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ON THE APPLICATION OF MONTE CARLO SOLUTIONS OF THE RADIATIVE TRANSFER EQUATION FOR CLOUDY TERRESTRIAL ATMOSPHERES

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ABSTRACT

When calculating radiances and radiative fluxes for cloudy terrestrial atmospheres, atmospheric scientists usually rely, with much complacency, on 1D analytic solutions of the radiative transfer equation (RTE). However, when high precision is, or should be, required, and when analytic solutions seem remote or impossible, researchers look to Monte Carlo solutions of the RTE; often as a last resort given their reputation for commandeering computer time. The primary purpose of this talk is to demonstrate that this reputation has waned somewhat as of late due to: i) recognition that atmospheric models can tolerate large amounts of radiative noise (stemming from numerics); ii) the obvious efficiency inherent to Monte Carlo algorithms on parallel computers; and iii) the development of atmospheric models that resolve clouds sufficiently well thereby making it worthwhile to step up from 1D to 3D radiative transfer. Discussions will be limited to the use of Monte Carlo algorithms to compute broadband heating rates in atmospheric dynamical models (from cloud-resolving models at one extreme and global climate models at the other), and to infer cloud properties from satellite imagery.

Key Words: radiation, clouds, climate

1. INTRODUCTION

Given the venerable history of Monte Carlo solutions of the radiative transfer equation for cloudy atmospheres [e.g., 1, 2, 3, 4, 5, 6, 7, and 8], this talk will begin by reviewing *some* of the studies that used Monte Carlo methods to compute radiances and fluxes for cloudy atmospheres. Up until very recently, Monte Carlo methods have been used in the atmospheric sciences as non-operational research tools. They have been used most frequently to demonstrate that reliance on 1D solutions inject biases into dynamical models and remote sensing; the two main branches of atmospheric science that routinely perform radiative transfer calculations. The majority of this talk will focus on use of Monte Carlo algorithms in dynamical models ranging from cloud-resolving models (CRMs) to global climate models (GCMs) and in passive remote sensing of clouds. But first, a review is provided regarding the role played by Monte Carlo radiative transfer in helping sort out a landmark crisis in atmospheric radiation.

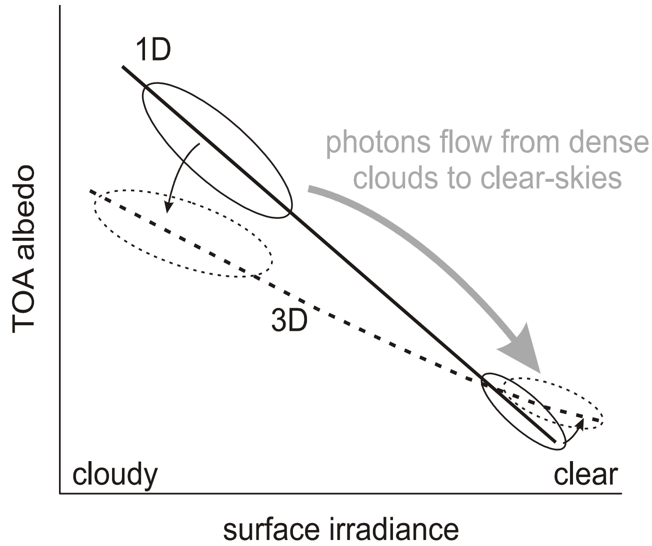

Figure 1: Solid line represents the relation between surface irradiance and TOA albedo as predicted by a 1D model. Dashed line is for a 3D model (or the real world). Due to horizontal transport of photons, albedo for cloudy scenes is smaller than that predicted by 1D theory (i.e., homogeneous clouds). It is smaller because some photons *find* their way to low density regions which are usually clear patches and so surface irradiance predicted by 1D theory is often underestimated. In essence, for 3D transport there is a net flow of photons from left to right across this diagram. This affects a flattening of the relationship and when interpreted solely in terms of 1D theory the implication is that the observations exhibit more absorption than that predicted by 1D theory.

2. INTERPRETATION OF OBSERVATIONS

Occasionally, Monte Carlo radiative transfer algorithms are employed to help interpret observations. The most renowned example was during a time of internal strife known infamously as the *anomalous absorption debate*. During the mid-1990s, some observations suggested that cloudy atmospheres absorb a great deal more solar radiation than that predicted by 1D radiative transfer models [9]. If true, the magnitude of anomalies being claimed would have had titanic implications for cloud and climate modelling. Some researchers went as far as postulating that a *new physics* had been identified... it was very politically-charged! In time, the debate was essentially quashed, save for the recognition that one could always fail to account for various trace gases and hence (slightly) underestimate atmospheric absorption.

Surface and top-of-atmosphere (TOA) radiation measurements seemed to indicate that atmospheric absorption of solar radiation far exceeded that predicted by models. Monte Carlo calculations where used to demonstrate that position of ordered pairs on a surface irradiance-TOA albedo plot differ for 1D and 3D transport (see Fig. 1). In fact, it was shown that if these plots are interpreted with 1D transport models, one can conclude that excessive absorption is taking place even for conservative scattering conditions [10].

Similarly, radiative fluxes measured on stacked aircraft were used to argue for anomalous absorption. A Monte Carlo study [5], however, demonstrated that estimation of flux convergence between the planes is not as straightforward as simply differencing their fluxes; as is the case with 1D transfer.

3. DYNAMICAL MODELS

Dynamical models span a tremendous range of scales. At the smallest scales there are direct-simulations of turbulent eddies and individual cloud particles. These simulations operate on such short time-scales that details of radiative heating are irrelevant. Then there are large-eddy simulations (LESs) and cloud-resolving models (CRMs). These models have horizontal grid-spacings Δx that typically lie between 5 m and 5 km, with most between 100 m and 1 km. Domains are generally 10 km to 500 km and characterized by cyclic horizontal boundary conditions. Simulations often span several weeks. The transfer of both solar and infrared radiation is handled ubiquitously by applying 1D, multi-layer solutions to each column in a domain. This is the independent column approximation (ICA). While the ICA might be a good approximation for some conditions, like stratocumulus over ocean, it is certainly invalid in general; especially for cumuliform clouds. Given the sudden transitions in extinction between clear-air and cloud, and the computational requirements of CRMs, it would appear that semi-analytic solutions of the 3D radiative transfer equation are unsuitable for use in CRMs. It is, however, a relatively straightforward task to perform, at least benchmark, simulations with Monte Carlo transport algorithms. Results will be shown for a 'bowling alley' configuration across the equatorial Pacific using the ICA and 3D Monte Carlo algorithms. The domain was $\sim$2000 km long and $\sim$100 km wide with $\Delta x = 1$ km.

At the other end of the scale are global climate models (GCMs). These are the models that generate all the publicity, for they are capable of simulating (quite well) global climate (change) on time-scales from seasons to centuries. Because GCM domains are rather large (i.e., Earth), and they attempt to address a myriad of processes, computer resources often limit Δx to between 50 km and 250 km. As such, most fluctuations in cloud density are completely unresolved in GCMs. It is rather difficult, therefore, to make a case for doing sophisticated radiative transfer in GCMs when all they actually provide are cloud fractions and mean condensed water contents. Indeed, virtually all GCMs employ two-stream approximations. But at the same time, the influence of unresolved fluctuations must be accounted for in order to avoid systematic energy budget biases (the bane of all GCMs).

Several analytic approximations to account for the radiative effects of subgrid-scale fluctuations of cloud water have been concocted over the past 15 years. They fall into two basic camps: weighting two-streams by assumed distributions of water content and averaging to give closed-form solutions [e.g., 11], and folding assumptions about variability into a two-stream solution [e.g., 12]. Either way, it appears to be simply too much to ask of a deterministic, closed-form solution for they all have demonstrable biases and crippling lim-

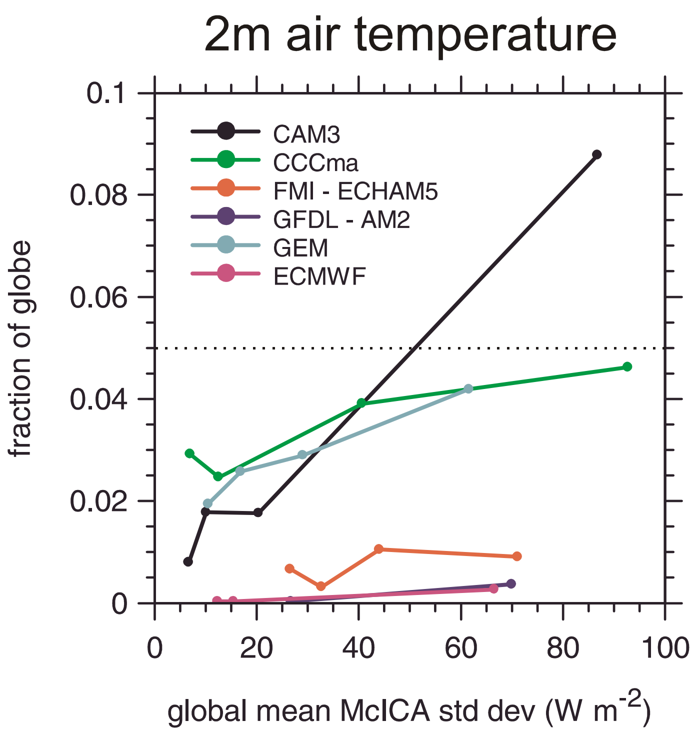

Figure 2: Fractions of the globe exhibiting differences in surface air temperatures that are statistically significant at the 95% confident level as a function of standard deviation of McICA-generated surface solar irradiance for 6 GCMs. The control run was a computationally intensive simulation in which McICA noise was essentially squelched.

itations; particularly when it comes to having to simultaneously account for horizontal and vertical fluctuations of cloud.

A stop-gap solution to the GCM radiative transfer conundrum has turned out to be a 2D Monte Carlo integration of the ICA (McICA) over space and radiation wavelength [13, 14]. First, subgrid-scale cloud structure is defined and subcolumns are generated stochastically; at least one for each spectral interval. Once the spectral integral is complete, the contributions are summed to get broadband heating profiles averaged over the GCM column. With typically 20-100 spectral quadrature points in a typical GCM code, the small sampling of unresolved cloud properties yields, as a by-product, substantial radiative noise yet the expectation value is precisely equal to the full ICA; which is generally taken to be the standard to which GCMs aspire given that so much of the atmosphere is unresolved. Hence, what McICA has achieved is removal of biases at the expense of noise that is uncorrelated in both time and space. As it happens, GCMs are quite capable of digesting surprisingly large amounts of conditional radiative noise. Figure 2 shows the fraction of the globe exhibiting statistically significant differences between simulations with varying amounts of McICA noise relative to a benchmark with almost no noise [15]. If two samples are drawn at random from a population, it is expected that their means will differ ∼5% of the time. For these experiments, all models have less than 5% of their surface showing significant differences in 2 m air temperature for surface solar irradiance standard deviations up to ~50 W m^{-2}. Hence, the noisy and noiseless simulations were effectively drawn from the same population. Operational versions of McICA generally produce standard deviations between 20 W m^{-2} and 40 W m^{-2}.

The newest generation of GCMs, referred to as multi-scale modelling framework (MMF) GCMs, represent a cross between conventional GCMs and CRMs [16]. Instead of a traditional cloud parametrization, an MMF-GCM uses a coarse-resolution CRM in each grid-cell of the host GCM (which still has Δx ~200 km). Most often, the CRMs used in MMF-GCMs have Δx of 1 km to 4 km, are 2D with cyclic boundary conditions, and exchange neither mass nor energy with their neighbours; that is left to the GCM. With a statistical sample of well resolved clouds across the globe, it is conceivable to abandon the usual ICA and use 2D/3D Monte Carlo radiative transfer at the global scale. Thanks to McICA it is known that GCMs can tolerate substantial radiative noise. This begs the question that small numbers of photons in 2D/3D Monte Carlo algorithms in MMF-GCMs will suffice and thereby soften the radiation subroutine's sudden, infelicitous demand for, already stretched, computer resources. Results will be shown that illustrate a MMF-GCM's response to ICA and 3D Monte Carlo radiative transfer.

4. REMOTE SENSING

To date, all operational algorithms that seek to retrieve cloud properties from satellite imagery rely on 1D radiative transfer. Passive solar wavelengths are used most often because they are sensitive over a wide range of conditions relative to thermal wavelengths, though the applicability of 1D theory gets squeezed from both ends. That is, if pixels are large ($> 10^2$ photon mean-free pathlengths), the cloud being viewed will be variable within the field-of-view and represented improperly; if the pixel is small ($<$ 10 photon mean-free pathlengths), cloud in neighbouring pixels will differ and there will be non-zero net fluxes of photons which, again, are not accounted for properly by 1D solutions. If concurrent measurements are made by active sensors, such as cloud-profiling radar (CPR) and lidar, they help the retrieval process greatly, but present space-borne active sensors are nadir-viewing only and yield only a narrow ($<$ 1 km wide) cross-section.

The European Space Agency's EarthCARE satellite [17], scheduled for launch in late-2013, is charged with retrieving cloud and aerosol properties to an accuracy that ensures TOA fluxes can be simulated to within 10 W m^{-2} for each $(10 \text{ km})^2$ pixel of its broadband imager. EarthCARE has nadir-pointing CPR and lidar as well as multi-spectral and broadband imagers. To achieve this goal, 3D radiative transfer must be acknowledged; especially at solar wavelengths. EarthCARE will be the first satellite mission that will attempt to apply 3D radiative transfer codes operationally. The methodology, based on Monte Carlo radiative transfer, and some preliminary results will be shown.

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