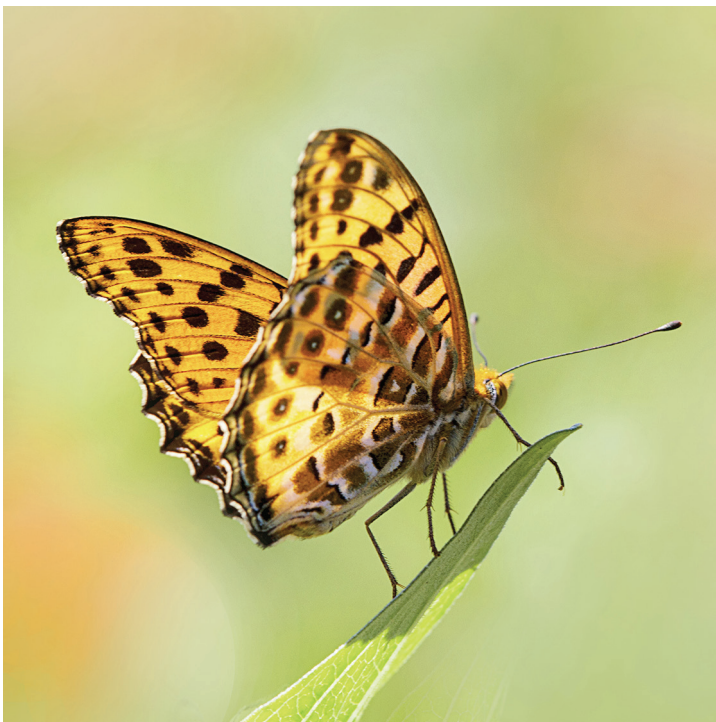




**METEOROLOGY**

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Reducing surface temperature errors at coastlines  
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## Reducing surface temperature errors at coastlines

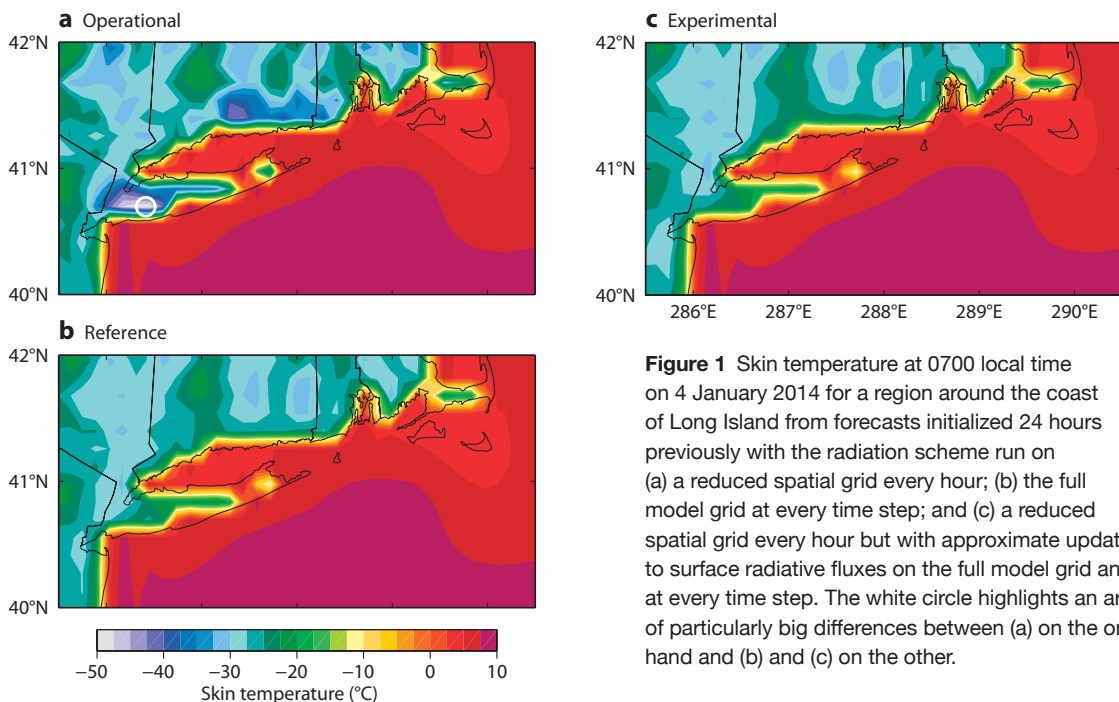
Robin Hogan, Alessio Bozzo

To limit its high computational cost, the current radiation scheme in ECMWF’s Integrated Forecasting System (IFS) is run on a coarser spatial grid than the rest of the model. As a result, surface radiative fluxes computed over the ocean may be used over land, where the surface temperature (‘skin temperature’) and surface albedo are very different. This can lead to large near-surface temperature errors at coastal land points. For example, in Norway night-time 2-metre temperature forecasts at coastlines can sometimes be too low by more than 10 °C. The radiation scheme is also run infrequently, which leads to errors in the diurnal cycle of skin temperature.

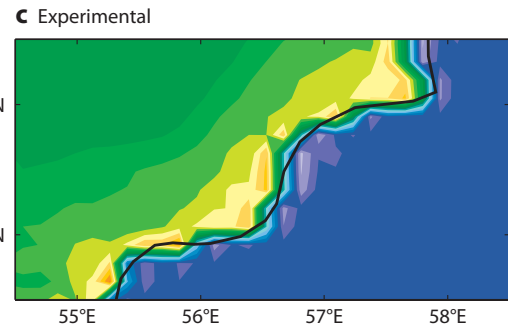
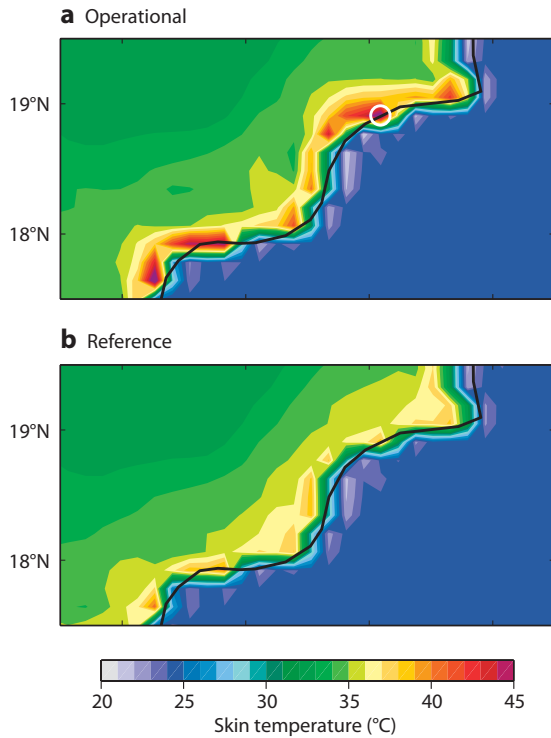
A computationally efficient solution to these problems has been developed, in which the surface longwave and shortwave fluxes are updated at every model time step and grid point according to the local skin temperature and albedo. The computational cost of performing approximate radiation updates is only 2% of the cost of the full radiation scheme, and the overall run time of the model is only increased by about 0.2%. Testing the new scheme by running daily five-day forecasts over an eight-month period has revealed a significant improvement in 2-metre temperature forecasts at coastal stations compared to observations.

### The ECMWF radiation scheme: accurate but slow

Since 2007, the ECMWF radiation package has been based on the Rapid Radiative Transfer Model for General Circulation Models (RRTMG). This model is very accurate and well validated against both observations and reference radiation calculations that represent individual spectral lines. It also captures cloud structure via the Monte Carlo Independent Column Approximation. However, the model’s accuracy comes at a cost: 252 individual radiative transfer calculations are required to represent the full shortwave (solar) and longwave (thermal infrared) spectral regions. The associated computational cost means that we cannot afford to run the radiation scheme at every model time step (typically 10–20 minutes) and grid point (a configuration hereafter referred to as the Reference Scheme). The current operational practice is to run it every hour in the high-resolution (HRES) forecast and every three hours in all other model configurations. To reduce computational cost further, the model fields are first interpolated to a reduced spatial grid with 6.25 times fewer grid points globally, and the resulting radiative fluxes are interpolated back to the original grid (a configuration hereafter referred to as the Operational Scheme).



**Figure 1** Skin temperature at 0700 local time on 4 January 2014 for a region around the coast of Long Island from forecasts initialized 24 hours previously with the radiation scheme run on (a) a reduced spatial grid every hour; (b) the full model grid at every time step; and (c) a reduced spatial grid every hour but with approximate updates to surface radiative fluxes on the full model grid and at every time step. The white circle highlights an area of particularly big differences between (a) on the one hand and (b) and (c) on the other.



**Figure 2** Skin temperature at 1400 local time on 4 January 2014 for a region around the southern coast of Oman from forecasts initialized 24 hours previously with the radiation scheme run on (a) a reduced spatial grid every hour; (b) the full model grid at every time step; and (c) a reduced spatial grid every hour but with approximate updates to surface radiative fluxes on the full model grid and at every time step. The white circle highlights an area of particularly big differences between (a) on the one hand and (b) and (c) on the other.

Figure 1 compares HRES skin temperature forecasts in the region of Long Island in the US state of New York using the Operational Scheme (Figure 1a) with forecasts using the Reference Scheme (Figure 1b). In this case the reduced grid in the Operational Scheme led to an underestimate by as much as 25 °C in one particular area (circled in Figure 1a), and forecasters at La Guardia Airport alerted ECMWF to the poor forecast at the time. Since this error occurred just before sunrise, it is purely a longwave effect. It can be seen that the ocean is much warmer than the land, leading to much larger longwave emission, but this was applied over some coastal land points, leading to them cooling too fast at night. This effect is compounded by the land having a much lower heat capacity than the ocean.

Figures 2a and 2b show early afternoon skin temperature forecasts along a desert coastline. This time the 10 °C overestimate is predominantly a shortwave phenomenon: the lower albedo of the ocean means that much more sunlight is absorbed than by the more reflective desert, but this extra absorption is applied to some coastal land points, leading to them warming too much.

### Radiation updates: approximate but fast

We seek a computationally efficient way to update the radiative fluxes at every model grid point and time step to account for the local values of skin temperature and albedo. If we can work solely with broadband fluxes, which bundle different parts of the spectrum together, then this will be much faster than the radiation scheme and its 252 spectral intervals. Note that only differences in surface properties are considered; the atmosphere and in particular clouds are assumed to be constant.

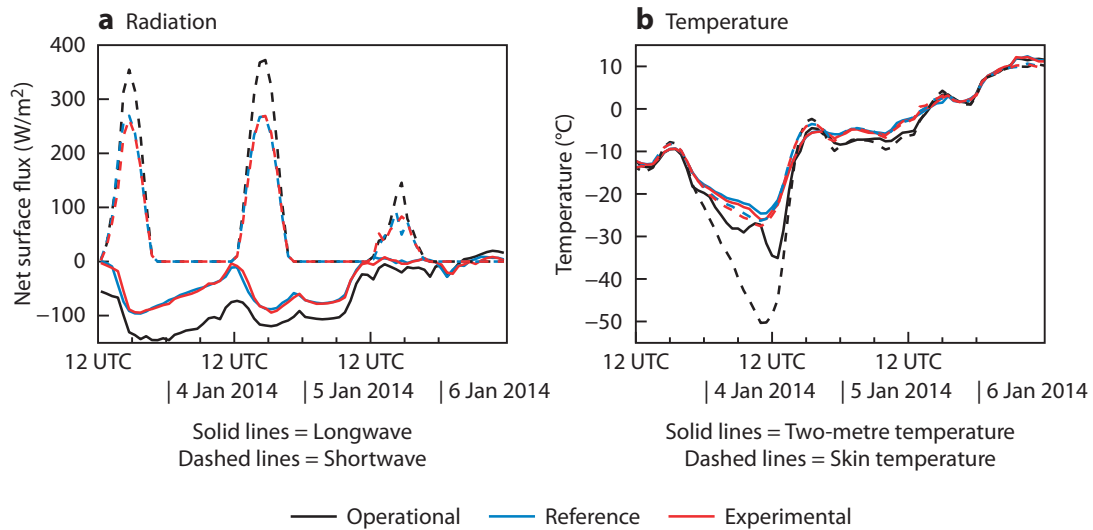
In the longwave part of the spectrum, we can use the fact that the broadband flux emitted by a blackbody is equal to  $\sigma T_{surface}^4$  (where  $\sigma$  is the Stefan-Boltzmann constant) to update the surface upwelling flux. This gives a much improved surface energy balance, but we have to decide where to deposit this excess energy in the atmosphere. It turns out that, due to strong water vapour and carbon dioxide absorption, typically around half of the longwave radiation emitted from the surface is absorbed in the first 500 m of the atmosphere. We have therefore configured the radiation scheme to compute the fraction of surface emission that is absorbed by each model level, and used this at every grid point to update also the longwave heating profile. This improves the response of the temperature profile in the lowest part of the atmosphere (boundary layer).

In the shortwave part of the spectrum, the IFS already scales the shortwave flux profile at each time step to account approximately for the change in sunlight incident at the top of the atmosphere as the sun moves through the sky (Morcrette, 2000). We have implemented an additional scheme proposed by Manners *et al.* (2009) that makes an approximate update to surface radiative fluxes to account also for the change in the path length of the solar beam through the atmosphere.

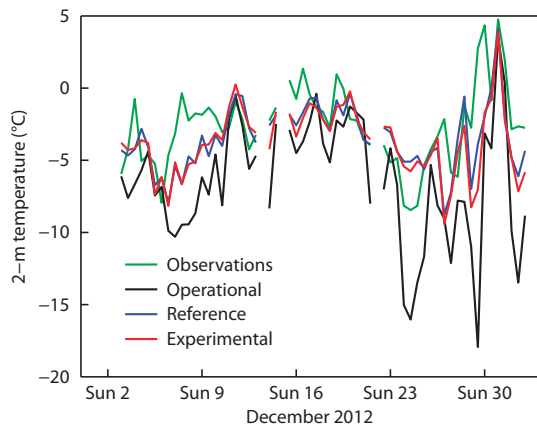
While these two schemes are important, they do not fix the problem highlighted in Figure 2. We therefore perform an update of the reflected surface radiation to ensure that it is consistent with the local value of broadband albedo. However, simply letting the extra reflected radiation escape to space would still result in errors of up to  $70 \text{ W/m}^2$  at desert coastlines, since in reality some of it will be reflected back down to the surface, with the possibility of further upward reflection and so on. To capture this feedback, we use the top-of-atmosphere and surface fluxes from the radiation scheme to compute the effective broadband transmittance and reflectance of the entire atmosphere. This enables the response of both upwelling and downwelling surface fluxes to a change in surface albedo to be computed while accounting for multiple reflections.

Figures 1c and 2c show that enhancing the Operational Scheme by the use of approximate radiation updates on the full model grid and at every time step (hereafter referred to as the Experimental Scheme) leads to skin temperature forecasts very similar to those obtained using the Reference Scheme (Figures 1b and 2b), but at a far lower computational cost.

Figure 3 shows the time series of net radiative fluxes (downwelling minus upwelling) and temperature for the point in Long Island with the largest errors in Figure 1. The forecast using the Operational Scheme can be seen to underestimate net longwave flux by around  $50 \text{ W/m}^2$  for the first day of the forecast, compared to a forecast using the Reference Scheme. This error is almost completely corrected by using the Experimental Scheme. Using the radiation updates also corrects a daytime error in shortwave fluxes, which was exacerbated by the snow cover at the time, leading to a large albedo contrast at the coast.



**Figure 3** Time series of (a) surface net shortwave and longwave fluxes and (b) 2-metre temperature and skin temperature at  $40.7^\circ\text{N } 286.4^\circ\text{E}$  (the point on Long Island indicated by the white circle in Figure 1a) for full 72-hour forecasts using the radiation scheme run on a reduced spatial grid every hour (Operational); the full model grid at every time step (Reference); and a reduced spatial grid every hour but with approximate updates to surface radiative fluxes at every time step and grid point (Experimental).

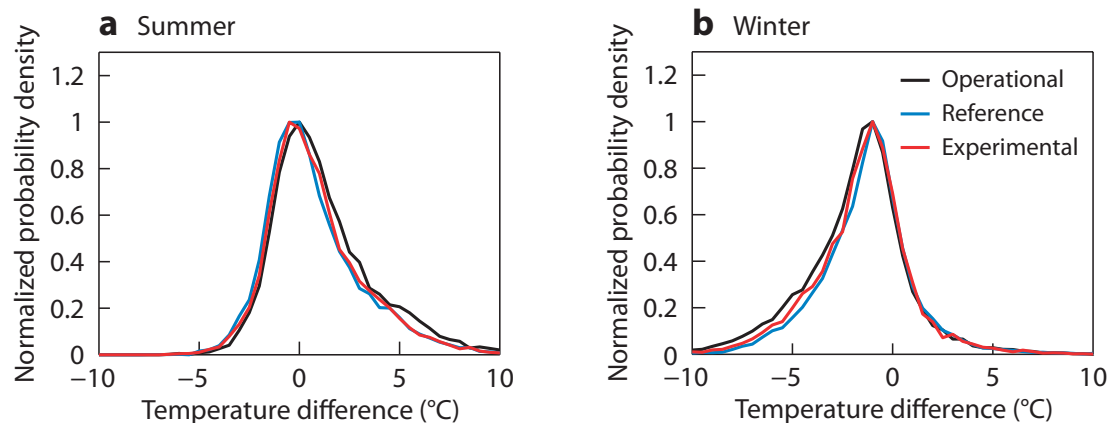


**Figure 4** Comparison of T639 2-metre temperature forecasts at 00 UTC and 12 UTC (lead times of 24 hours and 36 hours, respectively) against observations at Sortland, Norway ( $68.7^\circ\text{N}, 15.42^\circ\text{E}$ ) for December 2012.

### Comparison with observations

Eight months of daily forecasts have been produced using the HRES configuration (T1279, corresponding to a horizontal resolution of about 16 km, with radiation calls every hour) and the ensemble configuration (T639, corresponding to a horizontal resolution of about 32 km, with radiation calls every three hours). Two-metre temperatures have been compared with observations at European coastal stations. Figure 4 shows a time series at a site in northern Norway for December 2012, where it is clear that large temperature underestimates in the T639 model configuration are much improved by the use of the Experimental Scheme.

Figure 5 depicts the full eight months of data in the form of probability distributions of 2-metre temperature error. The distributions are significantly skewed for the Operational Scheme, with a tail of large positive temperature errors in summer at 12 UTC and a tail of large negative errors in winter at 00 UTC. These errors are reduced when using the Experimental Scheme, and indeed the error distributions are quite similar to running the Reference Scheme.



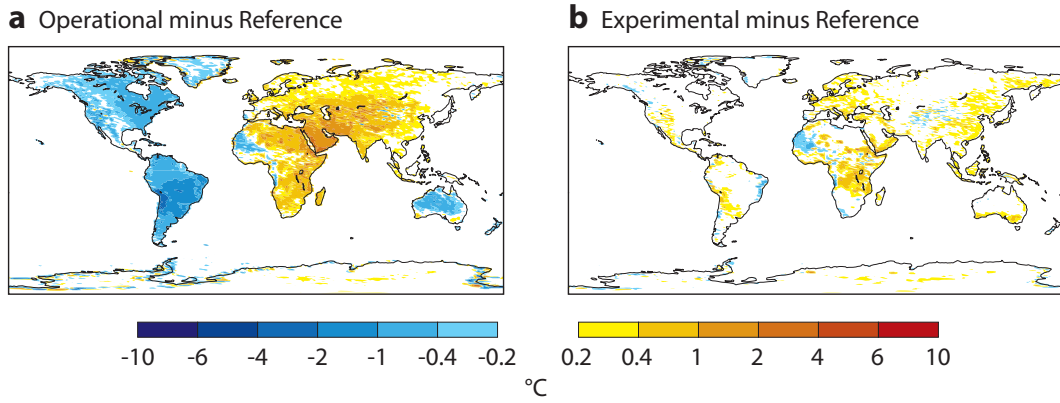
**Figure 5** Probability density functions (normalized to the maximum value) of the difference between forecast and observed 2-metre temperature at European coastal stations for (a) June to September 2012 forecasts at 12 UTC, 36 hours into each daily forecast, and (b) December 2012 to March 2013 forecasts at 00 UTC, 24 hours into each daily forecast.

### Improvement of the diurnal cycle and forecast skill

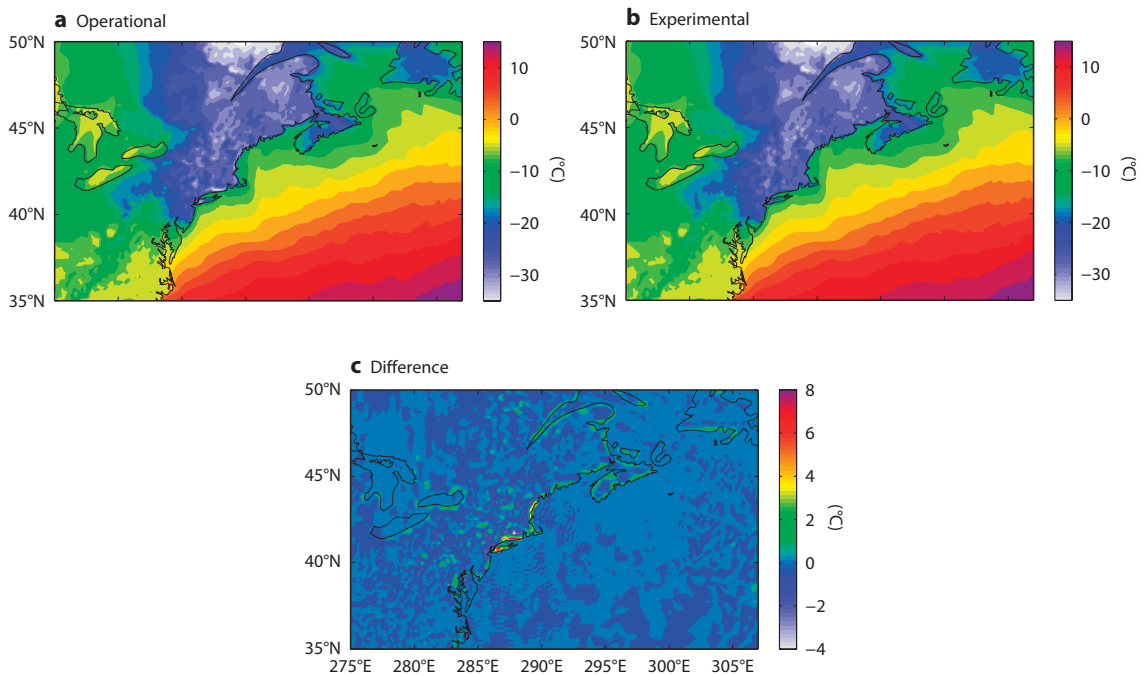
The new approach of performing approximate radiation updates on the full model grid and at every time step clearly results in significant improvements in coastal areas at very small computational cost, but the fraction of the globe affected is very small, so we might not expect a measurable improvement in global forecast skill. However, in model configurations that call the radiation scheme only every three hours, all land area forecasts currently suffer from the problem that longwave emission from the surface is held at a fixed value for three hours even though the skin temperature evolves significantly in this time. This lag in the longwave response to skin temperature changes means that land areas tend to warm up too rapidly in the morning and cool too rapidly at night.

Figure 6 demonstrates this effect: Figure 6a shows the mean June–September 2012 skin temperature error at 12 UTC for forecasts using the Operational Scheme, evaluated against forecasts using the Reference Scheme. We see a warm bias in land areas where 12 UTC corresponds to early afternoon, and a cold bias for night-time areas. Figure 6b shows a significant improvement as a result of applying the Experimental Scheme.

The impact on forecast skill for other weather parameters has also been assessed. Running the Reference Scheme rather than the Operational Scheme, we find no significant improvement to pressure forecasts or to temperature forecasts above the mid-troposphere. There is, however, an improvement to 1,000 hPa temperature forecasts that is measurable out to at least five days. As shown by *Hogan & Bozzo (2015)*, if we use the Experimental Scheme, then the skill of 1,000 hPa temperature forecasts is improved, but only by half as much as when running the Reference Scheme. This suggests that only half the improved skill from more frequent radiation calculations is associated with the better response to surface conditions, while the rest is associated with the response to changes in the atmosphere, which are not captured by approximate radiation updates.



**Figure 6** Difference in mean skin temperature ( $^{\circ}\text{C}$ ) at 12 UTC between reference forecasts with the radiation scheme run on the full model grid and at every time step (Reference) and (a) T639 forecasts with the radiation scheme run every 3 hours and on a reduced grid (Operational); and (b) the same as (a) but with approximate updates to the radiation fields on the full model grid and at every time step (Experimental). Forecasts were initialized from the analyses at 00 UTC every day for four months between 1 June and 30 September 2012, and values extracted 36 hours into each forecast.



**Figure 7** Two-metre temperature from (a) the Operational Scheme and (b) the Experimental Scheme, along with (c) the difference between the two. The data are for the same time and model resolution as shown in Figure 1, but for a larger area of the east coast of North America to put the large Long Island differences into context. Note that the exact locations of the largest errors in the Operational Scheme can change with both model resolution and model cycle (the latter if there is a change to the land-sea mask between cycles).

## Outlook

The method described here, for updating radiative fluxes and heating rates between calls to the full radiation scheme, successfully corrects coastal errors caused by the radiation scheme being run on a coarser grid than the rest of the model and less frequently than the model time step. It also improves the diurnal cycle of skin temperature over land. The approximate update method has been incorporated into IFS model cycle 41r2 and is expected to become operational in spring 2016.

This work highlights the importance of feedback from forecast users. ECMWF acted on it by advancing the science and designing, testing and implementing a solution. As illustrated in Figure 7, the results in this case indicate that there should be significant improvements to standard ECMWF forecast products, such as 2-metre temperature.

In terms of future developments, it should be recognised that the approximate updates described in this article are only needed because of the high computational cost of the current radiation scheme, and in particular the large number of spectral intervals it uses to represent gaseous absorption spectra. Reducing the accuracy of the spectral calculations has shown the potential to significantly improve the computational efficiency of the radiation scheme (Bozzo *et al.*, 2014). We plan to explore faster alternatives that retain as much of RRTMG's accuracy as possible, with the aim of developing a full scheme that is fast enough to be run much more frequently in space and time. Such a scheme would therefore be able to respond to the space–time variation not only in surface conditions but also in atmospheric state.

## Further reading

**Bozzo, A., R. Pincus, I. Sandu & J.-J. Morcrette**, 2014: Impact of a spectral sampling technique for radiation on ECMWF weather forecasts. *J. Adv. Modeling Earth Sys.*, **6**, 1288–1300. doi:10.1002/2014MS000386.

**Hogan, R. J., & A. Bozzo**, 2015: Mitigating errors in surface temperature forecasts using approximate radiation updates. *J. Adv. Modeling Earth Sys.*, **7**, 836–853. doi:10.1002/2015MS000455.

**Manners, J., J.-C. Thelen, J. Petch, P. Hill & J.M. Edwards**, 2009: Two fast radiative transfer methods to improve the temporal sampling of clouds in numerical weather prediction and climate models. *Q. J. R. Meteorol. Soc.*, **135**, 457–468.

**Morcrette, J.-J.**, 2000: On the effects of the temporal and spatial sampling of radiation fields on the ECMWF forecasts and analyses. *Mon. Weath. Rev.*, **128**, 876–887.

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European Centre for Medium-Range Weather Forecasts, Shinfield Park, Reading, RG2 9AX, England

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