What is the impact of 3D radiative effects on the global radiation budget?

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Contributions from
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Overview

● A puzzling bias
● Representing cloud structure in radiation schemes
● Conceptual models for 3D cloud-radiation effects
● The SPARTACUS solver
● How big is a cloud?
● An estimate of the global impact of 3D radiation
ECMWF cycle 43R1: clouds in uncoupled model climate

Cloud cover and LWP are too low, yet clouds are too reflective
“Improvements”: less cloud overlap and less heterogeneity

Cloud cover: model
- Total Cloud Cover: 67% (Global Mean: 67.5%)
- Probability of 4 or more clouds: 63.5%

LWP: model
- Liquid Water Path: 94% (Global Mean: 94.4%)

SW CRE: model
- TOA SW: 48% (Global Mean: 49.6%)
- 50S-50N: Mean: 53%

Cloud cover: MODIS
- Total Cloud Cover: 68.9% (Global Mean: 68.9%)
- Probability of 4 or more clouds: 66.9%

LWP: SSMI
- Liquid Water Path: 92% (Global Mean: 94.2%)

SW CRE: CERES-EBAF
- OA SW: 44% (Global Mean: 47.2%)
- 50S-50N: Mean: 49.3%

Cloud cover: difference
- Difference: MODIS - SSMI 50S-50N Mean: -5.45 (Global Mean: 5.58)

LWP: difference
- Difference: SSMI - CERES-EBAF 50S-50N Mean: -27.3 (Global Mean: 34.7)

SW CRE: difference (mean -3.6 W m\(^{-2}\))
- Difference: CERES-EBAF - MODIS 50S-50N Mean: -3.63 (Global Mean: 10.9)

Cloud cover is better, SW CRE is worse
2-m temperature bias (winter example)

- **RMS errors** are one way to judge whether a new model version improves forecasts.

- **Mean errors** are small but negative and grow during the forecast towards the climatic biases.

- A related puzzle: global-mean shortwave cloud radiative effect is about right but temperatures are a little low.
How do we compute how this interacts with radiation?
Plane-parallel, maximum-random overlap

- Most models circa 2000

- **Model variables needed:** cloud fraction, water content
- Reflection & transmission computed for clear & cloudy regions separately
- Fluxes merged at layer interfaces according to cloud fraction
Realistic overlap

- Increases cloud cover and hence magnitude of cloud radiative effect
- Net impact $-1.9 \, \text{W m}^{-2}$ at surface and TOA (Shonk & Hogan 2010)

**Extra input:** overlap decorrelation length from cloud radar $\sim 2 \, \text{km}$

- Ground-based (Hogan & Illingworth 2000, Mace & Benson-Troth 2002)
- CloudSat (Barker 2008, Shonk et al. 2010)
Tripleclouds (Shonk & Hogan 2008)

- Cloud structure *reduces* cloud reflectance
- Net impact 4.1 W m\(^{-2}\) (TOA), 3.8 W m\(^{-2}\) (surf)

- Cloud water fractional standard deviation \(~0.75\)
  - Satellite & cloud radar (Barker, Shonk, Cahalan, Oreopoulos, Rossow...)
- Cloud water overlap decorrelation length \(~1\) km
  - Ground-based cloud radar (e.g. Hogan & Illingworth 2003)
Monte-Carlo Independent Column Approximation (McICA) – Pincus et al. (2005)

- Info required similar to Tripleclouds but computationally faster
- Use of stochastic cloud generator leads to some noise in fluxes
- Now used in many (most?) global weather and climate models
Full Monte Carlo (being investigated by Barker et al.)

- “It’s better to solve the right problem approximately than the wrong problem exactly,” or “random errors are better than biases.” (for climate!)

- Use 3D cloud distribution generated by a stochastic model in each gridbox

- How many light rays are needed for random errors to be tolerable? 500?

  - NWP models tolerate random errors much less than climate models

- Monte Carlo at least provides good benchmark for approximate schemes
Mechanisms for shortwave 3D effects

- **Side illumination**
  - Strongest when sun near horizon
  - Increases chance of sunlight intercepting cloud

- **Side escape**
  - Strongest for overhead sun
  - Forward scattering leads to more sunlight penetration
  - Second-order importance

- **In-region transport**
  - Systematically reduces reflectance for all solar zenith angles
Idealized calculation: what is the albedo of this scene?

- Surface albedo = 0
- Reflectance of each cloud: \( R \)
- No absorption so transmittance \( T = 1 - R \)

**Independent column approximation**

- Reflectance of 2 non-absorbing clouds
  - Adding method with \( R^* = \frac{2R}{1+R} \)
- Reflectance of scene
  - Weighted average \( R_{\text{scene}} = \frac{R}{2} + \frac{R^*}{4} = \frac{R(1+R/2)}{(1+R)} \)
- Optically thick limit: \( R_{\text{scene}} = \frac{3}{4} \)

**Horizontal transport in regions**

- Mean reflectance of layer = \( \frac{R}{2} \)
- Reflectance of scene
  - Random overlap so apply adding method to mean reflectances: \( R_{\text{scene}} = \frac{2(R/2)/(1+R/2)}{2} = \frac{2R}{2+R} \)
- Optically thick limit: \( R_{\text{scene}} = \frac{2}{3} \)
Conceptual model for longwave 3D effects

- Radiation can now be emitted from the side of a cloud, increasing downwelling at the surface.
- A useful benchmark: *for an isolated, optically thick, cubic cloud in vacuum, 3D effects increase downwelling flux at the surface by a factor of 3.*

- Clouds are not cubes, the atmosphere is not a vacuum to longwave radiation: many radiation people assume 3D effects are negligible in the longwave... *are they right?*
**SPARTACUS** “Speedy Algorithm for Radiative Transfer through Cloud Sides”

- Starting point: “Tripleclouds” method
  - Represent cloud heterogeneity via three regions at each height

- Extra terms added to two-stream equations:

\[
\begin{align*}
dv^a / dz &= \beta e (-\gamma_1 v^a + \gamma_2 u^a) \\
f^{ab} v^a + f^{ba} v^b \\
- du^a / dz &= \beta e (-\gamma_1 u^a + \gamma_2 v^a + s^a) \\
f^{ab} u^a + f^{ba} u^b
\end{align*}
\]

- Assuming clouds are *randomly distributed*, we obtain:

\[
f_{ab} = \frac{L_{ab}}{2ca}
\]

- Length of cloud perimeter per unit gridbox area

- Fraction of gridbox occupied by clear skies (region a)
Matrix solution in a single layer (shortwave)

- Define diffuse upwelling, diffuse downwelling and direct downwelling as vectors $\mathbf{u}$, $\mathbf{v}$ and $\mathbf{s}$:

$$\mathbf{u} = \begin{pmatrix} u^a \\ u^b \\ \vdots \end{pmatrix}$$

- Write two-stream equations as:

$$\gamma_1 \frac{d}{dz} \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix} = \Gamma \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}$$

where 9x9 matrix is composed of known terms analogous to the standard two-stream:

$$\Gamma = \begin{pmatrix} -\Gamma_1 & -\Gamma_2 & -\Gamma_3 \\ \Gamma_2 & -\Gamma_1 & \Gamma_4 \\ \Gamma_4 & \Gamma_1 & -\Gamma_0 \end{pmatrix}$$

- Solution for layer of thickness $z_1$:

$$\begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}_{z=z_1} = \exp(\Gamma z_1) \begin{pmatrix} \mathbf{u} \\ \mathbf{v} \\ \mathbf{s} \end{pmatrix}_{z=0}$$

Matrix exponential
- Can compute using Padé approximant plus scaling & squaring method (Higham 2005)
Reflection and transmission matrices

- We want relationships between fluxes of the form:
  \[ u(0) = Tu(z_1) + Rv(0) + S^+s(0) \]

- Transmission matrix for 2 regions given by:
  \[ T = \begin{pmatrix} T^{aa} & T^{ba} \\ T^{ab} & T^{bb} \end{pmatrix} \]

  and likewise for \( R \) and \( S^\pm \)

- If matrix exponential is decomposed as:
  \[ \exp(\Gamma z_1) = \begin{pmatrix} E_{uu} & E_{uv} & E_{us} \\ E_{vu} & E_{vv} & E_{vs} \\ E_0 & & \end{pmatrix} \]

  then reflection and transmission matrices given by:
  \[ R = -E^{-1}_{uu}E_{uv} \quad T = E_{vu}R + E_{vv} \]

- For scalars, get same answer as traditional Meador & Weaver (1980) formulas

- For speed, only use matrix exponential for partially cloudy layers
Test with I3RC cumulus cloud

- Fully 3D simulations with MYSTIC
- Inputs needed by SPARTACUS

Thanks to Carolin Klinger & Bernhard Mayer, LMU Munich
Broadband shortwave SPARTACUS vs MYSTIC (Monte Carlo)

- Good match!
- Big difference in direct surface flux when sun low in the sky

Hogan et al. (JGR 2016)
- Good match!
- Big difference in direct surface flux when sun low in the sky
- Change due to in-region horizontal transport
- Change due to cloud edge effects

Hogan et al. (JGR 2016)
3D effects in observations of direct/total downwelling flux

- Troccoli & Morcrette (2014) reported biases in ECMWF direct solar radiation from, important for solar energy industry
- Bin observations and model by solar zenith angle and cloud fraction, considering only cases of boundary-layer clouds (thanks to Maike Ahlgrimm):

  ![Graph](image)

  • Next step: apply new 3D radiation scheme to the ECMWF cloud fields to verify that differences are due to 3D effects
Longwave...

- Good 1D agreement
- MYSTIC 3D effect: 30% (the same in broadband)
- Too big in SPARTACUS?
- Use *radiatively effective cloud edge length*: contour of a fitted ellipse
- Consider full cloud field
- Effective edge length not sufficient: *clustering* is also important
- We know how to estimate the radiatively relevant edge length; clustering can only be represented approximately (multiply by 0.7 in this case)
How can we characterize cloud edge length in a model?

**Morcrette (2012): MSG**

**Jensen et al. (2006) data:** MODIS stratocumulus
Characterizing cloud perimeter vs. cloud fraction

- Jensen et al. (2006) proposed effective cloud diameter $D$: diameter of identical circular clouds that have the same perimeter and area as the actual cloud field
  - If cloud area $A = \pi (D/2)^2$ and perimeter $P = \pi D$ then
  - Effective cloud diameter $D = 4A/P = 4 \times \text{cloud cover} / \text{normalized perimeter}$

- Problem with this concept is that effective cloud diameter computed from real cloud fields is strongly dependent on cloud cover

- We seek an effective cloud scale $S$ that is independent of cloud cover, and can be parameterized in GCMs
Morcrette (2012)

- Conceptual model: fill a checkerboard randomly with squares of size $S$:

- Morcrette (2012) found that perimeter simulated in this way behaves the same as in observations:
  
  $$ P = 4A(1-A)/S $$

- His MSG data for all clouds yields $S$ of around 10 km

Simulations  MSG data
Apply concept to MODIS data

- 1-km MODIS is higher resolution than MSG
- Application to Jensen et al. stratocumulus data suggests effective cloud scale of around 10 km
Estimates of effective cloud scale (Schäfer 2016, PhD thesis)

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Res (m)</th>
<th>Cloud scale (km)</th>
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</thead>
<tbody>
<tr>
<td>Cu</td>
<td>I3RC CRM</td>
<td>67</td>
<td>0.8±0.2</td>
</tr>
<tr>
<td>Cu</td>
<td>Azores radar</td>
<td>50</td>
<td>0.9±0.2</td>
</tr>
<tr>
<td>Sc</td>
<td>I3RC CRM</td>
<td>55</td>
<td>0.7±0.2</td>
</tr>
<tr>
<td>Sc</td>
<td>MODIS</td>
<td>1000</td>
<td>10±2</td>
</tr>
<tr>
<td>Ci</td>
<td>Stochastic model</td>
<td>49</td>
<td>4±1.5</td>
</tr>
<tr>
<td>Cb</td>
<td>Radar</td>
<td>333</td>
<td>14±6</td>
</tr>
<tr>
<td>Cb</td>
<td>CRM</td>
<td>250-350</td>
<td>5-30</td>
</tr>
</tbody>
</table>

- **Cu & Sc**: 1 km (0.7–1.4 range)
  - Approximate account for clustering
  - MODIS too coarse
- **Non-BL clouds**: 10 km (5–20 range)
- Obviously further refinement is needed!
What is the global impact of 3D radiative transfer?

- Offline calculations 1 yr of ERA-Interim clouds
- Compare McIICA to SPARTACUS 3D solver (Hogan et al. 2016)
- SW & LW effects both act to warm the surface
- Similar order to effect of cloud heterogeneity or doubling CO₂

Sophia Schäfer (PhD thesis, 2016)
● Introduction of 3D effects improves agreement with CERES in SW and LW
  - Is CERES longwave biased compared to model estimates (Allan and Ringer 2003)?
Impact on temperature (8x coupled 1-yr simulations)

- Impact on 2-m temperature over land compared to ECMWF IFS control:
  - Introducing realistic cloud overlap & inhomogeneity: $-0.3$ K
  - Introducing 3D radiation: $+0.4$ K (so $+0.7$ K due to 3D radiation) – is this the missing physics?
Computational cost inside ECMWF model

- New ECRAD radiation scheme with McICA solver is 30-35% faster
- ECRAD with SPARTACUS solver: matrix exponential and other matrix operations are the main cost so further optimization needed
Summary and outlook

• New capability to represent 3D radiative effects in a global model
• First estimates suggest 4 W m⁻² global impact on net fluxes at surface and TOA
  - Similar to the impact of cloud inhomogeneity and overlap
  - Longwave effects are significant
  - Could help explain the cold bias in the ECMWF model? …but many other factors need constraining too!

• Further work required:
  - More analysis of high resolution cloud observations and CRMs to characterize “effective cloud scale”
  - Comparison of SPARTACUS with full Monte Carlo calculations in a wide variety of scenes
  - Optimize SPARTACUS: perhaps treat it as a benchmark for more approximate schemes to represent 3D effects, e.g. perturbing cloud overlap (Tompkins & DiGuiseppe)

• SPARTACUS is an option in new ECMWF radiation scheme “ECRAD”
  - Offline version to be released under the OpenIFS license

• SPARTACUS idea will also be used to compute 3D effects in urban and vegetation canopies
Do subtle radiative effects really matter for an NWP centre?

- **Short to medium term**
  - Surface temperature forecasts are of first-order importance
  - Solar energy industry increasingly using radiation diagnostics from NWP

- **Monthly to seasonal (both coupled)**
  - Predictability on this timescale from stratosphere, MJO, ocean memory – all require accurate radiation
  - Difficult to get statistical significance when evaluating different seasonal forecast systems – but a prerequisite for a skilful system is a model with a good *climate*

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Global impact of cloud inhomogeneity and overlap

Fixing just horizontal structure (blue to red) would overcompensate the error

Fixing just overlap (blue to cyan) would increase the error

Need to fix both overlap and horizontal structure

Shonk & Hogan (2010)
Longwave equivalent

- Two-stream equations now look like this:

\[
\frac{d}{dz} \begin{pmatrix} u \\ v \end{pmatrix} = \Gamma \begin{pmatrix} u \\ v \end{pmatrix} + \begin{pmatrix} -b_0 \\ b_0 \end{pmatrix} + \begin{pmatrix} -b' \\ b' \end{pmatrix} z
\]

(No solar beam and Planck function assumed to vary linearly in optical depth via inhomogeneous terms)

- Solution is a bit more complex:

\[
\begin{pmatrix} u \\ v \end{pmatrix}_{z=z_1} = \exp(\Gamma z_1) \begin{pmatrix} u \\ v \end{pmatrix}_{z=0} \\
+ [I - \exp(\Gamma z_1)] \begin{pmatrix} c_0 \\ d_0 \end{pmatrix} + \begin{pmatrix} c' \\ d' \end{pmatrix}_{z_1}
\]

where:

\[
\begin{pmatrix} c' \\ d' \end{pmatrix} = -\Gamma^{-1} \begin{pmatrix} -b' \\ b' \end{pmatrix} \\
\begin{pmatrix} c_0 \\ d_0 \end{pmatrix} = \Gamma^{-1} \begin{pmatrix} c' + b_0 \\ d' - b_0 \end{pmatrix}.
\]
Extension to multiple layers: the adding method

- The adding method (e.g. Lacis and Hansen 1974) can be used to combine the reflectance and transmittance matrices of pairs of layers.
- In $N$-stream radiative transfer (e.g. $N=16$), the elements of the flux vector would represent different streams, but the method works just as well for different regions.
- We work up from the surface and compute the albedo of the whole atmosphere below each half-level.

$$\text{Albedo } A = \begin{pmatrix} A_{aa} & A_{ab} \\ A_{ba} & A_{bb} \end{pmatrix}$$

- After this we can head back down again to compute the fluxes.
- For one region, this is exactly the same as solving a tridiagonal system with forward elimination followed by backsubstitution.
How do we deal with cloud overlap?

- Edwards-Slingo method: overlap matrices

- Downward overlap \( \mathbf{V} = (V_{aa} & V_{ba} @ V_{ab} & V_{bb}) \) (similarly for upward overlap \( \mathbf{U} \))

- Matrix elements calculated from a decorrelation length following Shonk et al. (2010)

- Albedo just above a half level (A) is related to albedo just below a half level (B) by \( A = UBV \)
What is LW radiatively effective cloud edge length?

**Single cloud**

Original clouds

Ellipses remove radiatively irrelevant small-scale structure

Ellipsified “clouds”

**Full cloud field**

MYSTIC: solid lines

SPARTACUS: dashed lines

Clustering reduces effective edge length (nearest-neighbour spacing is 280 m vs. random value of 430 m)

Schäfer et al. (JGR 2016)
Heating-rate comparisons with MYSTIC

- Clustering has a fairly small effect on atmospheric heating rates
- 3D effects increase longwave CRF at surface by 30% in both MYSTIC and SPARTACUS (42% in SPARTACUS if clustering effect not represented)
What is the effective size of typical cumulus clouds?

- This study: between 0.5 and 1 km
- Neggers et al. (2003): cloud resolving model applied to a range of cumulus experiments
Towards a global estimate of the impact of 3D effects

- Instantaneous cloud radiative forcing applying SPARTACUS to one ERA-Interim clouds
- To get cloud edge length, assume cumulus horizontal length scale is 750-m, all other clouds 10 km

Night-time: positive LW effect
Low sun: negative SW effect
High sun: positive SW effect
Effective size of deep convection (Stein et al., BAMS 2015)

- Radar observations suggest cores of UK storms around 10 km wide
- Don’t trust size of storms in models with grid spacing larger than around 1 km (Met Office model in this case)