Global impact of 3D cloud-radiation interactions and importance of cloud geometry

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1) 3D cloud-radiation effects

- **Reality**: Radiation in multiple directions interacts with complex clouds.
- **Global models use 1D schemes** - radiation only moves vertically; inhomogeneity / overlap parametrised approximately.
- **Local 1D errors** of -25% to +100% in shortwave or up to 40% in longwave cloud radiative effect (CRE).
- **Errors in heating rate profiles** - in cloud development.

![Mechanisms of 3D cloud-radiation effects](image)

**Physical mechanisms**:
- Shortwave cloud side illumination increases cloud reflectivity, cloud side escape decreases cloud reflectivity.
- Longwave cloud side illumination and escape increase cloud warming effect.
- Shortwave entrapment decreases cloud reflectivity.

![Effects of 3D cloud-radiation](image)

**3) Evaluation against Monte Carlo benchmarks**

- **Shortwave** (Hogan et al. 2019):
  - Parametrised mean horizontal path profile agrees with Monte Carlo results within 6% for direct and 25% for diffuse radiation.
  - SPARTACUS captures 3D change to CRE and its dependence on SZA to within 10%; slightly overestimates atmospheric absorption.
  - Entrapment decisive for 3D effect.

![Profiles of cloud fraction and SZA](image)

**4) Global results**

- **Total 3D effect on climate**:
  - **Global fluxes** (net down, surface): Longwave +1.6 Wm⁻²; Shortwave +0.8 Wm⁻²; Total +2.4 Wm⁻².
  - **Temperature increases** by around 1K.
  - **Sensitivity** to entrainment and cloud geometry.

![Global effect on climate](image)

**5) Conclusions**

- **Cloud 3D effects on radiation are globally appreciable**; in total, they warm the Earth by about 2.4 Wm⁻² or 1K.
- **Shortwave**: Different 3D effects have opposite sign; warming entrainment effect dominates.
- **Cloud side effects** strongest for broken clouds, entrainment effect strongest for deep multilayer clouds.
- **Longwave**: warming effect.
- **SPARTACUS can capture 3D effects efficiently**.
- **ecRad results mostly agree well with Monte Carlo codes**.
- **ecRad and SPARTACUS will be implemented in ICON soon**.

**References**:

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