Plane-Parallel Albedo Bias

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An increase in the average albedo of the Earth-atmosphere system of only 10% is potentially capable of decreasing surface temperatures below those of the last Ice Age. Nevertheless, cloud albedo biases of 10% and more would be introduced into large regions of current climate models if clouds were given their observed liquid water amounts, because of the treatment of clouds as plane-parallel. Past work has focused on the 3-D shape of clouds and its contribution to this bias. The present work ignores the shape effect and focuses instead on the effect of cloud optical depth variability within a climate model grid square.

The plane-parallel approximation used in climate models such as general circulation models performs a single 1-D radiative transfer calculation for an entire grid square (consisting of many pixels), using a single pixel-averaged optical depth. In other words, the statistical variation of the optical depth within the grid square is ignored. We have found from Monte Carlo calculations that stratocumulus cloud albedo can often be treated in the "independent-pixel approximation," whereby, for radiative purposes, each cloud pixel is treated as 1-D. Basically, this finding means that inter-pixel variations in optical properties are often mild enough that whatever inter-pixel communication exists is, statistically speaking, nearly neutral (it is exactly neutral in a pure plane-parallel cloud). Unlike the plane-parallel approximation, the independent-pixel approximation considers the statistical variations of the optical depth within the grid square, but ignores imbalances in inter-pixel photon exchange.

To estimate the albedo bias introduced by the plane-parallel approximation, we use the independent-pixel approximation with parameters determined by the 1987 First ISCCP Regional Experiment (FIRE) field program for marine stratocumulus clouds. We model the vertically-integrated cloud liquid water path (LWP) so as to reproduce its observed probability distribution and -5/3 wave number spectrum. The model distributes the LWP by a cascade to smaller and smaller spatial scales, similar to models used in turbulence theory. It is intended to mimic the effect on liquid water of the upscale cascade of energy injected at the cloud thickness scale and transferred to the mesoscale by approximately 2-D motions.

In order to focus only upon horizontal variations of LWP, the usual microphysical parameters and the geometric cloud thickness are assumed to be homogeneous. To simplify comparison with the plane-parallel approximation, the pixel-averaged LWP is kept fixed at each step of the cascade. The cascade is described by a single fractal parameter $0<f<1$, determined by the observed variance of log(LWP). For non-absorbed wavelengths, the albedo bias can be found analytically as a function of f, mean optical depth τ, and sun angle θ. For typical values observed in FIRE ($f = 0.5$, $\tau = 10$, $\theta = 60°$), the absolute bias is 0.09. This is equivalent to a relative bias of 15% of the plane-parallel albedo (0.60) and represents a potential surface heating of 7.5°C according to simple climate models.

Study of the diurnal cycle during FIRE leads to a key unexpected result: the plane-parallel albedo bias is largest when the cloud fraction reaches 100%, (i.e., when the usual cloud-fraction correction vanishes). This is because cloud liquid water variability is maximum when cloud cover is maximum and because variability within the cloud has more effect on the pixel-averaged albedo than cloud-fraction does.