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# Including Three-Dimensional Radiative Transfer in a Two-Stream Radiation Scheme

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Clouds present climate modellers with many major challenges. Much uncertainty arises from their complex structure and their complicated interactions with short-wave and long-wave radiation. Studies have shown small changes in cloud properties to have large effects on radiation budget, implying that it is important to represent cloud–radiation interactions as faithfully as possible in our climate models.

Modern general circulation models use the Two-Stream approximation when representing the passage of radiation through the atmosphere. Two-Stream schemes rely on the assumption that radiation is only allowed to travel vertically upwards and downwards. This has the effect of excluding the horizontal transport of radiation through the sides of the cloud, and has marked effects on the transfer of both short-wave and long-wave radiation. When the Sun is low in the sky, a great deal of the direct beam should be intercepted by cloud sides (short-wave side illumination). For high Sun, forward scattering of the direct beam should result in downward diffuse radiation exiting through cloud sides (short-wave side escape). In both the short-wave and the long-wave, the radiation reaching a point at the surface should receive radiation from cloud sides as well as cloud bases (side exchange). In combination, these mechanisms have the effect of allowing too much radiation to reach the surface when the Sun is low in the sky and not allowing enough to reach the surface when the Sun is high in the sky.

Here, we introduce a new method of accounting for three-dimensional radiative transfer – referred to as TwoStream3D – which is straightforward to implement in a Two-Stream scheme. At the heart of the method is a single quantity that describes the rate of lateral radiative transport as a function of the area of cloud edge in each layer of a gridbox. We add extra terms to the equations describing the transfer of direct radiation, which can be solved to give a modified version of Beer's Law. We describe the transfer of diffuse short-wave and long-wave radiation using the Two-Stream equations, again with extra terms added. To account for the laterally transported radiation, three extra steps are performed.

Rigorous radiation calculations performed in other studies show that, for short-wave radiation, top-of-atmosphere cloud radiative forcing can be reduced by about 25% when the Sun is overhead and enhanced by over 100% when the Sun is low in the sky. Using a simple, one-band radiation code we are able to reproduce this solar zenith angle dependence for clouds of two different geometries (circular cumulus clouds and linear contrails). This implies that the inclusion of three-dimensional radiative transfer could be efficiently represented in a climate model. Finally, we implement the TwoStream3D method in an operational radiation code with the aim of evaluating the global 3D effect using re-analysis data.