ecRad:
A modular radiation scheme for IFS, OpenIFS, and for offline research

Robin Hogan and many colleagues at ECMWF

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Five “Grand Challenges” for radiation in NWP models
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- Surface
- Urban areas
- Orography
- Snow albedo
- Forests
- Coastlines
- Sea emissivity
- Land albedo datasets
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- Sub-grid heterogeneity
- Optical properties
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  - Solar spectrum
  - Water vapour biases
  - Middle atmosphere
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- GPUs
- Spatial/temporal/spectral resolution

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Overview of talk

• Brief history of the ECMWF radiation scheme
• ecRad: a new radiation scheme and impact on forecast skill
• Recent changes to aerosols and the stratosphere
• Using offline and online ecRad to understand 3D cloud radiative effects
• Plans for detailed representation of vegetation and urban areas
• Plans for a faster gas optics scheme
History of ECMWF radiation scheme

**Fouquart**
- liquid optics

**Solver:**
- Clear/cloudy regions
- 4 bands
- 16 bands (RRTM-G)

**Morcrette scheme**

**Aerosol:**
- Tanré

**Ozone:**
- Fortuin and Langematz

3 h

ERBE albedo
History of ECMWF radiation scheme

- **2000**: Fouquart liquid optics
- **2002**: Solver: Clear/cloudy regions
- **2004**: 4 bands, 16 bands (RRTM-G)
- **2006**: 6 bands
- **2008**: 1 h in DA
- **2010**: 1 h in HRES
- **2012**: 1 h in DA
- **2014**: 1 h in HRES
- **2016**: 1 h in HRES
- **2018**: 1 h in HRES

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**McRad**
- Solver: 1 h in DA, 1 h in HRES
- Reduced radiation grid
- 60-km MODIS
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- 1 h in HRES
- ERBE albedo

**McRad**
- Slingo, Lindner & Li
- McICA solver
- 14 bands (RRTM-G)
- 1 h in HRES
- Reduced radiation grid
- 60-km MODIS

**RRTM-G update**
- 1 h in DA
- 1 h in HRES
- 6 bands
- 14 bands (RRTM-G)

**Solar cycle**
- 5-km MODIS
- MACC
- GEMS
- Approx updates every timestep and gridpoint
- CAMS
- Reduced radiation grid
- ERBE albedo
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  - Plan to develop new scheme with fewer spectral intervals
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  - Liquid clouds: more accurate SOCRATES scheme
  - Ice clouds: Fu by default, Baran and Yi available
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  – 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
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- **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**
How do the three solvers compute how clouds interact with radiation?
Monte-Carlo Independent Column Approximation (McICA, Pincus et al. 2005)

Each wavelength sees a different cloud realization (OPERATIONAL)

- Use prognostic cloud fraction and assumed standard deviation of cloud water
- Stochastic cloud generator is fast but leads to some noise in fluxes
- McICA now used in many (most?) global weather and climate models
Tripleclouds (Shonk & Hogan 2008)

Approximate cloud variability by three regions: one clear and two cloudy

- Cloud overlap rules govern how radiation enters different regions at layer interfaces
- Fluxes and heating rates are noise-free, but this solver is slower than McICA
SPARTACUS (Hogan et al., Schäfer et al. 2016)

*Tripleclouds with lateral radiation exchange between regions*

- SPARTACUS makes ecRad the first GCM radiation scheme that can simulate 3D radiative effects
- Slower than Tripleclouds, and still under development and evaluation
Improved efficiency

(a) Radiation scheme configurations

- McRad, McICA, LWscat=0
- ecRad, McICA, LWscat=0
- ecRad, McICA, LWscat=1
- ecRad, McICA, LWscat=2
- ecRad, Tripleclouds, LWscat=1
- ecRad, SPARTACUS, LWscat=1

Time per profile (ms)

Relative to McRad
- -40.9%
- -38.4%
- -19.7%
- +0.8%
- +255%

(b) Radiation scheme components

- Preparation
- Gas optics
- Aerosol optics
- Cloud optics
- Cloud generator
- SW radiative transfer
- LW radiative transfer

Time per profile (ms)

Solver
- +5.3%
- +37.0%
- -37.8%
- -94.9%
- -83.3%
- -41.2%
- -13.5%
Improved efficiency

- ecRad is much faster than original McRad scheme in operational McICA configuration
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- Cloud treatment is much faster
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- Cloud treatment is much faster
Improved efficiency

- EcRad is much faster than original McRad scheme in operational McICA configuration
- Longwave scattering introduced in 46r1 with minimal cost
- Tripleclouds a bit more expensive
- 3D radiation much more expensive but feasible in research mode
- Cloud treatment is much faster
Reduced noise in ecRad’s McICA solver
Fast longwave scattering for clouds but not aerosols

No scattering (45R1)
For each layer, compute transmittance $T$ and sources $S^{\uparrow\downarrow}$ (reflectance $R = 0$)

Cloud & aerosol scattering

Cloud scattering only (46R1)
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Clear sky

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

Cloudy sky

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

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

**Cloud & aerosol scattering**

More expensive calculation of $T$, $R$ and $S^{\uparrow\downarrow}$

Compute total albedo and total upward emission

Cloudy sky

Compute fluxes

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Compute total albedo and total upward emission

Compute fluxes

Cloudy sky

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

LW solver cost +100%
Overall cost +36%
Fast longwave scattering for clouds but not aerosols

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**No scattering (45R1)**

For each layer, compute transmittance $T$ and sources $S^{↑↓}$ (reflectance $R = 0$)

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$F_{\text{top}}^↑ = TF_{\text{base}}^↑ + S^↑$

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**Cloud & aerosol scattering**

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Cheap no-scattering calculation

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**Cloudy sky**

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Cloud & aerosol scattering
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Cloud scattering only (46R1)
Cheap no-scattering calculation

Re-use $T$ and $S_{↑↓}$ in clear layers

$LW$ solver cost +100%
Overall cost +36%

$LW$ solver cost +16%
Overall cost +4%

Compute total albedo and total upward emission

Compute fluxes

Scattering only below cloud top

No scattering
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 reduced McICA noise

• Until 46R1, 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 uses 1-h radiation from operational cycle 46R1
  – Temperature RMSE down by 3%

Hogan & Bozzo (JAMES 2018)
The fight against compensating errors…

- 43R3 introduced ecRad along with a fix for liquid cloud optics

- 46R1 introduced LW scattering and fixed an ice-optics bug that had a similar but opposite impact

- Better overlap and cloud structure improves cloud cover, but reduces shortwave at the surface, which is already too cold

- Perhaps 3D radiation would help to improve fluxes and temperature?
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IFS model climate: *the good*…

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**the bad** (SW cloud radiative effect bias)
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…**the bad**… (SW cloud radiative effect bias)

...and the ugly (middle-atmosphere temperature bias)
Upper stratosphere 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*
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

Bozzo et al. (2017)
Aerosols

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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?*

Bozzo et al. (2017)
Main mechanisms for 3D radiative effects

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

- **Shortwave entrapment (new!)**
  - Horizontal transport beneath clouds makes reflection to space less likely
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Representing three extremes of “entrapment” in SPARTACUS

- We need albedo matrix $\mathbf{A}$ at layer interfaces

(a) Zero entrapment

(b) Explicit entrapment

(c) Maximum entrapment

No 3D effects requires matrix to be diagonal

$$\mathbf{A} = \begin{pmatrix} \alpha_{aa} & \alpha_{ba} \\ \alpha_{ab} & \alpha_{bb} \end{pmatrix} = \begin{pmatrix} \alpha & 0 \\ 0 & \alpha \end{pmatrix}$$
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43r3 SPARTACUS: full horizontal homogenization of radiation under clouds

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Better approach in 46r1: compute RMS horizontal migration distance of light paths beneath cloud

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Evaluating offline ecRad using Monte Carlo calculations on 100x100km scenes

Monte Carlo calculations by Howard Barker
Evaluating offline ecRad using Monte Carlo calculations on 100x100km scenes

- SPARTACUS with **explicit entrapment** matches **Monte Carlo** well, on average

Monte Carlo calculations by Howard Barker

---

### Cumulus

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### Frontal cloud

- Best explicit entrapment

### Stratocumulus

Monte Carlo calculations by Howard Barker

### Decaying Cb
Evaluating offline ecRad using Monte Carlo calculations on 100x100km scenes

- SPARTACUS with **explicit entrapment** matches **Monte Carlo** well, on average
- Huge difference between **maximum entrapment** and **zero entrapment**
Evaluating fluxes using all 65 scenes

• 3D radiative effect predicted by SPARTACUS agrees quite well with Monte Carlo

• The entrapment mechanism appears to win over side-illumination, implying shortwave 3D effects warm the climate system

• Very dependent on cloud size, which might not be realistic for these CRM scenes but needs to be parameterized in any global simulation
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Offline 3D radiative effect…

Surface SW 3D effect (mean -0.34 W m$^2$)

Surface LW 3D effect (mean 1.32 W m$^2$)

Surface net 3D effect (mean 0.98 W m$^2$)
Offline 3D radiative effect... ...online impact in a climate simulation

- 25-year free-running coupled simulation of the IFS
- Positive feedback in the Arctic associated with clouds and sea ice

Better agreement with annual cycle of observed sea ice
Towards “SPARTACUS-Surface”

- SPARTACUS technique to represent 3D interaction of radiation with clouds can be applied to trees (Hogan et al., GMD 2018) and buildings (Hogan, BLM 2019)

- Currently testing offline, but could be used to improve representation of forests and cities in IFS / OpenIFS in future
Example profiles of flux and net absorption

- *Meg Stretton’s PhD project:* compare profiles to explicit calculations using DART model
- Which details of an urban scene really matter which can be safely ignored? What level of detail can be justified in a weather or climate model?

**2-m vertical resolution**

**Solar zenith angle 30°**

- Downwelling direct
- Downwelling total
- Upwelling

- Wall
- Vegetation
- Roof
- Ground

121 W m⁻²
Example profiles of flux and net absorption

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- Which details of an urban scene really matter which can be safely ignored? What level of detail can be justified in a weather or climate model?

**2-m vertical resolution**

**Solar zenith angle 70°**
Efficiency: temporal versus spatial resolution

• Radiation is now 5% of high-resolution (HRES) model time, compared to 19% a decade ago

• Cost of radiation is a trade-off between temporal/spatial/spectral resolution and physical sophistication, and compared to other global NWP centres, ECMWF has lowest temporal/spatial resolution and highest spectral resolution (Met Office uses 3.7 times fewer spectral intervals!)

<table>
<thead>
<tr>
<th>Centre</th>
<th>Radiation timestep (h)</th>
<th>Horiz. coarsening</th>
<th>Spectral intervals</th>
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<td>HRES</td>
<td>ENS</td>
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<tr>
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<tr>
<td>DWD</td>
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**Z2T: Tropics −20° to 20°**

**Z2T: NH 20° to 90°**

1h coarse grid – 3h coarse grid
3h fine grid – 3h coarse grid
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- How can we afford even more frequent radiation and more physical sophistication (e.g. 3D effects)?

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EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS
How can we optimize the spectral integration?

- Three options under consideration:
  - RRTMGP: optimized RRTM-G from U. Colorado
  - Neural network: collaboration with NVIDIA
  - Full-spectrum correlated-k scheme (Pawlak et al. 2014, Hogan 2010)

RRTM-G uses 16 LW bands...
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RRTM-G uses 16 LW bands... reorder and discretize to 140 spectral intervals
FSCK reorders the entire spectrum: only 30-35 intervals required for same accuracy?
Summary and outlook

• Modular design of ecRad makes it well suited for research and operational use
  – We can test alternative modules (e.g. new solvers) while keeping everything else fixed
  – ecRad has been implemented in IFS, MesoNH and ICON models

• Offline version (available under an identical license to OpenIFS) helps research work
  – Offline ecRad has >20 users worldwide
  – Easier to implement and test new features offline

• Outlook for the “Grand Challenges” in the coming years
  – Overhaul surface treatment, including 3D interactions with cities and forests
  – Package of physically-based improvements to clouds
  – Role of aerosols in predictability; upgrade water vapour continuum
  – Remove middle-atmosphere temperature bias via new UV solar spectrum and ozone
  – Much more efficient gas optics and spectral integration
Further reading

- Radiation in NWP (ECMWF Technical memo, 2017)
- ecRad (JAMES 2018)

Radiation in numerical weather prediction


Research, Forecast and Copernicus Departments

816

AGU100

Journal of Advances in Modeling Earth Systems

RESEARCH ARTICLE
10.1029/2018MS001364

Key Points:
- A new radiation scheme for the ECMWF model is described that is 4% faster than the original scheme.
- We describe how longwave scattering by clouds can be represented with only a 4% increase in computational cost, improving forecast skill.
- A sequence of changes have reduced the long-ranking error bias in the middle to upper atmosphere of the ECMWF model.

Correspondence to:
Robin J. Hogan, robin.hogan@ecmwf.int

Citation:

European Centre for Medium-Range Weather Forecasts, Reading, UK

A Flexible and Efficient Radiation Scheme for the ECMWF Model

Rebia J. Hogan and Alessio Bozzo

Abstract
This paper describes a new radiation scheme, ecRad, for use both in the model of the European Centre for Medium-Range Weather Forecasts (ECMWF), and also for noncategorical research. Its modular structure allows the spectral resolution, the description of cloud and aerosol optical properties, and the solver, to be changed independently. The available solvers include the Monte Carlo Independent Column Approximation (MCICA), TripleCloud, and the Blue Sky Algorithm for Radiative Transfer through Cloud Sides (SPARCUS), the latter of which makes ECMWF the first global model capable of representing the 3-D radiative effects of clouds. The new implementation of the operational MCICA solver produces less noisy atmospheric heating rates, and is 4% faster, which can yield indirect forecast skill improvements via simulating the radiation scheme more frequently. We demonstrate how longwave scattering may be simplified for clouds but not aerosols, which is only 4% more computationally costly overall than neglecting longwave scattering and yields further modest forecast improvements. It is also shown how a sequence of radiation changes in the last few years has led to a substantial reduction in stratospheric temperature biases.

Plain Language Summary
Solar and thermal infrared radiation provide the energy that drives weather systems and ultimately controls the Earth’s climate. Accurately simulating these energy flows is therefore a crucial part of the computer models used for weather and climate prediction. This paper describes a flexible and efficient new software package, ecRad, for computing radiation exchange. It became operational in the forecast model of the European Centre for Medium-Range Weather Forecasts (ECMWF) in July 2017, and is 4% computationally faster than the previous package. This offers the possibility to update the radiation fields in the model simulations more frequently for the same overall computational cost, which we show in turn can improve the skill of weather forecasts. A unique feature for a radiation package of this kind is the ability to simulate radiation flows through the sides of clouds, not just through the base and top, making it well suited as a tool for research into atmospheric radiation exchange.

1. Introduction