ECMWF Feature article

from Newsletter Number 155 – Spring 2018

METEOROLOGY

A new radiation scheme for the IFS

Cover image: mishoo/istock/Thinkstock

www.ecmwf.int/en/about/news-centre/media-resources

doi:10.21957/ab84rhs9t5

This article appeared in the Meteorology section of ECMWF Newsletter No. 155 – Spring 2018, pp. 26-31.

A new radiation scheme for the IFS

Robin J. Hogan, Alessio Bozzo

Radiation is a fundamental process that drives atmospheric flows at all scales. It is key to both improving short-range surface temperature forecasts and meeting ECMWF's strategic aim of pushing the boundaries of predictability at medium-range and longer timescales. In 2007, the 'McRad' radiation scheme became operational in ECMWF's Integrated Forecasting System (IFS). It incorporated two major advances: very accurate gas optical properties in both the shortwave and longwave from the Rapid Radiative Transfer Model for general circulation models (RRTM-G), and the Monte Carlo Independent Column Approximation (McICA) for efficient treatment of cloud sub-grid heterogeneity. Many weather and climate models have since incorporated one or both of these advances.

Two shortcomings of McRad have motivated the recent development of a new ECMWF radiation scheme, 'ecRad'. Firstly, *flexibility*: to facilitate ongoing scientific development, we need the ability to swap individual components of the radiation scheme for faster and more accurate ones, but the non-modular design of McRad makes this very difficult. Secondly, *efficiency*: the large number of spectral intervals (252) required by RRTM-G made McRad 3.5 times slower than its predecessor. The result is that the radiation scheme has to be run on a much coarser grid than the rest of the model, and in all operational model configurations except high-resolution forecasts (HRES) we only call the radiation scheme every 3 hours. In HRES the scheme is called every hour.

The new radiation scheme ecRad, which became operational in July 2017 (IFS Cycle 43r3), is faster and more flexible. It uses a new implementation of McICA that is less noisy in partially cloudy conditions. Improvements in longwave radiative transfer reduce biases in temperature profiles. As implemented in IFS Cycle 43r3, ecRad brings slight improvements in forecast skill. Its modular structure facilitates radiative transfer research and opens the door to more substantial improvements in forecast skill in the future.

Modular structure

The new scheme is made up of five largely independent components. The first is taken from McRad while the others (amounting to 16,000 lines of code) are new. The components are shown in Figure 1 along with the flow of data between them. They are:

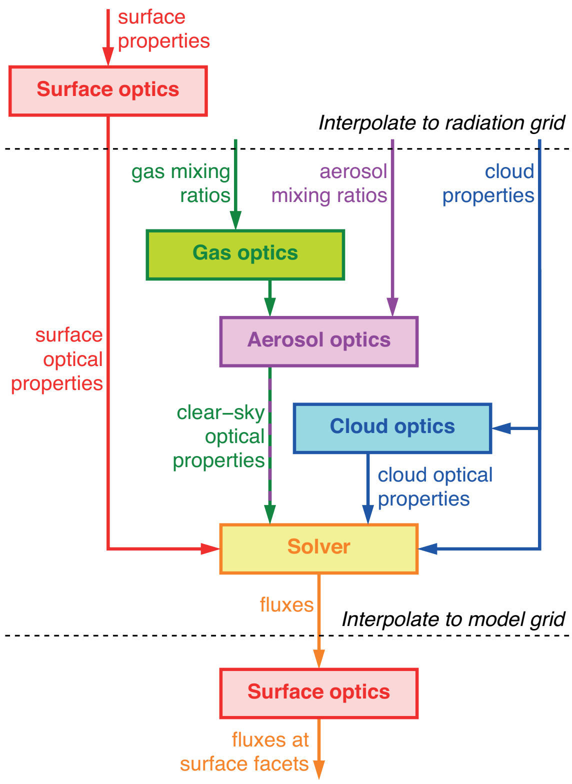

Figure 1 Schematic illustrating the five main components of ecRad (differently coloured boxes) and the flow of data between them (arrows).

 doi:10.21957/ab84rhs9t5

1. **Gas optics:** this component computes gas absorption and scattering in each spectral interval and dictates the spectral resolution, which is one of the main factors determining the computational cost of the entire scheme. Currently only RRTM-G is available, but we plan to add alternatives in future in order to give the user the option of choosing a different trade-off between accuracy and cost.
2. **Aerosol optics:** this component adds the aerosol contribution to the clear-sky optical properties. The number of aerosol species is run-time configurable with optical properties provided by a NetCDF configuration file. In this framework we are able to support various types of climatological aerosol distribution as well as prognostic aerosol schemes including the latest 15-species version of the IFS bulk aerosol scheme.
3. **Cloud optics**: new parametrizations are available in addition to those operational in McRad. For liquid clouds, the older Slingo scheme had been found to overpredict optical depth, so the ecRad default is a parametrization adapted from that used in the UK Met Office radiation scheme. For ice clouds, the Fu scheme is still used, but alternative schemes based on more recent measurements of ice size distributions and scattering patterns are undergoing testing.
4. **Solver:** this component merges clear-sky and cloudy optical properties, accounting for cloud fraction, heterogeneity and overlap, and solves for the profile of fluxes in each spectral interval. McRad had only one solver: McICA without longwave scattering. Three solvers are available in ecRad. Operationally we use a new implementation of McICA that is more efficient, generates less stochastic noise and includes the option to turn on longwave scattering. Also available are the Tripleclouds and SPARTACUS solvers, discussed below. In addition, we have added the ability to choose between three cloud overlap schemes, and to change both the width and the shape of the sub-grid probability density function of cloud water content.
5. **Surface optics:** development of this component is in progress. It is intended to represent the radiative interaction with complex surfaces, such as urban areas and forests; the theoretical basis for the latter was described by *Hogan et al.* (2018). It will run on the full model grid rather than the lower-resolution radiation grid, and compute radiative fluxes at each facet of the surface. This will enable the energy budget to be treated separately for the streets, walls and roofs of the planned ‘urban tile’, and likewise for the vegetation and ground of forest tiles.

Greater efficiency

Figure 2 shows the computational cost of various versions of the radiation scheme when run in the coupled IFS at TCo1279 resolution (corresponding to a grid spacing of 9 km). The top two bars of the top panel show that ecRad is around 35% faster than McRad when in a similar configuration (McICA solver with no longwave scattering); this is the configuration used operationally in IFS Cycle 43r3. The lower panel shows a breakdown of the computational cost by component, highlighting the impact of individual optimisations. An overarching change is to make spectral interval rather than atmospheric column the fastest varying dimension in optical-property arrays. This improves performance overall since conditional operations (which inhibit vectorisation) depend on the presence of cloud or whether the sun is above the horizon, factors that are functions of atmospheric column but not spectral interval. For the moment this makes gas optics slower because this component has not yet been recoded, so the output arrays have to be permuted, but this is more than compensated for by a speed-up in other components.

The job of the cloud generator in a McICA solver is to stochastically produce a different cloud-profile realisation for each spectral interval, consistent with the specified cloud overlap and horizontal heterogeneity. The ecRad cloud generator is much faster because it has been devised to use far fewer random numbers. An even greater speed-up has been achieved in computing cloud optical properties: McRad recomputed them in each of the 252 spectral intervals, when in fact it is only necessary to compute them in the 30 broader spectral bands in which the coefficients of the cloud optics parametrizations are defined.

Radiation now occupies a very small fraction of model time: with ecRad it is only 3.5% in coupled simulations at a resolution of TCo1279 with the radiation scheme called every hour. This figure includes the cost of interpolating back and forth between the model grid and the radiation grid. This is a large improvement on the 19% reported when McRad was implemented in the uncoupled HRES in 2007. The efficiency gain is a consequence of several factors in addition to ecRad optimisations: (1) the longer model time step in 2007, while radiation was still called every hour, (2) the additional cost of the ocean model (9% of wall-clock time in HRES), and (3) in 2007 radiation was run on a grid with six times fewer grid points than the rest of the model, compared to ten times fewer now.

Hogan et al. (2017) have demonstrated that the forecast degradation due to the coarser grid is very small, partly thanks to the use of approximate radiation updates on the finer model grid that mitigate problems at coastlines.

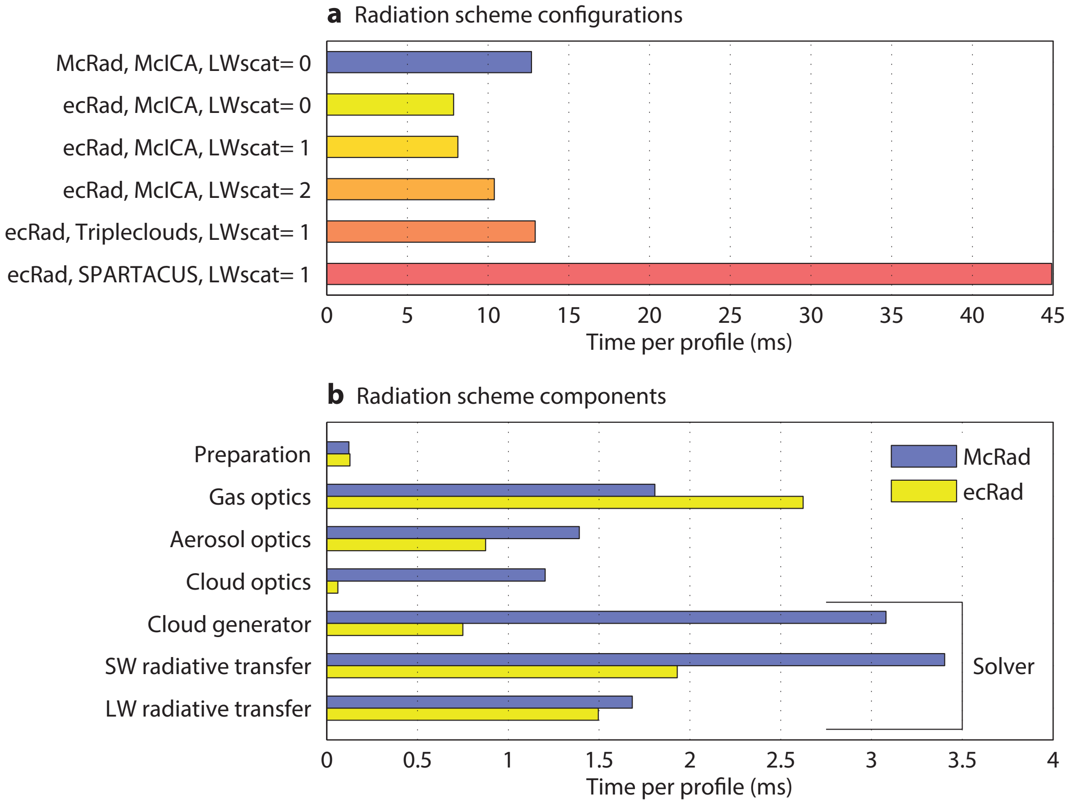

Figure 2 Computational cost of (a) various configurations of the radiation scheme, expressed in terms of the time needed to run it per atmospheric profile, where the labels on the left indicate the scheme name, solver name and longwave scattering configuration (0 = no longwave scattering, 1 = scattering by clouds only, 2 = scattering by clouds and aerosols), and (b) the first two configurations broken down by different radiation scheme components.

Better McICA solver

A downside to the McICA approach is that it can produce significant stochastic noise in atmospheric heating rates. Even though 252 realisations of the cloud profile are generated, many are in absorbing parts of the spectrum where the cloud radiative effect is not significant; indeed, only around 40% of the spectral intervals have a clear-sky optical depth less than 3. Moreover, the McRad implementation of McICA exacerbates the noise in partially cloudy situations, since many of the stochastic profiles generated are then cloud-free.

The problem is illustrated in Figure 3: a real profile of shortwave and longwave heating rates in a partially cloudy column extracted from the 137-level IFS. We compare the McRad and ecRad implementations of McICA to the alternative 'Tripleclouds' solver available in ecRad, which is considerably more expensive than McICA (see Figure 2) but generates no stochastic noise. The noise in the McRad implementation is large, with up to 5 K/day errors in the longwave heating rate compared to 'Tripleclouds', which is used as a proxy for the truth. In all model configurations except HRES, the radiation time step is 3 hours, so these erroneous temperature tendencies accumulate over a number of model time steps.

 doi:10.21957/ab84rhs9t5

The ecRad implementation of McICA does exhibit noise, but the amplitude of errors in Figure 3 is significantly lower than for McRad. This has been achieved thanks to two improvements. Firstly, total cloud cover is now computed deterministically from the cloud fraction profile and the overlap rules, so removing stochastic noise in cloud cover (even though the cloud profiles within the cloudy part of the gridbox are still stochastically generated). Secondly, we make use of the fact that clear-sky radiation calculations (i.e. fed by the same atmospheric profiles except with the clouds removed) are already performed for diagnostic purposes, so we can use the cloud generator to produce only cloudy profiles, and then compute the total-sky flux profile as a weighted average of the clear and cloudy profiles. This leads to much better sampling of the cloudy part of the column in partially cloudy conditions. Details were given by *Hogan & Bozzo* (2016).

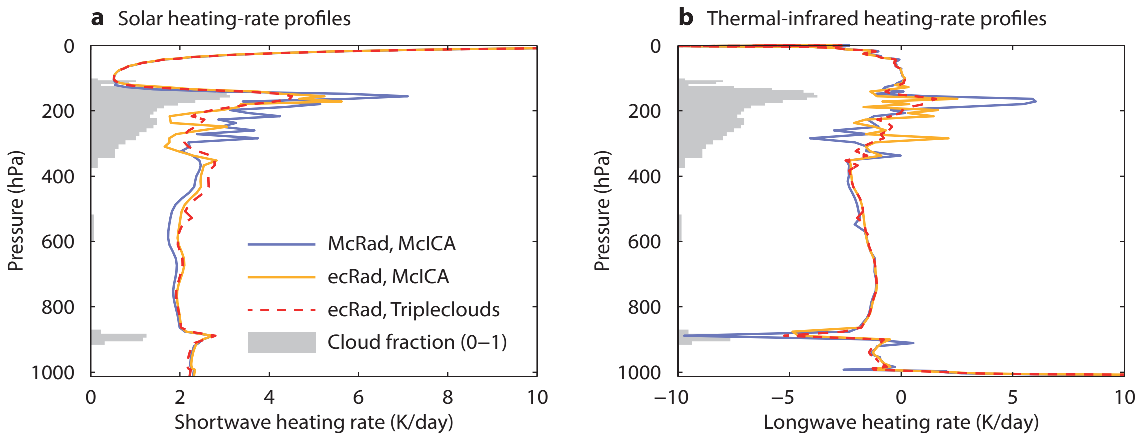

Figure 3 Profiles of (a) instantaneous solar heating-rates and (b) instantaneous thermal-infrared heating-rates for a single column of the atmosphere, comparing the previous McRad scheme (with noise of up to 5 K per day), the ecRad scheme with the reduced-noise McICA solver, and ecRad with the computationally more expensive but noise-free Tripleclouds solver. The grey shading indicates the location of clouds.

Improvements in longwave radiative transfer

The longwave part of ecRad has been improved: the two-stream radiative transfer equations are now solved exactly under the assumption that the Planck function varies linearly within each model level, while the treatment in McRad is more approximate. As shown in *Buizza et al.* (2017), this tends to reduce extrema in the temperature profile, warming the tropopause by around 0.5 K and cooling the stratopause by around 1 K. Both of these changes reduce existing biases.

Turning on longwave scattering in ecRad is under testing for one of the next operational IFS cycles. Physically, the introduction of scattering results in optically thick clouds no longer behaving as a black body (with an emissivity of one) but rather reflecting a certain fraction of incident radiation. This change in turn reduces top-of-atmosphere outgoing longwave radiation and increases surface downwelling longwave radiation. Unfortunately, inclusion of scattering doubles the cost of the longwave solver and increases the total cost of ecRad by 32% (the difference between the second and fourth bars in the top panel of Figure 2). But in practice only longwave scattering by clouds is important, while for aerosols it can be neglected. This enables not only the clear-sky part of the calculation to use the no-scattering assumption, but also the layers above the highest cloudy layer in the all-sky part of the calculation. Thus longwave scattering by clouds may be included with only a 3% increase in the total cost of the scheme (the difference between the second and third bars in the top panel of Figure 2).

doi:10.21957/ab84rhs9t5

Impact on forecasts

The impact of various configurations of ecRad on medium-range forecasts skill is summarised in Figures 4 and 5 for a 3-hour radiation time step, which is used in ensemble forecasts (ENS). The ecRad configuration operational in IFS Cycle 43r3 includes the reduced-noise McICA solver and a better solution to the longwave equations, but does not include longwave scattering. Its impact on temperature and wind compared to McRad is overall slightly positive. The introduction of longwave scattering yields a further extratropical improvement of around 1% at all forecast lead times. Note that McRad included an approximate treatment of longwave scattering, but it was only implemented for ice clouds and only affected clouds of low to moderate optical depth.

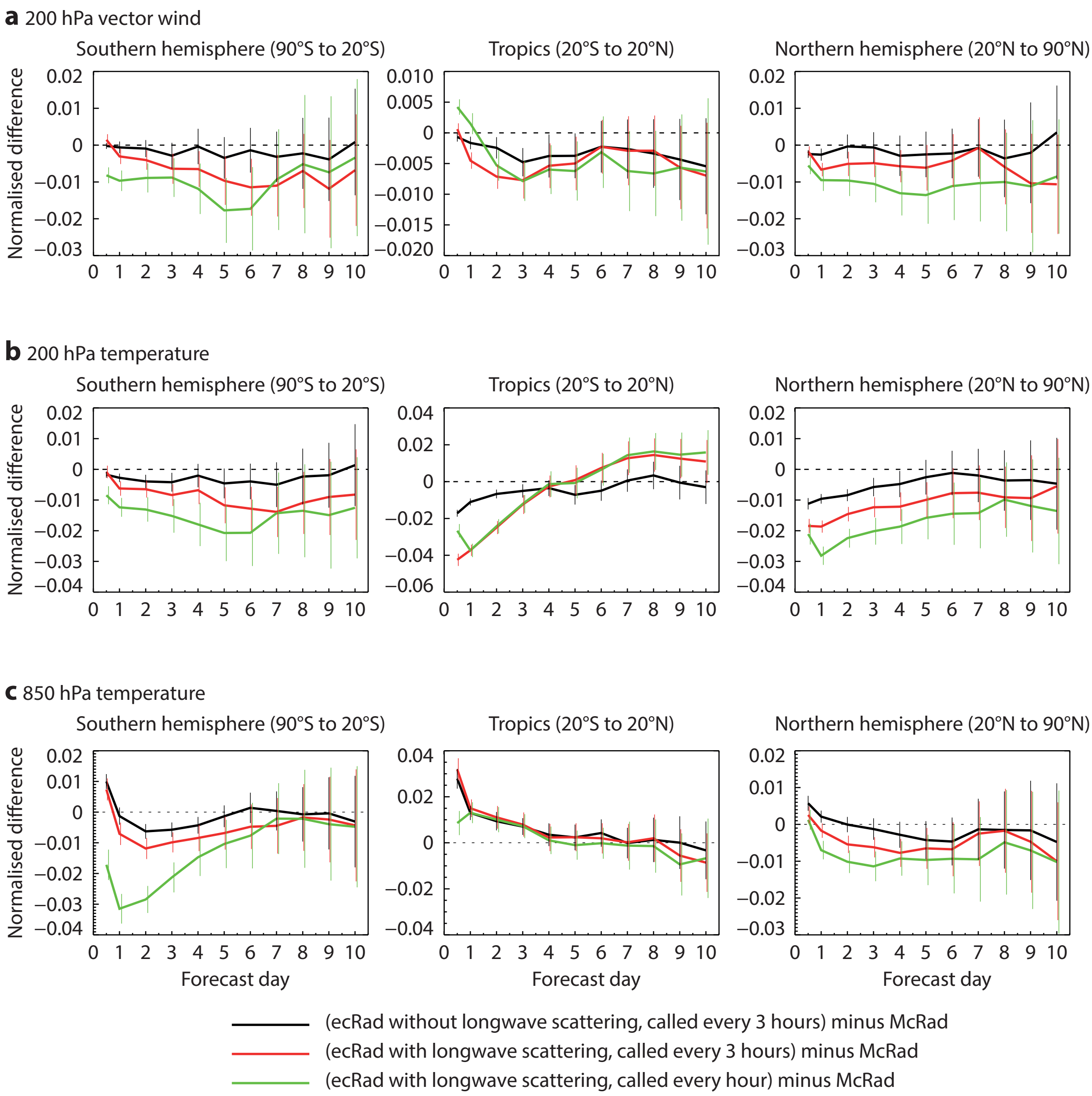

Figure 4 Normalised change to root-mean-square error in (a) 200 hPa vector wind, (b) 200 hPa temperature and (c) 850 hPa temperature when switching from the McRad radiation scheme to three configurations of the ecRad scheme. A value of –0.01 indicates a reduction in error of 1%. The uncoupled forecasts were performed at TCo399 resolution from June to September 2016 and evaluated against the then operational forecasts (IFS Cycle 41r2).

doi:10.21957/ab84rhs9t5

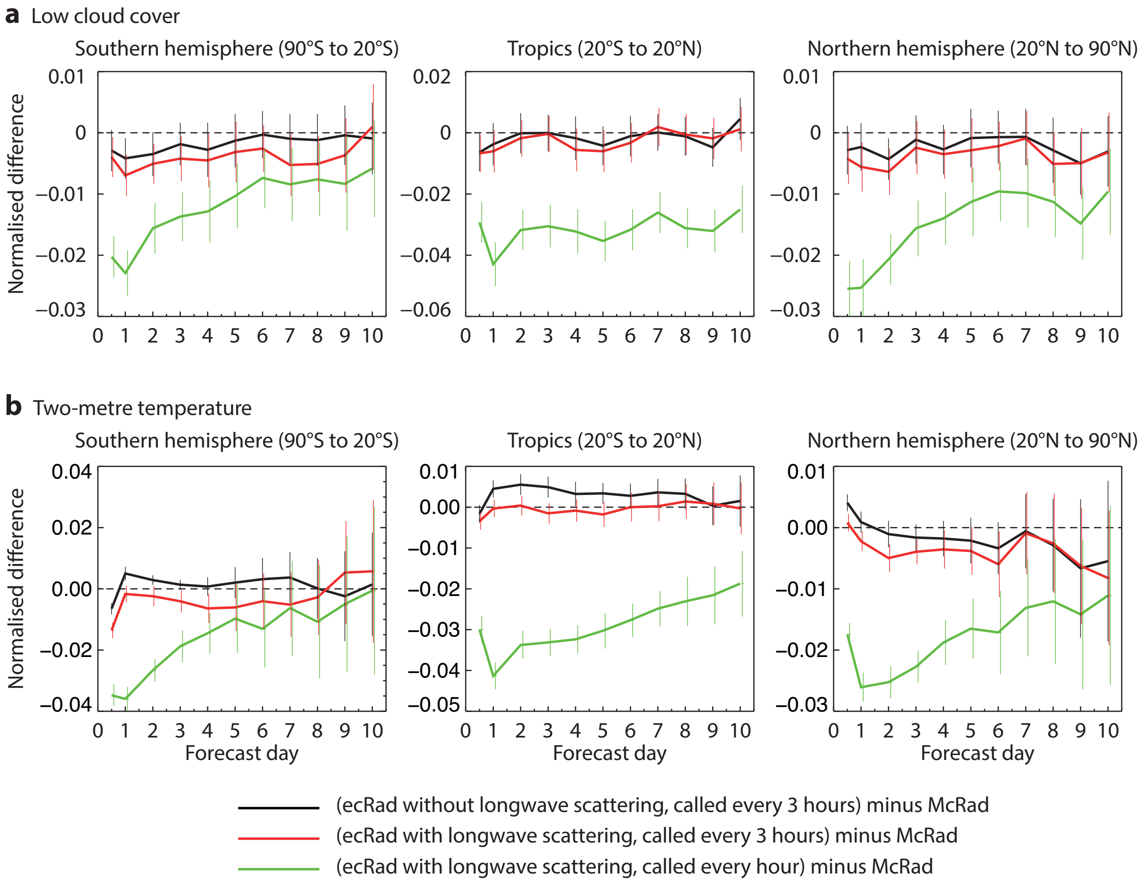

Figure 5 As Figure 4 but showing the change to root-mean-square forecast error for (a) low cloud cover and (b) 2-metre temperature.

Larger improvements in skill are potentially available indirectly from the greater efficiency of ecRad, by reinvesting the time saved into calling the radiation scheme more frequently than every 3 hours. A reduction in the ENS radiation time step to 1 hour to align it with HRES is under consideration for one of the next operational IFS cycles. Figure 5 shows that in deterministic forecasts this significantly improves 2-metre temperatures at all lead times, especially in the tropics, and appears to be associated with an improvement in the prediction of low cloud cover. As shown by *Hogan et al.* (2017), the same improvement is obtained in ENS skill scores, and more than half of the improvement could be obtained by reducing the radiation time step to 2 hours rather than 1 hour.

Facilitating radiation research

The flexibility and capabilities of ecRad make it an excellent tool for radiative transfer research. For example, the availability of the SPARTACUS solver (*Hogan et al.*, 2016) makes the IFS the only global model capable of representing 3D radiative effects at a reasonable computational cost. This makes it possible to estimate the global impact of 3D radiative transfer. Our current best estimate is that 3D radiative transfer increases longwave and shortwave downwelling fluxes at the surface each by around 1 W/m^2, which in turn warms the land surface by on average 0.5 K in 1-year free-running coupled IFS simulations. This is of a similar order to the impact of changing the specification of cloud overlap and horizontal heterogeneity within observational uncertainty.

The introduction of ecRad has also made it easier to test alternative aerosol formulations in the radiation scheme. This has facilitated the introduction of a new aerosol climatology, based on data provided by the Copernicus Atmosphere Monitoring Service (CAMS), in IFS Cycle 43r3 (*Buizza et al.*, 2017). It is also underpinning ongoing development of the prognostic aerosol scheme in the IFS, which is used for global CAMS forecasts. The interaction between prognostic aerosols and radiation will shortly be turned on for operational CAMS forecasts, and will be in the next CAMS reanalysis. Aerosol variability can influence surface temperature, particularly during intense events such as volcanic eruptions, dust storms and forest fires. For example, the wildfires that occurred in the North-West Territories of Canada during August 2017 were amongst the largest by both extent and total carbon emission in the region over the last decade. Figure 6 shows the difference between forecasts with prognostic and climatological aerosols being fed to the radiation scheme, revealing that the thick smoke plume on 14 August reduced surface solar radiation by 50–100 W/m^2, which in turn reduced mean daytime temperatures in the area by up to 5 K.

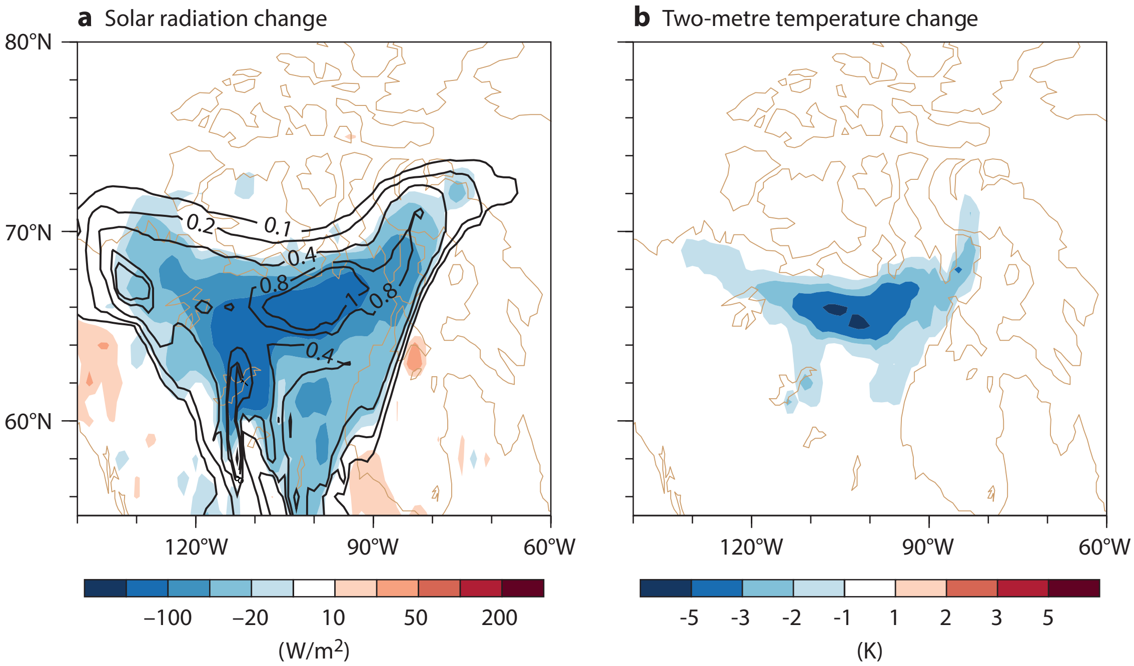

Figure 6 Impact of prognostic aerosols from the IFS bulk aerosol scheme on forecasts initialised at 00 UTC of (a) surface downwelling solar radiation averaged over the first full day of the forecast over Canada, and (b) 2-metre temperature averaged over 0600–1800 local time (forecast lead times of 12–24 hours), for 14 August 2017 when extensive forest fires occurred in Northern Canada. The contours in the left-hand panel show the 24-hour average optical depth of biomass burning aerosols.

An offline version of ecRad has been available for non-commercial use under the terms of the OpenIFS licence since February 2017. It now has users in Algeria, China, France, Germany, the United Kingdom and the United States. It is being used at the University of Reading to generate greenhouse-gas and aerosol radiative forcing products from the CAMS interim Reanalysis (CAMSiRA), and at the University of Leipzig and Laboratoire de Météorologie Dynamique in Paris to improve our understanding of the radiative properties of clouds observed by aircraft and satellites. It has also been implemented in the limited-area Meso-NH model.

Outlook

A number of ecRad developments are planned for the coming years. A surface component will be added that can rigorously treat radiative interactions with complex surfaces, such as urban areas and forests. We plan to upgrade the treatment of cloud properties, aiming for consistency with the assumptions made in the cloud, convection and assimilation schemes, and to introduce the radiative effects of rain and convective cloud. We also plan to develop and test an alternative, faster gas optics scheme with fewer spectral intervals.

 doi:10.21957/ab84rhs9t5

Further reading

Buizza, **R.**, **P. Bechtold**, **M. Bonavita**, **N. Bormann**, **A. Bozzo**, **T. Haiden**, **R. Hogan**, **E. Holm**, **G. Radnoti**, **D. Richardson** & **M. Sleigh**, 2017: IFS Cycle 43r3 brings model and assimilation updates. *ECMWF Newsletter* **No. 152**, 18–22.

Hogan, **R.J.** & **A. Bozzo**, 2016: ECRAD: a new radiation scheme for the IFS. *ECMWF Technical Memorandum* **No. 787**.

Hogan, **R.J.**, **S. A. K. Schäfer**, **C. Klinger**, **J.-C. Chiu** & **B. Mayer**, 2016: Representing 3D cloud-radiation effects in two-stream schemes: 2. Matrix formulation and broadband evaluation. *J. Geophys. Res.*, **121**, 8583–8599.

Hogan, **R.J.**, **M. Ahlgrimm**, **G. Balsamo**, **A. Beljaars**, **P. Berrisford**, **A. Bozzo**, **F. Di Guiseppe**, **R.M. Forbes**, **T. Haiden**, **S. Lang**, **M. Mayer**, **I. Polichtchouk**, **I. Sandu**, **F. Vitart** & **N. Wedi**, 2017: Radiation in numerical weather prediction. *ECMWF Technical Memorandum* **No. 816**.

Hogan, **R.J.**, **T. Quaife** & **R. Braghiere**, 2018: Fast matrix treatment of 3D radiative transfer in vegetation canopies: SPARTACUS-Vegetation 1.0. *Geosci. Model Dev.*, **11**, 339–350.

doi:10.21957/ab84rhs9t5