Modelling atmospheric radative transfer: *ecRad* practical

Robin J. Hogan and Shannon L. Mason

European Centre for Medium Range Weather Forecasts, Reading, UK

March 17, 2021

1   Introduction

In this practical, the offline version of ECMWF's atmospheric radiation scheme *ecRad* (Hogan and Bozzo, 2018) will be used to gain an understanding of how radiative transfer is modelled, and how both radiative fluxes and atmospheric heating rates are sensitive to gas concentrations, clouds and aerosols. The input data consist of a slice through the atmosphere from the North Pole to the South Pole at a longitude of 5°E at 12 UTC on 11 July 2019, as represented by ECMWF's ERA5 reanalysis system. The data are stored at 137 levels from the surface to the middle mesosphere (a pressure of 1 Pa), and have been extracted at every 0.5° interval in latitude. This slice includes a range of atmospheric and surface conditions, from marine stratocumulus to deep convection, sea ice to a hot desert surface, and pristine marine air over the Southern Ocean to the dust-laden Saharan boundary layer.

2   Getting started

2.1   The command-line interface at ECMWF

Create and enter the directory in which you want to run the practical, and type

```
/home/rd/parr/public/create_ecrad_practical.sh
```

which will copy over some files and make a couple of symbolic links. To run the Python plotting scripts, you will also need to type

```
module load python3
```

If you start a new terminal or come back to an existing *ecRad* practical then you will need to reload the `python3` module.

2.2   The command-line interface outside ECMWF

This practical is designed to be used on a Unix or Linux system with a command-line interface. You will need to have Python version 3 installed on your system and accessible as `python3`.

Download and compile *ecRad* either from `https://confluence.ecmwf.int/display/ECRAD` or from GitHub (`https://github.com/ecmwf/ecrad`). You need version 1.3 or later. Enter the `practical` directory of the package and you are ready to go.

If *ecRad* has been installed in a directory you cannot (or wish not to) write to then you will need to create some symbolic links and copy over some data from the `practical` directory. Suppose that *ecRad* has been compiled in `/usr/local/ecrad-1.3` then this can be done by creating and entering the directory in which you want to run the practical, and then typing:

```
/usr/local/ecrad-1.3/bin/create_practical.sh
```

2.3   The Jupyter notebook

The other sections of this document assume you are using the command-line interface to both *ecRad* and the Python plotting scripts. Alternatively, you can run the entire practical from inside a Jupyter notebook, contained in `radiation_practical.ipynb` in the same directory:

1. A Python3 environment is required, with the following dependencies installed using a Python package manager such as pip or conda: jupyterlab, xarray, seaborn.

2. Install *ecRad* as described in section 2.2 and enter the `practical` directory.

3. In a terminal, type

   ```
   jupyter lab
   ```

   to start Jupyter Lab; your default web browser will open and act as the graphical user interface. (Note: If running Python remotely via ssh, you may need to run jupyter lab with the `--no-browser` option and set up port-forwarding so you can access Jupyter Lab from your local web browser.)

4. From Jupyter Lab, use the file browser on the left to navigate to the ecrad `practical` directory and open `radiation_practical.ipynb`. You may also open terminal and text editing windows within Jupyter Lab, to use while completing the practical exercises.

The content of the Jupyter notebook is very much the same as this document.

3   The control experiment

After getting set up as described above, list the contents of the directory by typing `ls -l`, which will show the following files:

ecrad_practical.pdf   This document.

ecrad   A symbolic link to the *ecRad* executable.

data   A symbolic link to the *ecRad* data directory.

config.nam   A Fortran namelist file for configuring *ecRad* in its control configuration.

era5slice.nc   A netCDF file containing the input data; some of its contents are shown in Figs. 1 and 2.

*.py   Python scripts for plotting the data; call with `--help` to get usage information, and see section 7.

ecradplot   A directory containing the Python library for plotting *ecRad* data.

radiation_practical.ipynb   The Jupyter notebook.

Now type the following:

```
./ecrad config.nam era5slice.nc control.nc
```

This runs *ecRad* on the input data using the configuration specified in `config.nam` and writes the output to `control.nc`.

To plot the data, type

```
./plot_output.py era5slice.nc control.nc
```

This produces the file `era5slice_control.png`. To plot profiles of the outputs at a latitude of $10°N$, type

```
./plot_output_profile.py 10 era5slice.nc control.nc
```

This produces the file `era5slice_control_profile_10N.png`. The following command plots the surface and top-of-atmosphere fluxes for all latitudes:
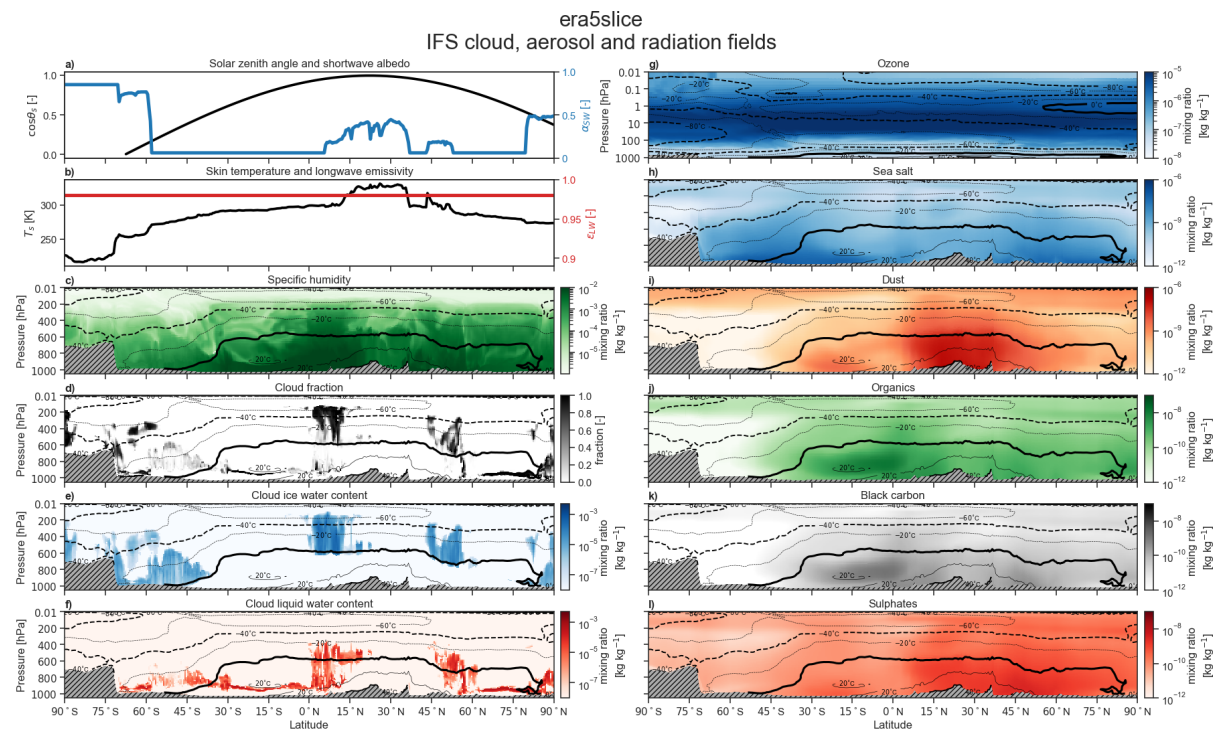
Figure 1: Surface and radiation (a & b), atmospheric composition (c & d), cloud (e–g) and aerosol (h–l) properties at longitude of 5°E at 12 UTC on 11 July 2019 from ERA5 data in `era5slice.nc`. Vertically-resolved data are overlaid with contours of atmoheric temperature. Hatching indicates regions below surface pressure. To produce this image yourself, type "`./plot_input.py era5slice.nc`", which will generate an image `era5slice.png`.

```
./plot_output_scalar.py era5slice.nc control.nc
```

producing the file `era5slice_control_surface_and_TOA.png`. Note that if additional output files are provided as arguments to `plot_output_scalar.py`, they will be overplotted in different colours.

Have a look at the figures that have been created using an image viewer such as `ristretto`, `eog` or `xv`. There are three types of variable:

- Upwelling and downwelling shortwave (solar) and longwave (thermal-infrared) irradiances, i.e. the radiative power passing through a horizontal surface at a particular height in the atmosphere, with units of W m^{-2}. The labels of the plots use the more common term "flux" instead of irradiance, and we will use the same for the remainder of this document. The net flux is defined as the downwelling minus the upwelling flux.

- Shortwave and longwave atmospheric heating rates (HR) computed from the vertical divergence of the net flux in pressure coordinates:

$$\text{HR} = -\frac{g_0}{C_p}\frac{\mathrm{d}F_n}{\mathrm{d}p}, \tag{1}$$

where F_n is the net flux (shortwave or longwave), p is pressure, g_0 is the acceleration due to gravity (standard gravity) and C_p is the specific heat of dry air. The plots use units of Kelvin per day (K d^{-1}).

- Cloud radiative effect, which is a flux minus the equivalent flux computed without clouds present in the profile, and is commonly used to quantify the warming or cooling effect of clouds on the climate system. *ecRad* output files contain both all-sky and clear-sky fluxes.

Questions

1. As anyone who has flown in an aeroplane knows, clouds (especially low-level clouds) are turbulent. Explain why, with reference to the radiation fields. Thick low-level clouds are present at 71°N and 15°S.
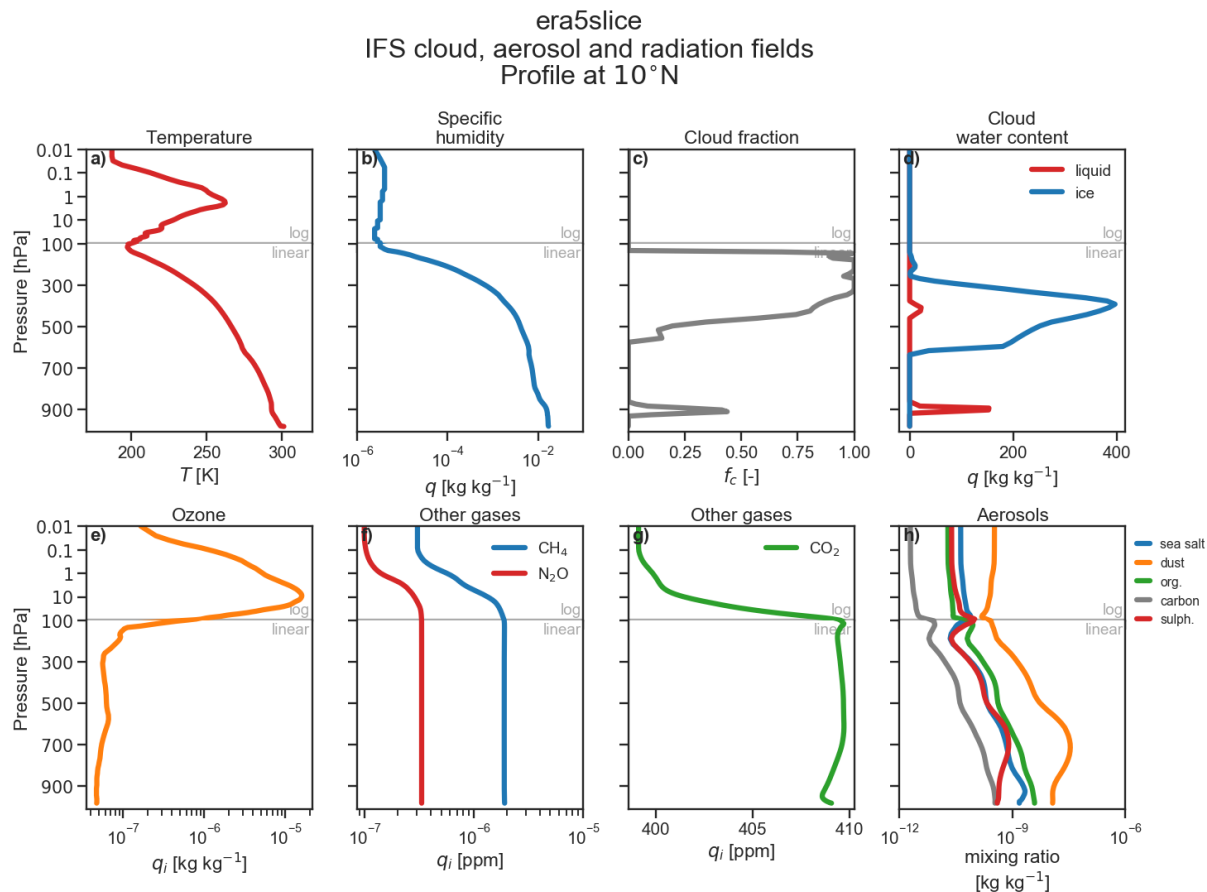
Figure 2: Profiles of thermodynamic (a & b), cloud (c & d), atmospheric composition (e–g) and aerosol (h) properties at a latitude of 10°N along the slice of ERA5 data in `era5slice.nc`. To produce this image yourself, type "`./plot_input_profile.py 10 era5slice.nc`", which will generate an image `era5slice_profile_10N.png`.

2. The net (shortwave plus longwave) heating rate at the stratopause (around 1 hPa) in the Tropics is around $+10\,\mathrm{K\,d}^{-1}$. Explain why you would not expect the temperature here a week later to be much warmer.

3. Explain why the shortwave cloud radiative effect drops sharply polewards of around 80°N, yet optically thick clouds are present all the way to the North Pole.

4 Greenhouse gases

The remainder of the practical consists of running *ecRad* with different configurations, plotting the change to fluxes and heating rates, and trying to understand the differences. This section is concerned with investigating the effect of changing the concentration of absorbing gases, but the general procedure for performing an experiment is the same in the next two sections which concern perturbing clouds and aerosols.

Let's investigate the radiative impact of doubling the concentration of carbon dioxide. Usually in the context of climate-change research, a doubled-CO_2 experiment is with respect to preindustrial concentrations (surface volume mixing ratio of around 280 ppmv), but since our control experiment is from 2019 (surface volume mixing ratio of around 412 ppmv) we will double the 2019 value. Copy the configuration file as follows

```
cp config.nam config_co2x2.nam
```

Edit the new configuration file with your favourite editor (e.g. `emacs` or `gedit`) to change these lines:

```
!co2_scaling = 1.0,
```

```
experiment_name = "Control",
```

to these:

```
co2_scaling = 2.0,
experiment_name = "2x CO2",
```

Then run *ecRad* on it:

```
./ecrad config_co2x2.nam era5slice.nc co2x2.nc
```

For a full list of available namelist parameters, see the User Guide at the *ecRad* web site[*]. Lines starting with the "!" character are ignored.

You can compare this experiment with the control as follows:

```
./compare_output.py era5slice.nc control.nc co2x2.nc
```

and plot selected profiles at a latitude of $-17°N$ with

```
./compare_output_profile.py -17 era5slice.nc control.nc co2x2.nc
```

Note that if multiple output files are provided as arguments then they will be overplotted, each using the same control. To compare the fluxes and cloud radiative effect at the surface and top-of-atmosphere at all latitudes, use

```
./compare_output_scalar.py era5slice.nc control.nc co2x2.nc
```

and again multiple output files can be provided as arguments.

Questions and exercises

1. Will the stratosphere warm or cool in response to increasing CO_2 and why?

2. By perturbing ozone concentrations (e.g. setting the namelist variable `o3_scaling` to 0.7), explain the mechanisms by which stratospheric ozone depletion leads to a cooling of the Earth system in the shortwave and the longwave.

3. By perturbing methane concentrations (e.g. setting the namelist variable `ch4_scaling` to 2.0), estimate how many times stronger a greenhouse gas methane is than carbon dioxide, *per molecule,* in terms of instantaneous longwave radiative forcing at top-of-atmosphere. You need to know that the 2019 concentration of methane is around 1.905 ppmv, and that the number of molecules of an ideal gas is proportional its volume mixing ratio with no dependence on the molecular mass. The 5th IPCC report stated that methane has a global warming potential 28 times that of carbon dioxide over a 100-year time period. Why might this be different from your number?

5 Clouds

Some of the following involve changing the algorithm used to perform the radiative transfer. The impact on computational cost (important for the configuration of a radiation scheme in a weather or climate model) can be estimated by prefixing the `./ecrad` command with `time` and looking at the `user` time reported after *ecRad* has finished.

Questions and exercises

1. Many models neglect scattering of longwave radiation by clouds for computational expediency. What is the change to longwave cloud radiative effect when longwave scattering is turned off (set `do_lw_cloud_scattering` to `false`)? Why is it of this sign?

2. The control simulation assumes sub-grid fluctuations in cloud water content such that the fractional standard deviation (the standard deviation divided by the mean) is one. What is the impact on shortwave and longwave cloud radiative effect when clouds are homogeneous (set `fractional_std` to 0.0) and why?

---

[*]https://confluence.ecmwf.int/display/ECRAD

3. The control simulation makes the assumption of *exponential-random* vertical overlap of clouds, which means that vertically separated clouds are randomly overlapped with respect to each other, while vertically contiguous cloud layers decorrelate with separation distance according to an overlap decorrelation length that varies with latitude. What is the impact of making the clouds in all layers overlap randomly (set `overlap_decorr_length_scaling` to 0.0) and why?

4. The control simulation uses the *Triplecloud* solver (Shonk and Hogan, 2008) for performing radiative transfer calculations in the presence of clouds, including the effect of sub-grid fluctuations in cloud water content. The operational ECMWF model uses the *McICA* solver (Pincus et al., 2003), which uses a stochastic model to generate sub-grid cloud distributions and can be selected by changing `sw_solver_name` and `lw_solver_name` both to `"McICA"`. Looking at the atmospheric heating rates (e.g. using `plot_output_profile.py` at 7°N), and the overall computational cost, explain the pros and cons of using McICA versus Triplecloud in an operational context.

5. Ice optical properties are an uncertain part of a radiative transfer scheme. Investigate the size of this uncertainty by switching from the default Fu ice optics model to that of Yi et al. (2013) (set `ice_model_name` to `"Yi"`). Is the main impact in the longwave or shortwave?

6. A unique property of *ecRad* is the availability of the *SPARTACUS* solver (Hogan et al., 2016) for approximately representing the 3D radiative effects of clouds, available by changing `sw_solver_name` and `lw_solver_name` both to `"SPARTACUS"`. What is the effect on both the radiation fields and the computational cost?

6   Aerosols

Questions and exercises

1. Turn off the interaction of radiation with aerosols by setting the namelist parameter `use_aerosols` to `false`. With reference to the surface fluxes, what do you think the impact of Saharan aerosols is on both daytime and nighttime surface temperature?

2. The *direct* downwelling solar radiation is that part of the solar radiation field that has not yet been scattered, and to a first approximation its value at a particular point in the atmosphere is proportional to $\exp(-\tau)$, where τ is the optical depth of the atmosphere above that point along a path towards the sun. Use a clear-sky profile of direct downwelling solar radiation over Africa to estimate the optical depth of the atmosphere with and without aerosols.

3. Concentrating solar power installations focus the direct solar beam to generate energy, whereas photovoltaic power installations can use all downwelling solar radiation. Which of these installations is most sensitive to dust storms?

4. From the effect of aerosols on shortwave radiation at the top-of-atmosphere, do aerosols have a warming or cooling effect on climate? What would the effect on climate be if you turned all the aerosols into black carbon (set each of the elements of `i_aerosol_type_map` to 11 and check the output of *ecRad*)? Why?

7   Quick guide to Python scripts

`plot_input.py <in.nc>`   Plot the main fields in the input file (`era5slice.nc` in this practical) to the image file `<in>.png`.

`plot_input_profile.py <lat> <in.nc>`   Plot profiles of a selection of properties in the input file at the specified latitude (in degrees north) to `<in>_profile_<lat>.png`.

`plot_output.py <in.nc> <out.nc>` Plot the fluxes and heating rates from the specified output file versus latitude and pressure, with the input file providing the temperature and latitude information, and save the result in `<in>_<out>.png`.

`plot_output_profile.py <lat> <in.nc> <out1.nc> [out2.nc ...]` Plot profiles of variables from one or more output files at the specified latitude, saving the result in `<in>_<out1>[_<out2>...]_profile_<lat>.png`.

`plot_output_scalar.py <in.nc> <out1.nc> [out2.nc ...]` Line plots versus latitude of upwelling fluxes at top-of-atmosphere, downwelling fluxes at the surface, top-of-atmosphere cloud radiative effect, cloud cover and surface direct shortwave flux, for one or more output files. The result is saved in `<in>_<out1>[_<out2>...]_surface_and_TOA.png`.

`compare_output.py <in.nc> <out1.nc> <out2.nc>` Plot the difference between the fluxes and heating rates in second output file (the experiment) and the first (the control), saving the result in `<in>_<out2>_vs_<out1>.png`.

`compare_output_profile.py <lat> <in.nc> <out1.nc> <out2.nc> [out3.nc ...]` Compare profiles at the specified latitude of the fluxes and heating rates in several output files, where the first is treated as the control, and write the output to `<in>_<out2>[_<out3>...]_vs_<out1>_profile_<lat>.png`.

`compare_output_scalar.py <in.nc> <out1.nc> <out2.nc> [out3.nc ...]` Compare net fluxes at top-of-atmosphere and the surface, as well as the cloud cover and surface direct shortwave flux, from several output files, where the first is treated as the control. The result is saved in `<in>_<out2>[_<out3>...]_vs_<out1>_scalar.png`.

References

Hogan, R. J., and A. Bozzo, 2018: A flexible radiation scheme for the ECMWF model. *J. Adv. Model. Earth Syst.,* **10,** doi:10.1029/2018MS001364.

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

Pincus, R., H. W. Barker, and J.-J. Morcrette, 2003: A fast, flexible, approximate technique for computing radiative transfer in inhomogeneous clouds. *J. Geophys. Res. Atmos.,* **108,** 4376, doi:10.1029/2002JD003322.

Shonk, J. K. P., and R. J. Hogan, 2008: Tripleclouds: an efficient method for representing horizontal cloud inhomogeneity in 1D radiation schemes by using three regions at each height. *J. Climate,* **21,** 2352–2370.

Yi, B., P. Yang, B. A. Baum, T. L'Ecuyer, L. Oreopoulos, E. J. Mlawer, A. J. Heymsfield and K.-K. Liou, 2013: Influence of ice particle surface roughening on the global cloud radiative effect. *J. Atmos. Sci.,* **70,** 2794–2807.