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Physical processes in present and future large-scale models

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Summary

Fast radiative transfer models and representation of clouds - Robin Hogan

Introduction

Accurate representation of radiative transfer is crucial for both weather and climate models, but compromises must be made in the formulation of the radiation schemes in such models in order to balance the need for accuracy with the need for computational efficiency. The myriad of ways that radiation can interact with complex cloud fields present a particular challenge. The purpose of this short article is to give a perspective on the appropriate level of sophistication required in the various parts of a radiation scheme.

A radiation scheme can be thought of as an integration of instantaneous monochromatic radiances over the following four dimensions: (1) angle, (2) time, (3) wavelength and (4) space within a model gridbox to account for sub-grid cloud structure. The resulting profiles of broadband fluxes are used within the rest of the model to heat the surface and atmosphere. Each of these four dimensions needs to be discretized, and by comparing the number of quadrature points typically used for each dimension we may ask whether we are using the available computer time efficiently and whether there are good ideas out there to get extra accuracy for modest extra cost. We now consider each dimension in turn.

Integration over angle

This dimension is represented very crudely: in virtually all weather and climate models, the entire diffuse radiation field is represent by only two discrete dimensions, i.e. an upwelling and a downwelling flux. This “two-stream” approximation is so ubiquitous that the resulting errors are rarely given any thought. However, Barker et al. (2015) recently reported that in the shortwave this leads to systematic errors of up to around 8 W m^{-2} in magnitude at the surface and top-of-atmosphere that depend strongly on solar zenith angle. Much better accuracy is achieved by moving to four streams, but the increased computational cost of up to a factor of 8 makes this option unaffordable. A very promising alternative was proposed by Räisänen (2002), who demonstrated that by tuning the coefficients of the two-stream approximation separately for liquid clouds, ice clouds and aerosols, the two-stream errors could be reduced by more than a factor of two for no significant increase in computational cost.
Integration over time

The discretization of this dimension is determined by the frequency with which the radiation scheme is called. In the case of ECMWF, the high-resolution deterministic model calls the scheme every hour, but all other model configurations (the ensemble system, seasonal forecasts and reanalysis) call it only every 3 hours. This leads to measurable degradation in forecast skill due to the lagged response of radiative heating to evolving surface and cloud conditions. Manners et al. (2009) and Hogan and Bozzo (2015) demonstrated that errors at the surface could be largely mitigated by performing approximate updates to the radiation fields between calls to the full radiation scheme. Calling the radiation scheme only every 3 h can also lead to stratospheric temperature biases of 3-5 K, but it was recently reported by Hogan and Hirahara (2015) these can be largely removed by averaging the solar zenith angle over the sunlit fraction of the radiation timestep.

Integration over wavelength

By contrast to the other dimensions, in most correlated k distribution models of gaseous absorption, a large number of spectral intervals are used to integrate over wavelength. For example, the ECMWF model uses the Rapid Radiative Transfer Model for GCMs (RRTM-G), which employs 252 intervals across the full shortwave and longwave spectrum. This scheme has been demonstrated to be very accurate, but its cost means that representation of the other dimensions must be severely curtailed. For the ECMWF model it means that the radiation scheme must be called infrequently in time (discussed above) but also only at every 6th gridpoint in space, leading to errors at coastlines (Hogan and Bozzo 2015). It is therefore pertinent to ask whether sufficient accuracy could be achieved with far fewer spectral intervals, enabling more computational resource to be allocated to the other three dimensions. Some other weather and climate models (for example that of the Met Office) use fewer than half the number of spectral intervals. Promising results have also been found by doing away with the concept of bands and using the *full-spectrum* correlated-k method (e.g. Hogan 2010), requiring far fewer spectral intervals. Further work is required to test this idea in a large-scale model.

Integration over space to represent cloud structure

The state-of-the-art around 15 years ago was to represent each model grid-point by a clear and a cloudy region, with the cloud properties being assumed to be horizontally homogeneous in the cloudy region. This could therefore be thought of as only two quadrature points to represent cloud structure within a gridbox. The neglect of horizontal cloud structure has been found to lead to a 12% overestimate in the magnitude of the cloud radiative effect (Shonk and Hogan 2010). Many models, possibly most, now use the Monte Carlo Independent Column Approximation (Pincus et al. 2003) in which each spectral interval is given a different cloud profile enabling cloud structure to be represented very efficiently and this bias to be removed.

A potentially important effect not represented by any existing radiation scheme in weather and climate models are flows of radiation through cloud sides. Barker et al. (2015) reported that these flows lead to shortwave biases of around the same magnitude and sign as the two-stream errors reported above. Hogan and Shonk (2014) proposed a fast method to represent these 3D effects in the shortwave that (with Sophia Schäfer at the University of Reading) we have recently extended to the longwave and which we refer to as the SPeedy Algorithm for Radiative TrAnsfer through CloUd Sides (SPARTACUS). Preliminary calculations suggest that the longwave 3D effect, assumed negligible until now by many in the radiative transfer community, has a magnitude at the surface of more than half the shortwave 3D effect. We are currently implementing and testing this in the ECMWF model, in order to estimate the global impact of 3D effects and therefore whether the extra computational cost required to represent them can be justified.

Outlook

Considering the four dimensions over which a radiation scheme integrates provides a framework to judge whether we have got the balance between accuracy and cost about right. In the case of angle and to some extent time, there are “tricks” that improve accuracy at essentially no extra cost. For the other two dimensions I would argue that the number of spectral intervals could probably be significantly reduced with only a minor decrease in accuracy, enabling more time to be spent solving the radiative transfer problem including phenomena whose omission leads to significant biases in current models, such as 3D effects and longwave scattering. Work is ongoing at ECMWF to develop a more flexible radiation scheme in which different spectral discretizations, radiative transfer solvers and cloud/aerosol scattering models can be easily interchanged to properly test these trade-offs.

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