random overlap in the sun overhead case. This compares to the true value of 51%. In many scenes, cloud is present as a single continuous block, and thus the MAX-RAN cloud cover lies quite close to the MAX value, as in Oreopoulos and Khairoutdinov (2003). By design, the EXP-RAN parameterization produces the correct cloud cover for the sun overhead case.

Starting from the sun overhead value, the true cloud cover increases with the descending sun and reaches a final value for low sun angles that is slightly in excess of the random overlap assumption. Keeping the radar retrieval 2D geometry caveat in mind, this nevertheless appears to indicate that the first assumption of the new parameterization scheme is justified; namely, at low sun angles the cloud tends to be randomly overlapped.

Only the new scheme EXP-SZA-RAN renders an apparent total cloud cover that varies as a function of sun angle, since this effect is neglected in the standard calculations. Relative to neglecting the SZA effect altogether, all three parameterization forms make a reasonable approximation to the true cloud cover value. However, all three schemes underpredict the increase in cloud cover for SZA < 60°, with the underprediction being severe for the cosine form of parameterization 2. The tuning factor of $J = 0.5$ in parameterization 3 was selected to minimize the errors over the full range of SZA, but in any case the scheme is seen to overpredict the cloud cover at low sun angles, approaching the random overlap limit too rapidly. Examining the cloud cover error panel on the right, it is clear that for these Chilbolton scenes, the simple linear form of parameterization 1 is superior, with total cloud errors varying by less than a minimal 2% for SZA < 80°. Therefore the linear parameterization $L = (1 - 2\theta_0/\pi)L_0$ is used throughout the rest of this work.

For each cloud scene, a set of GCM radiation calcu-
lations were conducted with each overlap assumption and then compared to a benchmark TICA calculation in terms of the bias in TOA albedo and transmittance (Fig. 2). For sun overhead conditions, the EXP-RAN gives the best match to the benchmark, since $L_0$ was chosen to give zero total cloud cover errors in this case. The small error in reflection will occur because of sub-cloud differences in layer-by-layer overlap and inaccuracies in the way the GCM handles the overlap calculation.

All of the standard schemes produce a significant change in reflectance errors between low and high sun angles. For instance, the MAX-RAN scheme has an albedo that is too small by just 1% (absolute) when the sun is overhead, which increases to over 10% as the sun approaches the horizon. In contrast, the bias of the RAN overlap reduces from an overestimation of nearly 5% to an underestimation of 3%. Similar magnitude changes are observed in the transmittance (Fig. 2b).

The new scheme EXP-SZA-RAN appears to greatly reduce this change in radiation error, with the albedo remaining within a 1% (absolute) value for all solar zenith angles less than 75°. Beyond this limit the cloud proxy provided by the radar data becomes less reliable in any case. The same significant improvement is also seen in the transmittance.

The heating rate ratios for the Chilbolton scenes reveal the vertical structure of the heating rate biases for two SZAs of 15° and 72° (Fig. 3). The heating rate error structure shows a dipole structure since many of the scenes consist of mid- and upper-tropospheric ice clouds (for reasons outlined in the appendix), resulting in a peak in cloud cover at 400 and 200 hPa (solid lines in figure). The mean cloud cover at any particular height is small, with a peak value less than 20%, since this profile is the average of many scenes with clouds at different heights.

The heating rate profiles show that overlap assumptions that overestimate the cloud fraction, such as the RAN scheme with the sun overhead, tend to produce too much solar warming in the upper layer of the clouds, as expected, and a corresponding relative cool-
Fig. 2. (a) Mean TOA albedo bias and (b) mean transmittance (surface net solar radiation normalized by the TOA value) bias for the identical Chilbolton scenes used in Fig. 1.

Fig. 3. Heating rate ratio between the GCM experiments (see legend) and the benchmark TICA calculation for the same scenes analyzed in Fig. 1 for a SZA of (a) 15° and (b) 72°. On the rhs, the mean true cloud cover as a function of height is shown (thick solid line) for comparison (see upper scale) and the thick bar indicates the apparent TCC.
ing at lower layers and beneath the cloud base. The reverse is true of the MAX and MAX-RAN schemes. The EXP-SZA-RAN scheme is seen to restrict the heating rate errors to within 5% of the benchmark TICA calculation at all heights for both low and high values of SZA.

The analysis was repeated for over 650 scenes at Palaiseau. Encouragingly, although an identical value of $L_0/4.0 \text{ km}$ is used for this site without adjustment, it nevertheless gives a good estimate of the total cloud cover for the sun overhead case (Fig. 4a). That said, the meteorological conditions of the two sites are very similar, and therefore this does not indicate that $L_0/4 \text{ km}$ would be the best value to use globally. As for the Chilbolton site, the EXP-SZA-RAN parameterization reproduces that SZA-dependent cloud cover tendency and its final value at low sun angles very well, and the corresponding biases in the reflection statistic are also minimized by the new scheme, again with errors less than 1% for all SZAs less than 75° (Fig. 4b).

4. Impact in 3D GCM

The new parameterization was implemented into the full ECMWF global forecast model and a set of short 3-h forecasts were conducted with a T159 (approximately equivalent to 100 km) horizontal resolution and 91 vertical layers. The differences in the TOA net SW radiation fields at the 3-h range are used to assess the impact of the new overlap treatment. The 3-h range is used to prevent heating rate changes feeding back on the large-scale circulation. To show the flexibility of the new scheme, it is tested with two common SW schemes—those of Morcrette (1991) and the SW version of the Rapid Radiative Transfer Model (RRTM) radiation code (Mlawer and Clough 1997).

a. IFS radiation code

The impact of the new overlap treatment combined with the operational Integrated Forecasting System (IFS) SW scheme is shown in Fig. 5. The new overlap scheme mostly impacts the regions of low sun angle as designed, and the impact is clearly not spatially uniform since it must depend on the cloud structure and coverage. It is recalled that although it will affect the sub-cloud structure, the new scheme is unlikely to have any significant impact in a grid box that contains one or more cloud layers that are, or are close to being, overcast. The local impact of the scheme on the 3-h mean TOA net solar radiation is generally less than 10 W m$^{-2}$.
with a local maximum anywhere in the domain of 39 W m$^{-2}$. The global mean impact is 0.9 W m$^{-2}$.

b. RRTM radiation code

The set of short forecasts were repeated using RRTM SW, with additional integrations conducted using the MAX-RAN and RAN overlap assumptions in the SW to place the new parameterization into context (Fig. 6). The largest impact occurs when switching from the MAX-RAN to the EXP-RAN scheme (Fig. 6a), with a mean increase in TOA SW radiation of 2.6 W m$^{-2}$ and a peak anywhere within the domain in excess of 170 W m$^{-2}$. The influence of the new scheme (Fig. 6b) is not altered substantially by substituting the IFS radiation code for RRTM SW, with a mean of 1.0 W m$^{-2}$, although it is notable that the influence at very low sun angles is reduced. Thus the new scheme represents an influence that is a little under half that derived from implementing the EXP-RAN scheme of Hogan and Illingworth (2000). For a smaller decorrelation length scale $L_0$, the influence of the EXP-RAN would increase at the expense of the EXP-SZA-RAN assumption. Finally, moving to the fully random overlap treatment adds an additional 0.9 W m$^{-2}$. It is seen that the influence is mainly at SZAs less than 75°, showing that for lower sun angles, the EXP-SZA-RAN has resorted to an overlap very close to random.

By design, the short 3-h forecast did not allow the overlap assumption to impact the general circulation of
the model. Thus a further set of 13-month 3-member ensemble integrations was conducted, again using the T159 model with the same vertical resolution. The impact of the EXP-SZA-RAN scheme on the global mean radiative budget statistics was similar, with an increase of 0.5 W m\(^{-2}\) using the IFS radiation scheme. However, no shift in mean climate characteristics, such as cloud ice or liquid water amounts, was noted with changes smaller than the interensemble variability.

One might conclude that the minor climate dynamical impact stems from the fact that the scheme has the greatest effect at low sun angles when solar heating rates are small. However, a further pair of climate integrations were conducted to ascertain the consequences of switching from the MAX-RAN to the EXP-RAN scheme of Hogan and Illingworth (2000), and these also revealed no significant impact on the model climate, even though it has been demonstrated that, locally, the EXP-RAN can substantially alter the SW budgets for sun overhead conditions. This implies that while vertical overlap changes may accumulate layer by layer to have significant (if localized) effects on TOA and surface fluxes, it is generally not altering the local vertical gradient of shortwave heating rates sufficiently to impact the dynamics (see Tompkins and Di Giuseppe 2003). That said, a model with a more sensitive land surface scheme than that used in the IFS model and/or an interactive ocean may show an enhanced sensitivity to the overlap assumption used.

5. Conclusions

Shortwave radiative transfer depends on the cloud field geometry as viewed from the direction of the sun. The photon trajectory and cloud interaction will be entirely different for sun overhead and for low sun angles. Currently, GCMs neglect this effect since the cloud geometry in terms of the cloud positions within the grid cell is unknown. Here a simple extension to a commonly used EXP-RAN overlap scheme of Hogan and Illingworth (2000) is presented to account for the SZA effect.

The new scheme states that for low sun angles, the apparent cloud cover as appreciated by an incoming unscattered photon is best approximated by assuming that clouds are randomly overlapped. The EXP-RAN scheme specifies a vertical decorrelation length scale for continuous cloud blocks; thus the new scheme assumes a zero decorrelation length scale when the sun is on the horizon. Using a large number of cloud scenes derived from the Chilbolton radar, it was shown that this assumption appears to be valid. These data also reveal that the increase in apparent cloud cover as the sun descends is well approximated by reducing the decorrelation length scale \( L \) linearly with solar zenith angle from its sun overhead value \( L_0 \) to zero. Thus the new scheme parameterizes the decorrelation length scale as

\[
L = (1 - \frac{\theta_s}{\pi})L_0,
\]

where \( \theta_s \) is the solar zenith angle. The new scheme was thus christened the EXP-SZA-RAN scheme because of the additional SZA dependence.

Using the tilted ICA (TICA) as a benchmark calculation, the extended scheme was found to dramatically improve the error growth in SW radiation statistics over a wide range of solar zenith angles, both for the Chilbolton cloud scenes for which the sun overhead decorrelation length scale was tuned and for 650 independent scenes from Palaiseau.

The impact in the 3D ECMWF forecast model was assessed using two commonly used SW radiation schemes. The new scheme has the most impact for SZA exceeding 30\(^\circ\), with a global mean impact of around 1.0 W m\(^{-2}\). To put this impact into context, this is just under half the effect that arises when switching from the classical MAX-RAN to the EXP-RAN scheme of Hogan and Illingworth (2000), assuming a decorrelation length scale of 4 km for sun overhead conditions. For decorrelation length scales exceeding 4 km, this ratio would be larger. In yearlong integrations using imposed sea surface temperatures, it was found that neither the change from MAX-RAN to EXP-RAN nor the addition of the SZA effect in the new EXP-SZA-RAN scheme described here had any significant feedback on the large-scale atmospheric dynamics.

Finally, it is noted that the linear parameterization for the SZA-related change in cloud geometry was derived from just two European locations for a period on the order of 1 yr. It is apparent that a refined empirical relationship may improve the fit when applied globally. To this end, analysis of the radar data from the recently launched CloudSat (Stephens et al. 2002) will prove to be invaluable.

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APPENDIX

Cloud Data Input for TICA Tests

To test the GCM parameterization against the benchmark TICA, a significant number of cloud scenes were required. These are derived from cloud ice (Hogan et al. 2006) and liquid water (Boers et al. 2000) retrievals from the vertically pointing radar data at two different European sites, available as part of the European Union Cloudnet project (Illingworth et al. 2007). The near-continuous observations from April to November 2003 at Chilbolton and between March 2003 and September 2004 at Palaiseau were used.

Assuming a horizontal wind speed (e.g., Mace et al. 1998; Hogan and Illingworth 2000), fixed to 5 m s⁻¹ here, the 30-s data points are equivalent to a 150-m cell. The data are divided into scenes of 40 km in length, roughly the grid spacing of the ECMWF operational forecast model as of September 2005. Missing data are replaced by the mean of all data points in the horizontal window of ±1.5 km, if available; otherwise the scene is discarded, as are scenes with optical depths below unity.

The proxy offered by a 2D cloud field slice to its full 3D parent scene becomes increasingly poor at lower sun angles (Barker et al. 1999; Pincus et al. 2005a), with the accuracy depending on the scene’s mean cloud depth, cloud cover, and number of cloud elements. Scenes with cloud cover exceeding 90% are thus rejected. In any case, overlap is almost irrelevant for nearly overcast states. For the periods given above, the procedure outlined results in over 150 scenes for Chilbolton and over 650 for Palaiseau.

The GCM calculation horizontally averages all the grid boxes in a scene to obtain the mean cloud cover and cloud water content as radiation scheme inputs. The cloud cover in the vertical assumes the standard overlap assumptions of MAX, RAN, MAX-RAN, and EXP-RAN in addition to the new scheme EXP-SZA-RAN. The TICA calculation performs a radiation calculation for each column in a cloud scene; thus cloud overlap assumptions are not required. The solar zenith angle effect enters the calculation by increasing the optical depth and reducing the solar constant as usual, and also by applying a horizontal shift at each height h by h tan(SZA) as in Di Giuseppe and Tompkins (2005) to approximate the method of Várnai and Davies (1999). An example scene with the data correction and the SZA shift applied is shown in Fig. A1.

Fig. A1. (top) The raw data of a 40-km cloud scene and number of instances of missing data. (middle) The same scene after a correction method has been applied to replace the missing data; see text for details. (bottom) The translated field for an SZA of 75°.

Differences between the TICA and GCM schemes will arise because of incorrect cloud geometry in the GCM due to the inadequacies of the overlap rules, which the new scheme presented here intends to correct. Further differences could be due to horizontal variability in cloud condensate on the subcloud scale. To prevent this, the TICA uses horizontally averaged cloud water/ice content in each scene, while the Cahalan et al. (1994b) GCM subgrid-scale cloud water correction factor implemented by Tiedtke (1996) is removed.

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