Absorption of Sunlight by Gases and Absorbing Aerosols in Clear and Cloudy Atmospheres

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Abstract

Most of the radiative transfer algorithms used in global climate models (GCMs) underestimate the amount of solar radiation absorbed in cloudy atmospheres by up to 25 W m^{-2}. This cloud absorption anomaly compromises our understanding of the role of clouds in the climate system. We used a spectrum-resolving (line-by-line) multiple scattering model to provide a more comprehensive description of the solar radiative forcing of the Earth's atmosphere. These calculations have revealed three constituents whose absorption is usually underestimated in cloudy conditions. Errors and oversimplifications in the treatment of water vapor can account for about half of the cloud absorption anomaly. Even though most GCM radiative transfer algorithms can accurately describe the water vapor absorption in clear skies, they often underestimate the absorption by this gas within clouds by (i) using the same background (unsaturated) water vapor mixing ratios both inside and outside of clouds, and (ii) neglecting the near-infrared water vapor continuum absorption produced by the far wings of water vapor lines. Tropospheric aerosols are the second constituent whose absorption is routinely underestimated in global climate models. Even though aerosols embedded within clouds absorb little sunlight, small numbers of weakly-absorbing aerosol particles (10 to 200 per cubic centimeter) can produce surprisingly strong absorption when they are distributed at levels above the cloud tops. This absorption is enhanced in cloudy skies where the aerosols absorb both the incoming solar beam and the upwelling solar radiation that is diffusely reflected by the cloud tops. Their absorption increases with increasing aerosol absorption optical depth and increasing cloud albedo. The upwelling radiation that is scattered into the largest emission angles is absorbed most strongly because it must traverse long optical path lengths on its way out of the atmosphere. In addition, unlike water vapor and other absorbers embedded within clouds, optically-thin aerosols above the cloud tops can produce enhanced absorption even at very large solar zenith angles. In the global annual average, regions occupied by optically-thick low clouds and uniformly-mixed aerosols with column-integrated visible optical depths between 0.1 and 0.2 will absorb between 3 and 8 W m^{-2} more than equivalent clear sky regions. This absorption enhances the solar heating rates by 0.1 to 0.2 K per day (10 to 20%) at levels above the cloud tops. Aerosol-laden atmospheres with overlapping low and middle cloud decks can absorb up to twice this much solar radiation. The final constituent that contributes enhanced absorption in cloudy skies is stratospheric ozone. The weak Chappuis band centered near 0.6 microns contributes little to the absorption in clear skies, but, like the tropospheric aerosols, this band absorbs both the incoming and reflected solar radiation in cloudy atmospheres. This absorber enhances the absorption by only about 3 W m^{-2} in cloudy skies, but it increases the stratospheric heating rates by about 0.5 K day^{-1} (~6%) in the global-annual average. Taken together, these enhancements in water vapor, aerosol, and ozone absorption in cloudy atmospheres can account for much, if not all of cloud absorption anomaly.