On the computation of apparent direct solar radiation

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Near-forward-scattered radiation coming from the vicinity of Sun's direction impacts the interpretation of measurements of direct solar radiation by pyrheliometers and sun photometers: a substantial part of the measured "direct" radiation can actually be scattered radiation. This issue is also relevant for concentrating solar power applications. Here, a Monte Carlo radiative transfer model is employed to study the apparent direct solar transmittance $t(\alpha)$, that is, the transmittance measured by an instrument that receives the radiation within a half-field-of-view (half-FOV) angle α from the centre of the solar disk, for various ice cloud, water cloud and aerosol cases. The contribution of scattered radiation to $t(\alpha)$ increases with increasing particle size, and it also depends strongly on ice crystal shape and roughness. The Monte Carlo calculations are compared with a simple approach, in which $t(\alpha)$ is estimated through Beer's law, using a scaled optical depth that excludes the part of the phase function corresponding to scattering angles smaller than α. Overall, this optical depth scaling approach works very well, although with some degradation of the performance for ice clouds for very small half-FOV angles ($\alpha < 0.5 - 1\,\mathrm{deg}$), and in optically thick cases. The errors can be reduced by fine-tuning the optical depth scaling factors based on the Monte Carlo results. It is also shown that the optical depth scaling used in delta-two-stream approximations employed in numerical weather prediction and climate model radiation calculations is inappropriate for simulating the direct solar radiation received by pyrheliometers.