Challenges for radiation in NWP models

Robin Hogan, Alessio Bozzo, Mark Fielding, Howard Barker, Frederic Vitart, Sophia Schaefer, Inna Polichtchouk and many colleagues at ECMWF

r.j.hogan@ecmwf.int
Radiation and predictability

- Predictability of the first kind: *anomalies via initial conditions*
- Predictability of the second kind: *means via boundary conditions*

**ECMWF forecasts**
- Improve fast interactions between radiation and other processes
- Evaluate processes important for climate in NWP mode?
- Reduce regional biases

**Weather**
- Improve background state on which weather systems propagate

**Climate**
- ECMWF physics testing

<table>
<thead>
<tr>
<th>Short range</th>
<th>Medium range</th>
<th>Monthly/seasonal</th>
<th>Annual</th>
<th>Multi-annual</th>
</tr>
</thead>
</table>

EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
Challenges for radiation in NWP models

- **Middle atmosphere**
  - Solar spectrum
  - Ozone
  - Non-LTE effects
  - Code optimization
  - GPUs
  - Spatial/temporal/spectral resolution

- **Clear-sky absorption**
  - Water vapour continuum
  - Aerosols

- **Clouds**
  - 3D effects
  - Particle size
  - Longwave scattering
  - Sub-grid heterogeneity
  - Optical properties

- **Surface**
  - Sea emissivity
  - Snow albedo
  - Forests
  - Urban areas
  - Land albedo datasets
  - Orography
  - Coastlines

- **Urban areas**
  - Particle size
  - Optical properties
  - Longwave scattering
  - Sub-grid heterogeneity
  - Ozone
  - Non-LTE effects
  - Code optimization
  - GPUs
  - Spatial/temporal/spectral resolution

- **Efficiency**
  - Water vapour biases
  - Solar spectrum
  - Non-LTE effects
  - Code optimization
  - GPUs
  - Spatial/temporal/spectral resolution

- **3D effects**
  - Particle size
  - Longwave scattering
  - Sub-grid heterogeneity
  - Optical properties

- **Optical properties**
  - Longwave scattering
  - Sub-grid heterogeneity
  - Optical properties

- **Overlapping**
  - Water vapour biases
  - Solar spectrum
  - Non-LTE effects
  - Code optimization
  - GPUs
  - Spatial/temporal/spectral resolution

- **Sub-grid heterogeneity**
  - Particle size
  - Longwave scattering
  - Sub-grid heterogeneity
  - Optical properties

- **Particle size**
  - Longwave scattering
  - Sub-grid heterogeneity
  - Optical properties

- **Optical properties**
  - Longwave scattering
  - Sub-grid heterogeneity
  - Optical properties

- **Longwave scattering**
  - Sub-grid heterogeneity
  - Optical properties

- **Sub-grid heterogeneity**
  - Optical properties
  - Longwave scattering

- **Ozone**
  - Non-LTE effects
  - Code optimization
  - GPUs
  - Spatial/temporal/spectral resolution

- **Non-LTE effects**
  - Code optimization
  - GPUs
  - Spatial/temporal/spectral resolution

- **Code optimization**
  - GPUs
  - Spatial/temporal/spectral resolution

- **Spatial/temporal/spectral resolution**
  - Code optimization
  - GPUs
  - Spatial/temporal/spectral resolution
Modular radiation scheme for ECMWF: ecRad

• Gas optics
  – RRTM-G (as before)
  – Plan to develop new scheme with fewer spectral intervals

• Aerosol optics
  – Number of species and optical properties set at run time
  – Supports prognostic & diagnostic aerosol

• Cloud optics
  – Liquid clouds: more accurate SOCRATES scheme
  – Ice clouds: Fu by default, Baran and Yi available

• Solver
  – McICA, Tripleclouds or SPARTACUS solvers
  – SPARTACUS makes the IFS the only global model that can do 3D radiative effects
  – Better solution to longwave equations improves tropopause & stratopause
  – Longwave scattering optional
  – Can configure cloud overlap, width and shape of PDF

• Surface (under development)
  – Rigorous and consistent treatment of radiative transfer in urban and forest canopies

• Offline version available for non-commercial use under OpenIFS license
Improved efficiency

- Much faster than original scheme in operational configuration

- 3D radiation is more expensive, but feasible in research mode

- Cloud treatment is much faster
Fast longwave scattering for clouds but not aerosols

**No scattering**
For each layer, compute transmittance $T$ and sources $S^{\uparrow\downarrow}$ (reflectance $R = 0$)

- $F_{\text{base}}^{\downarrow} = TF_{\text{top}}^{\downarrow} + S^{\downarrow}$
- $F_{\text{top}}^{\uparrow} = TF_{\text{base}}^{\uparrow} + S^{\uparrow}$

Re-use $T$ and $S^{\uparrow\downarrow}$ in clear layers

**Cloud & aerosol scattering**
More expensive calculation of $T$, $R$ and $S^{\uparrow\downarrow}$

Compute total albedo and total upward emission

Compute fluxes

**Cloud scattering only**
Cheap no-scattering calculation

Re-use $T$ and $S^{\uparrow\downarrow}$ in clear layers

Scattering only below cloud top

LW solver cost +100%
Overall cost +36%

LW solver cost +16%
Overall cost +4%
Impact on forecast skill

• Latest version of ecRad reduces temperature RMSE by ~0.5% compared to older McRad scheme
  – Combination of longwave scattering, reduced biases and (possibly) reduced McICA noise

• All model configurations except HRES call radiation every 3 h

• Reinvest 40% speed-up by calling radiation every 2 h?
  – Temperature RMSE reduced by 1-2%, associated with better low clouds especially over tropical rainforests

• Ensemble system plans to use 1 h radiation from operational cycle 46R1
  – Temperature RMSE down by 3%

Hogan & Bozzo (submitted to JAMES)
Are we using our computer time wisely?

- Temporal, spatial and spectral resolution in various global NWP models:

<table>
<thead>
<tr>
<th>Centre</th>
<th>Radiation timestep (h)</th>
<th>Horiz. coarsening</th>
<th>Bands</th>
<th>Spectral intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HRES</td>
<td>ENS</td>
<td>HRES</td>
<td>ENS</td>
</tr>
<tr>
<td>ECMWF</td>
<td>1</td>
<td>3</td>
<td>10.24</td>
<td>6.25</td>
</tr>
<tr>
<td>NCEP</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>DWD</td>
<td>0.4</td>
<td>0.6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Météo France</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Met Office</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CMC</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>JMA</td>
<td>1</td>
<td>1 (SW), 3 (LW)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>FSCK</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

- ECMWF has lowest spatial resolution for radiation
  - Experiments show this barely degrades forecasts (unlike 3-h radiation timestep)
- Met Office NWP model uses 3.7 times fewer g-points than RRTM-G
- Full-spectrum correlated-k estimates of coarsest possible spectral resolution
IFS model climate: the good…

<table>
<thead>
<tr>
<th></th>
<th>Global SW</th>
<th>Global LW</th>
<th>Land SW</th>
<th>Land LW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild et al. (2015) Surface downwelling</td>
<td>184.7</td>
<td>341.5</td>
<td>184</td>
<td>306</td>
</tr>
<tr>
<td>Observations</td>
<td>4 ± 5</td>
<td>−2 ± 4</td>
<td>6 ± 10</td>
<td>−4 ± 7</td>
</tr>
<tr>
<td>43 climate models</td>
<td>3.7</td>
<td>−0.1</td>
<td>3.6</td>
<td>−2.0</td>
</tr>
<tr>
<td>ERA-Interim</td>
<td>0.4</td>
<td>−0.9</td>
<td>0.4</td>
<td>0.7</td>
</tr>
<tr>
<td>Coupled IFS climate</td>
<td>−0.4</td>
<td>−0.9</td>
<td>0.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

...and the ugly (middle-atmosphere temperature bias)

...the bad… (SW cloud radiative effect bias)
Errors due to neglecting 3D effects

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

- **Shortwave entrapment**
  - Horizontal transport beneath clouds makes reflection to space less likely

- **Longwave side emission**
  - Radiation can now be emitted from the side of a cloud
  - 3D effects can increase surface cloud radiative effect
Evaluation of “SPARTACUS” solver for representing 3D radiative effects

• “Speedy Algorithm for Radiative Transfer through Cloud Sides”: solve two-stream equations for (a) clear and (b,c) cloudy regions but add terms for lateral exchange

• For direct beam (considering two regions):

\[
\frac{dF^a}{d\delta'} = -\frac{\delta^a}{\mu_0} F^a - f^{ab}_{\text{dir}} F^a + f^{ba}_{\text{dir}} F^b
\]

\[
\frac{dF^b}{d\delta'} = -\frac{\delta^b}{\mu_0} F^b - f^{ba}_{\text{dir}} F^b + f^{ab}_{\text{dir}} F^a
\]

• Geometric terms \(f^{ab}\) depend on a parameterization of “cloud scale”

• Tested offline against Monte Carlo calculations for 59 varied scenes from Canadian and Met Office models at ~200 m resolution

Hogan et al. (2016)
Global impact of the specification of cloud structure and 3D effects

- Shonk and Hogan (2010) estimated the instantaneous change to cloud radiative effect of sub-grid cloud structure and overlap (W m\(^{-2}\))

- Best estimate from SPARTACUS suggests 3D effects have similar net impact to overlap decorrelation, but opposite sign

- Impact of turning on 3D effects in a free-running coupled simulation of the ECMWF model (5 member 20 years, average final 5 years): warm the surface by around 1 K, improve Arctic sea-ice bias

### Mechanism Summary

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Shortwave surface</th>
<th>Longwave surface</th>
<th>Net surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add horizontal structure</td>
<td>+6.7</td>
<td>-2.9</td>
<td>+3.8 (±2)</td>
</tr>
<tr>
<td>Add overlap decorrelation (EXP-RAN minus MAX-RAN)</td>
<td>-4.1</td>
<td>+2.2</td>
<td>-1.9 (±0.2)</td>
</tr>
<tr>
<td>Add 3D effects</td>
<td>+0.9</td>
<td>+1.2</td>
<td>+2.1</td>
</tr>
</tbody>
</table>

### Figures

(a) 2-m temperature (K), mean=0.936, land=1.25

(b) Atmospheric temperature (°C)
Towards a consistent radiative treatment of complex surfaces

- The IFS currently treats urban areas as crops, grassland or forest.
- The *infinite street canyon in vacuum* is ubiquitous in urban models (e.g. MORUSES, TEB):
  
  - Scattering/absorption by walls treated by SPARTACUS-like exchange terms
  - Add gas/aerosol in the canopy *coupled spectrally* to the atmosphere above
  - Use a building-separation canopy distribution fitted to observations
  - Possibly add street trees by solving two-stream equations in clear/vegetated regions with coupling terms (SPARTACUS-Vegetation: Hogan et al. 2018)

---

**Sky view factor**

- Increasing complexity

(a) Flat
(b) Closed forest canopy
(c) Urban canopy
(d) Open forest canopy
(e) Vegetated urban canopy
Geometry of real cities

- Geometry aspects of radiative transfer determined entirely by
  - Building height $H$ (assumed constant)
  - The probability distribution of wall-to-wall distances $p_{ww}(x)$

- If probability distribution is exponential:
  - $p_{ww}(x) = \exp \left( -\frac{x}{L} \right) / L$

- ...then the propagation of direct solar radiation through the urban canopy follows Beers law, and is easy to incorporate into a two-stream scheme:
  - $F_{\text{dir,street}} = F_{\text{dir,top}} \exp \left( -\frac{H}{L} \tan \theta_0 \right)$
Exponential fits much better than infinite street. 

Exponential predicts direct-beam much better.
How important is air in the canopy for LW radiative transfer?

- Offline ecRad with MLS standard atmosphere over urban surface 10 K warmer than air above
- Full longwave spectral resolution in canopy
How important is air in the canopy for LW radiative transfer?

- Offline ecRad with MLS standard atmosphere over urban surface 10 K warmer than air above
- Full longwave spectral resolution in canopy

---

![Diagram showing air temperature difference and net outward flux](image)

- Air temperature difference (K)
- Net outward flux (W m⁻²)
- Building height (m)

Legend:
- Ground
- Wall
- Canopy
- Ground vacuum
- Wall vacuum
- Canopy vacuum
How important is air in the canopy for LW radiative transfer?

- Offline ecRad with MLS standard atmosphere over urban surface 10 K warmer than air above
- Full longwave spectral resolution in canopy

• Validation needed!
Aerosols

- Atmospheric forcing depends on absorption optical depth:

  - Reduced absorption over Arabia in new CAMS climatology weakens the overactive Indian Summer Monsoon, halving the overestimate in monsoon rainfall
  - Increased absorption over Africa degraded 850-hPa temperature, traced to excessive biomass burning in CAMS
  - We can measure the impact of aerosols on the tropical atmosphere more easily than the absorption optical depth itself! Use to provide information on aerosol errors?
Middle atmosphere warm bias

- Historically, IFS has had a huge warm bias in upper stratosphere and above
- Improved in recent cycles (better longwave in ecRad, CAMS ozone, better solar zenith averaging)
- Remaining bias could be removed in stratosphere by updating solar UV which is 7-8% too high in IFS
- Lower mesosphere could be improved with a diurnal cycle of ozone (even if approximate)
- But resolution-dependence of lower stratosphere temperature (due to waves) needs to be addressed
Exploring the cause of the polar lower stratosphere cold bias

- Up to 5 K too cold
- Problem in IFS for at least 25 years
- Common to most/all global models

- Water vapour bias compared to MLS (%)
- Erroneous transport of water vapour from troposphere, emits too strongly in longwave
- What if we artificially reduce humidity seen by radiation?
- Just for experimental purposes, not operations!

- Cold bias removed!
Impact of removing polar cold bias

- Monthly forecast experiment artificially reducing humidity seen by radiation leads to *improvement in troposphere monthly forecast skill* (good example of radiation interacting with other processes)

- What’s the dynamical mechanism? Is it related to polar vortex variability or QBO teleconnections?

- *In the last 2 months, Filip Vana has developed a better Semi-Lagrangian advection scheme for the IFS that largely cures the excessive humidity transport – next step is to verify that it also improves monthly predictive skill!* 

![Diagram](image)

*Thanks to Frederic Vitart (blue is good!)*
Summary and outlook

• Need to make progress on many fronts to improve radiative transfer in NWP models

• Traditional approach is to reduce biases in the *model climate*, for example:
  – Aerosol changes can improve tropical biases in monsoons
  – 3D radiation is an option in the ecRad radiation scheme, and can possibly improve polar biases
  – Fixing lower stratosphere temperature bias improves monthly forecast skill

• It is possible, but more tricky, to improve forecasts via other means
  – Understanding the interaction between radiation and other processes is crucial
  – Faster radiation schemes can be called more frequently leading to better cloud-radiation interactions
  – Better interaction with complex surfaces should improve local forecasts, especially in urban areas

• What are the opportunities from better collaboration between those working on radiation in weather and climate, and from the land surface up to the mesosphere (and other planets)?

• *I wish you all a stimulating and enjoyable workshop!*
Why does more frequent radiation improve tropical forecasts?

• Fractional change to 5-day forecast RMSE… but what is the mechanism for improvement over rainforests?

Low Cloud Cover

20% better

2-m temperature

10% better
What is the cause of near-surface temperature errors at individual sites?

• Some locations are much more difficult than others!
  – Sapporo is a large city, by the coast, surrounded by mountains, with large annual snowfall
• ECMWF has a new task force to unpick the causes of surface temperature errors (including BL, clouds, surface schemes)
• But there are obvious areas where radiation needs to be improved, e.g. coastlines, forests and urban areas

• Far too little downwelling LW: not enough cloud?
• Early evening error could also be signature of urban heat island (Oke 1982), not in model
Improved accuracy

- As well as being much faster, reformulation of McICA scheme generates less stochastic noise

- Calling radiation more frequently than 3 h has a much greater impact on forecast skill than calling it every model gridpoint
Test of revised water vapour continuum in near infrared

- Measurements from “CAVIAR” project (Shine et al. 2016) suggest water vapour continuum in near-IR could be up to a factor of 10 too small in RRTM-G
- In coupled climate runs, troposphere warms by ~0.5 K; 1 K over summer pole
- In forecasts, impact on RMSE for temperature and wind depends on existing small biases in these quantities