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Radiative Transfer in Stratified Multifractal Clouds

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One primary objective of meteorological studies is to improve the performance of climate predictive models in order to make predictions of the response of the climate system to the increasing concentration of greenhouse gases. However it faces three related difficulties: a) the wide range of space-time scales over which the dynamics and thermodynamics occur, b) the extreme (often turbulent) variability of the atmosphere - even at a fixed scale, leading to highly inhomogeneous clouds and c) the mounting evidence that the atmosphere does not appear 3-D (isotropic) at the smallest scales, nor 2-D at the largest scales (isotropic in the horizontal with negligible variability in the vertical), rather structures become more and more relatively flat as they get larger and larger, more and more convective as they get smaller, i.e. the atmosphere is differentially stratified at all scales. The stratification is scaling (power-law) and intermediate ($D = 23/9 \approx 2.55$) between the 2-D and 3-D extremes. Concerning cloud radiative properties, the supposed lack of significant vertical variability implied by 2-D stratification is used to justify the independent pixel approximation (IPA) in which satellite images are converted into optical thickness surrogates by using the plane parallel approximation at pixel scales.

Over the last twenty years, many studies have been devoted to radiative transfer in inhomogeneous (e.g. fractal) or plane-parallel cloud fields. Although these studies are of great value, their vast majority have been limited to numerical investigations in relatively optically thin clouds. An exception to this was our earlier development of a formalism where we have presented asymptotic forms for single scattering statistics in optically thick multifractal and isotropic conservative clouds (i.e. turbulent fluxes, the direct result of turbulent cascades). An essential result of this work was that short- and long-photon paths exhibit quite different scaling behaviours: in the near regime the direct transmission is approximately exponential with a renormalized extinction

coefficient $\kappa_{eff} < \kappa$, where the transmission behaves as if all scattering events were related to the most probable singularity in the cloud density field. In the far regime, the transmission falls of much more slowly (on account of the so-called "Levy holes''). In this presentation we show how the latter study 1) can be extended to non-conservative general multifractal clouds, either isotropic or stratified, and 2) how the analytic single scattering results can be generalized to multiple scattering - at least for optical thickness below a "super thick'' limit ($\tau >> 100$). Indeed, the theoretical and numerical single scattering analytic results give accurate predictions for the mean cloud optical properties of typical clouds. We present new results on the transmission statistics in general multifractal clouds. By "renormalizing'' the radiation, we also relate the mean transmission statistics to those of a renormalized homogeneous cloud. By varying the extinction coefficient, we are able to study the effect of increasing cloud thickness, for typical cloud mean optical thickness in the range $10-200$. For example, using observed multifractal isotropic cloud characteristics, we predict that the mean cloud transmission decreases with the 0.88 power of the total optical thickness (the corresponding homogeneous exponent being unity). For clouds with a total optical thickness of 100 (with $1 - g = 0.15$) this is a non-negligible 38% effect with respect to homogeneity. In addition, the atmosphere being not 2-D, we argue that tubes of radiative fluxes (at least in optically thick clouds) will be fractals so that a fractal extension of the classical IPA must be made. Since fractal tubes are much longer than non-fractal ones, the intensity/optical thickness relations are expected to be quite different.

These multiple scattering predictions are numerically tested using the discrete angle radiative transfer (DART) approach in which the radiances decouple into non-interacting families with only four (for 2-D clouds) radiance directions each. Since in thick clouds the phase function is of secondary importance (it doesn't affect the scaling exponents; the prefactors however do depend on them), this approach is justified because photons actually undergo many scatterings. The steady-state radiative transfer equation is then replaced by a linear algebra problem involving a finite scattering matrix. Using new highly accurate, rapid sparse matrix techniques, one is therefore in a position to solve exactly and rapidly the radiative transfer equation in a great variety of non homogeneous media.

By explicitly and realistically modeling the stratification and more generally the anisotropy (associated with different cloud types), this work therefore aims to provide the key link between the horizontal radiance fields, the cloud liquid water and aerosol concentration fields.