Radiation across spatial scales (and model resolutions)

Robert Pincus

University of Colorado and NOAA/Earth System Research Laboratory
325 Broadway, R/PSD
Boulder Colorado 80305 USA
Robert.Pincus@colorado.edu

ABSTRACT

This note examines issues related to computing radiative fluxes in global models at mesh sizes from roughly 100 to 10 km. Longwave radiation has not received much attention because both physical and radiative phenomena keep scales short and horizontal variability small. I take as the departure point the Monte Carlo Independent Column Approximation, looking first at how Monte Carlo sampling of clouds might need to be re-thought as resolution increases. The applicability of the Independent Column Approximation is then addressed; this approximation is formally inappropriate for many sub-columns in high-resolution models, but the failure introduce relatively small average errors and mitigation requires information that's fundamentally unavailable, the ICA is likely the best that can be done at this time. Geometric issues could be more important for the direct solar beam, especially as it influences surface heating rates, although the limited experience available suggests that it is in treating subgrid-scale topography, rather than subgrid-scale clouds, where the greatest impacts may be felt.

1 Grid scales, cloud scales, and radiation scales

Speakers at this workshop were asked to consider the question "How can we represent the impacts of sub-grid heterogeneity efficiently and consistently across the range of model resolutions?" where, for the purposes of this article, I'll take that range to run from the "large scale", with grid sizes of order 100 km, to the "convective scale" with grid sizes of roughly 10 km.

When computing the interactions between clouds and radiation there are two sets of scales to be concerned with: the scales of the clouds and any inherent scales imposed by radiative transfer itself. Clouds, of course, vary across an enormous range of spatial scales, and one of the challenges of cloud parameterization in large-scale models is to represent this evolving variability and its impacts on the large-scale state (through processes such as precipitation). A lot of time at this workshop was spent considering optimal ways to describe this variability (i.e. the relative advantages of schemes that predict cloud fraction explicitly, e.g. Tiedtke (1993); Wilson et al. (2008), as opposed to those the predict the entire sub-grid distribution of total water, e.g. Tompkins (2002)), but it's important to note that all existing schemes describes the one-point statistics - that is, the probability distribution of clouds without respect to their arrangement in space. This becomes relevant in section 2.4.

What about the scales for radiation? Shortwave (solar) and longwave (terrestrial) radiation are quite different. Clear skies are essentially transparent to shortwave radiation, so that transport is ballistic and the scale is determined by the geometry of the problem. In cloudy skies shortwave radiation is dominated by nearly conservative multiple scattering which, when clouds are thick enough, looks a lot like diffusion. Mutiple scattering introduces a "radiative smoothing scale" (Marshak et al., 1995) discussed in more detail below.

Longwave radiation, even in clear skies, is dominated by emission and absorption; clouds primarily act to increase the opacity of the atmosphere. The relevant scales are . . . well, in fact, relatively little work has been done on the horizontal scales for longwave radiative transfer. That's because the longwave radiation field is quite horizontally uniform - the atmosphere doesn't support large thermal gradients in the horizontal, and thermal emission is isotropic.

There are two related reasons why might parameterizations might depend on the scale of the model in which they're used. First, because parameterizations are used to represent the impact of sub-grid scale processes on the the resolved state, they become unnecessary and even undesirable as the phenomena become explicitly resolved. Processes may have natural scales that encompass several grid columns, while parameterizations normally consider each column independently. As one example, the quasi-equilibrium assumption underlying most parameterizations of deep convection (Arakawa and Schubert, 1974; Moorthi and Suarez, 1992) asserts that the area of strongly-convective updrafts in each grid cell is vanishingly small and all compensating subsidence occurs in the same grid cell - an assumption that fails at model resolutions much coarser than are required to explicitly resolve convective updrafts, so that a "grey zone" (see `http://www.knmi.nl/samenw/greyzone/`) exists where convection is neither well-resolved nor well-parameterized. The gradual breakdown of the "independent column approximation" (as it is called in the radiative transfer community) is the subject of sections 2.3 and 2.4. Conversely, as grid sizes shrink the number of possible realizations of some processes (e.g. the number of shallow cumulus clouds) may become small enough that discrete representations may be more appropriate. This is the subject of the section 2.2.

2 Representing cloud/radiation interactions

2.1 McICA: Treating cloud variability in radiation parameterizations

All cloud parametrizations predict some amount of subgrid-scale variability in cloud optical properties, whether that variability is as simple as a cloud fraction dividing homogeneous clear skies from homogeneous cloudy skies or is more complicated, such as would arise from a distribution of cloud properties within a grid cell, as predicted for example from an assumed-PDF cloud scheme. Even the simplest schemes can produce a subgrid-scale distribution of column-integrated optical thickness, though, since multiple partly-cloudy layers and a "cloud overlap" assumption also imply a distribution of optical properties within each column (Barker et al., 2003). Radiation parameterizations must account for this variability, including the non-linear dependence of radiation fields on the optical properties of the atmosphere.

The Monte Carlo Independent Column Approximation (McICA, see Pincus et al., 2003) was developed to compute radiative fluxes in an unbiased way in clouds with arbitrary inhomogeneity, whether arising from cloud overlap, sub-grid scale variability implied by an assumed-PDF scheme, or some combination. McICA draws discrete samples from the distribution implied by the overlap assumption and internal variability and uses these to estimate the flux. The domain-averaged broadband flux $\overline{F}$ for a single column with uniform optical properties is a sum over G spectral quadrature points:

$$\overline{F}(x,y,t) = \sum_{g}^{G} w_g F_g(x,y,t). \tag{1}$$

If sub-grid-scale variability is represented with a set of S equally-weighted (or randomly chosen) samples the domain-mean flux is the linear average of the flux computed independently in each sample:

$$\overline{F}(x,y,T) = \sum_{s}^{S}\sum_{g}^{G} w_g F_g(x,y,T). \tag{2}$$

This calculation is quite expensive because $G \sim 100$ so that even small values of S imply thousands of individual radiation computations. McICA subverts this problem by setting $S = G$ and associating each sample of the configuration space with a different quadrature point in the k-distribution,

$$\overline{F}(x,y,T) \approx \sum_{g}^{G} w_g F_g(s'_g; x,y,T) \tag{3}$$

where this association is chosen randomly at each point in time and space. McICA (Eq. 3) is a Monte Carlo estimate of the full independent column calculation (Eq. 2) and is, by construction, unbiased but potentially subject to random noise.

As model resolutions increase McICA might break down in at least two ways – either because drawing hundreds of independent samples becomes inappropriate or because the Independent Column Approximation breaks down. I'll first address issues related to the Monte Carlo sampling used by McICA, then treat the Independent Column Approximation.

2.2 Samples, scales, and continuity

The idea of representing the subgrid-scale distribution of cloud properties was developed by Klein and Jakob (1999) who used the technique to develop synthetic satellite observations. In this context each sample is thought of as a satellite imager pixel (roughly 1 km). This is consistent with the sample size and model resolution: the minimum sample scale l implied by N samples in a grid column of size L is $l \sim \sqrt{L^2/N}$; the the model resolution (T106) and number of samples (100) used by Klein and Jakob (1999) implies that each sample corresponds to about 12 satellite pixels. For McICA the number of samples may be larger (the RRTMG package used at ECWMF, for example, has 112 samples in the shortwave and 140 samples in the longwave), and model resolutions have certainly increased; at 10 km resolution this implies a scale for each sample of roughly 630 m.

Before discussing issues for radiative transfer at these scales it's worth thinking about whether we can justify drawing 250 independent cloud samples in a 10 km grid cell. Models do not tend to produce a large number of partly-cloudy layers at one time (Jakob and Klein, 1999), so if clouds are assumed to internally homogenous many of the samples will be the same (i.e. the distribution of possible cloud configurations will be well-sampled). But to draw 250 independent samples from a continuous PDF is to assert that the entire PDF is realized within the grid cell. One could alternatively interpret the distribution in a more probabilistic sense and choose $N' < N$ realizations. This is similar to the way convection is treated by Plant and Craig (2008), but consistency with this viewpoint involves understanding the lifetime of the realizations relative to the model time step and potentially rethinking the way microphysical process rates are calculated (see Axel Seifert's contribution to this volume).

An emphasis on consistent representations of variability requires us to think explicitly about sampling issues they are likely not important from a practical point of view with respect to radiation. That's partly because the coupling between radiation and the state of the atmosphere is loose, such that radiation strongly influences the atmosphere only where its effects can accumulate over time, and partly because unbiased random noise, whatever its source, does not typically change model evolution (see, e.g., Plant and Craig, 2008; Eckermann, 2011)

2.3 The radiative independence of samples

Assuming that we are able to find reasonable solutions for the MC part of McICA (that is, that we can identify a self-consistent method for sampling subgrid-scale variability in cloud properties across model resolutions) we must then address the well-known scale dependence of the ICA. Radiative fluxes in the atmosphere depend in principle on the full three-dimensional distribution of optically-active components, and especially the distribution of optically thick clouds. In most applications, however, the equation describing the three-dimensional transport of radiation is replaced by a substantially more tractable one-dimensional equation, with variability only in the vertical. The Independent Column Approximation treats horizontal variability by applying the one-dimensional equation repeatedly; the difference between this and the full solution is that the ICA neglects "three-dimensional radiative transfer effects" caused by the net transfer horizontal of radiation (Cahalan et al., 1994). The magnitude of three-dimensional radiative effects depends on the degree of difference among columns in the same radiative neighborhood.

The ICA is valid when most variability in optical properties exists at scales larger than the so-called "radiative smoothing scale" λ (Marshak et al., 1995). This value depends on the properties of the clouds themselves and is, to a rough approximation, the geometric mean of the cloud depth Δh and the inverse of the mean local extinction σ . The local extinction can be further estimated from the particle number concentration N, extinction efficiency $Q_{\text{ext}} \sim 2$, and particle radius r as $\sigma \approx N\pi Q_{\text{ext}} r^2$. In moderately dense clouds (e.g. oceanic stratocumulus) λ is of order a few hundred meters, suggesting that three-dimensional radiative transfer are not insignificant in samples with implied scales of 600 m, as above.

The impact of three-dimensional radiative transfer depends on the solar zenith angle (e.g. Welch and Wielicki, 1984). The direct beam is affected mostly by the displacement of cloud shadows, as I discuss in the next section, but the partitioning of scattered shortwave radiation can be significantly different in three-dimensional calculations compared to one-dimensional calculations. When the sun is high radiation can escape from cloud edges, increasing transmission and decreasing reflection (Davis and Marshak, 2002). When the sun is low on the other hand, radiation can enter the clouds from their sides, decreasing transmission and increasing reflection in three-dimensional clouds relative to their plane-parallel counterparts (Várnai and Davies, 1999).

Full three-dimensional solutions to the radiative transfer equation are enormously computationally expensive (Pincus and Evans, 2009). One class of parametric solutions is "stochastic radiative transfer," so-called because the atmosphere is treated as a randomly-distributed binary mixture of clouds and clear skies (see Cairns et al., 2000; Malvagi et al., 1993, among many examples). But there are several significant barriers to using such schemes in global models. First, the schemes would need to be generalized to allow for internal variability in cloud optical properties in addition to the mixtures of clear and cloudy skies. Much more importantly, all such methods need some measure of the spatial scale of the cloud elements embedded in the clear sky - in other words, some parameter related to a characteristic cloud size. But size is precisely the information that *isn't* available from parameterizations that determine the one-point statistics of cloud properties within each grid cell. One could develop further parameterizations for this spatial scale, but it's worth asking whether adding layer upon layer of parameterization to this problem increases accuracy or simply complexity.

Even if a solution can be found it's not clear how important it is to treat three-dimensional radiative effects in large-scale models. Again, models are much more sensitive to systematic biases than to random noise. Because the one-dimensional approximation for radiative transfer has opposing effects at high and low sun angles the diurnal-average impact is normally quite small (Pincus et al., 2005). In addition, three-dimensional radiative transfer is most important when clouds are broken (e.g. Benner and Evans, 2001), which is precisely when cloud fractions and cloud radiative effects are small. So, although one can imagine a path towards treating three-dimensional radiative transfer effects at small scales, that path involves a lot of conceptual work, more computation, but more ambiguity and no obvious reduction in bias.

2.4 The radiative independence of model columns

Though I'm pessimistic about the need for treating three-dimensional radiative transfer effects caused by multiple scattering in global forecast models, there is one three-dimensional effect that initially appears simple enough to treat and large enough to matter – the casting of shadows on the surface, especially by deep clouds. One can easily imagine that interactions between deep convection and surface heating might depend on whether clouds cast shadows directly beneath their bases, as they must using one-dimensional radiative transfer, or if those shadows are displaced horizontally when the sun is not directly overhead. Several studies (Frame et al., 2008; Wapler and Mayer, 2008) have investigated this issue by coupling the Tilted Independent Column Approximation (Várnai and Davies, 1999), which computes three-dimensional effects on the direct beam, to cloud scale models. The results indicate that getting the shadow location precisely correct is unimportant to cloud evolution, which reflects the short lives of the shadows themselves.

But if shadows are fleeting, rocks are not, and one of the most interesting threads of work I came across in reviewing the literature for this workshop treats the parameterization of sub-grid orography as it affects surface radiation fluxes (Chen et al., 2006; Lai et al., 2010; Essery and Marks, 2007; Helbig and Löwe, 2012). These fluxes may be affected by the casting of shadows from neighboring cells but are more strongly influenced by slope and aspect, both of which can be deterministically sampled. It may be the effects of persistent topography, rather than transient clouds, that need the most attention as model resolutions increase.

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This workshop marked, almost exactly, the tenth anniversary of my first visit to ECMWF; the stimulation and excitement I feel walking through the gates have only grown with each visit. I thank the organizers for inviting me to speak and to hear a set of terrific talks, and to engage in a provocative set of discussions. I'm quite grateful for the generous financial support offered by the Centre to participate in this workshop.

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