The Effects of Cloud Heterogeneity on Radiant Fluxes at the Top and Bottom of the Atmosphere

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The radiative transfer community is increasingly understanding the crucial role of horizontal cloud heterogeneity in determining the albedos and transmittance properties of clouds. At the same time, the potentially large implications for general circulation model (GCM) parameterizations have not been widely recognized. This project involves a collaboration by four different institutions (UCSB, Scripps, McGill, Météorologie Nationale), and aims at understanding, modelling, and theoretically and empirically quantifying the heterogeneity.

Relating the heterogeneity of the clouds to that of the radiation fields necessarily involves models of cloud intermittency. In the last ten years, great strides in turbulence, chaos, and fractals have enormously broadened the scope of scaling (scale invariant) notions, making such models natural candidates for radiative transfer studies.

Scale invariance is now recognized as a symmetry principle in which the statistical behavior of small- and large-scale structures is related by a scale-changing operation that depends only on the scale ratio; there is no characteristic size. It is now clear that the relevant scale changes can be quite general, involving not only stratification (e.g., because of gravity), but also differential rotation (the Coriolis force), and other more complex operations. Between the inner viscous scale and the outer planetary scale, the fundamental dynamical equations of the atmosphere involve no characteristic length; this is the physical basis of the scaling.

Furthermore, it is now known that nonlinear dynamical systems which are invariant over wide ranges of scale generically give rise to multifractal fields, fractal structures, and wild statistics which require an infinite number of exponents to characterize. Fortunately multifractal universality classes exist which involve only three fundamental exponents. These universality classes lead to great simplifications in both modelling and data analysis. In the first part of the talk we showed how they can be exploited to yield a robust data analysis technique called "Double Trace Moments" which directly yields the universal parameters. We described how this technique combined with energy spectra was applied to satellite radiance fields in the visible, infrared, and near-infrared range. Data came from the National Oceanic and Atmospheric Administration, Geostationary Operational Environmental Satellite, and LANDSAT satellites and were analyzed over the range of scales ≈160 m to ≈4000 km. The scaling was found to be well respected through the entire range (which included the mesoscale). The basic multifractal parameters were estimated, including the degree of multifractality ($\alpha \approx 1.35$), which was found to be near the value found for turbulent velocity and temperature fields.

We then indicated how universality could be used to make cloud models that respect the same symmetries as passive scalar clouds while having the observed multifractal parameters. Such models of cloud liquid water distribution were used as the basis for a detailed radiative transfer study. At this stage no effort was made to use anisotropic scale invariance to model the stratification or differential rotation; the fields were isotropic (self-similar) multifractals. The cloud parameters were $\alpha=2$ (corresponding to near log-normal probabilities), $C_1=0.5$ (the codimension of the mean field characterizing the mean sparseness), and $H=0$ (indicating that the field was conservative). This involves spectral exponent a little smaller than those observed in aircraft studies. Using cyclic horizontal boundary conditions and uniform vertical incident radiation, the radiance fields associated with these clouds were then determined. The simulations were performed on large (1024 x 1024 point grids) using the Cray 2 at Palaiseau, France: the transfer was calculated in two dimensions to allow the widest possible range of scales.

In order to simplify the calculation so as to make it possible to determine the entire (internal) radiance fields, discrete angle (DA) phase functions were used. These phase functions only permit scattering through 90°; the radiances decouple into non-interacting families with only four radiance directions each. The phase functions were position independent; for simplicity we used isotropic DA phase functions. For validation purposes, the calculations were made using two completely different numerical techniques: Monte Carlo and relaxation. The four radiances (at 90° from each other) were then used to calculate the total radiance, the vertical and horizontal fluxes, and the nondiffusive component. This decomposition facilitates comparison with standard models. For example, in plane-parallel clouds, the horizontal fluxes are identically equal to zero; whereas in diffusive models, the nondiffusive component is identically zero.

By varying the extinction coefficient, we were able to study the effect of increasing cloud thickness; clouds with mean optical thickness between 12 and 195 were studied. The major conclusions are

1. Horizontal fluxes were typically less than 10% of the total flux; hence locally, the radiance fields were close to plane parallel, even though globally, the radiative response was far from plane parallel.
2. The nondiffusive component was often very large; this points to the importance of "streaming" or "channeling" of photons through the more tenuous regions. It also indicates that the diffusion approximation will be poor even in optically thick clouds.
3. The overall transmittances were compared with those of equivalent plane parallel clouds and with those obtained using the independent pixel approximation (each column independent). The agreement was generally poor, although the independent pixel approximation was much better than the plane-parallel approximation. For example, in the case of thick clouds, if the transmittances were used to estimate optical thickness, errors of a factor of ≈8 would occur in the latter, but only ≈3 in the former. Such effects could readily account for the "albedo paradox."

The last part of the presentation involved simulating First ISCCP Regional Experiment (FIRE) pyranometer data on August 8, 1989. These hemispheric data were characterized by a series of large highs and lows in irradiance associated with the passage of small cumulus clouds. Using an all-sky camera, lidar, and radiosonde data, we developed a cloud model (with corresponding size, aspect ratio, height and geometrical thickness) to reproduce the observed fluctuations through Monte Carlo simulations. The model involved an array of (internally uniform) cylindrical clouds 0.5 km in diameter with optical depth of 12 at regular spacings of 2.5 km. By advecting the field past the sensor at roughly the observed velocity, many of the features of the pyranometer trace could be reproduced quantitatively, including the (near constant) minimum values, the maximum values when the sun was not obscured, and the fine structure associated with the cloud edges and cloud shadowing.