Climate Change - BE1

Radiation budget

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1 Introduction

The objectives of this module are:
- to develop a simple model for radiative heat fluxes at the earth's surface;
- to produce a simple program that will calculate these exchanges for any given location on the earth's surface, for any date, and at any time of the day;
- to use the program to calculate the daily variations in heat flux for the site of the Ecole Centrale, for different dates;
- to verify (where possible) the results of the calculations by comparison with other data.

2 Radiation budget

We will simplify the radiative transfer in the atmosphere by considering only two classes of radiation – shortwave radiation, emitted by the sun, and longwave radiation, emitted by the atmosphere and the earth.
The net radiation reaching the earth's surface R_N can be expressed as:

$$R_N = K\downarrow + K\uparrow + L\downarrow + L\uparrow \tag{1}$$

where:

$K\downarrow$: short wave radiation emitted downwards (+ve)
$K\uparrow$: short wave radiation emitted upwards (-ve)
$L\downarrow$: long wave radiation emitted downwards (+ve)
$L\uparrow$: long wave radiation emitted upwards (-ve)

We now need to develop models for these different terms.

3 Short wave radiation

The radiation emitted by the sun can be expressed in terms of the solar irradiance $S_0 = 1370\,\mathrm{W\cdot m^{-2}}$ (actually, in practice, $1360 \leq S_0 \leq 1380$).
This emitted radiation is then attenuated by:
- atmospheric turbidity; this will depend on the path length through the atmosphere;
- scattering and absorption in clouds; this will depend on the cloud cover.

An empirical model for the *transmissivity* of the atmosphere τ_K, for short wave radiation, is given by:

$$\tau_K = (0.6 + 0.2\sin\Psi)(1 - 0.4\sigma_{CH})(1 - 0.7\sigma_{CM})(1 - 0.4\sigma_{CL}) \tag{2}$$

BURRIDGE and GADD 1974

where:

Ψ : solar elevation angle (angle of sun above horizon)
σ_{CH} : cloud cover (0-1) for high level clouds
σ_{CM} : cloud cover (0-1) for middle level clouds
σ_{CL} : cloud cover (0-1) for low level clouds

Then the incoming radiation $K\downarrow$ is given by:

$$K\downarrow = S_0\tau_K\sin\Psi \quad \text{(during the day)} \tag{3a}$$
$$= 0 \quad \text{(at night)} \tag{3b}$$

4 The solar elevation angle

The solar elevation angle Ψ depends on:
- the latitude
- the longitude
- the solar declination angle (the angle of the sun above the equator)
- the time of day

4.1 A simple formula for the solar elevation angle

$$sin\psi = sin\varphi\ sin\delta_s - cos\varphi\ cos\delta_s\ cos\left(\frac{\pi t}{12} + \lambda_e\right) \tag{4}$$

where:

φ : latitude (North positive) [radians]
λ_e : longitude (East positive)[radians]
δ_s : the solar declination angle [radians]
t : the time of day, in UTC (Universal Coordinated Time) [hours]

For a description of Universal Coordinated Time, see Appendix. The relationship between UTC and local time, for a particular place and date, can be obtained from the website `www.worldtimebuddy.com`.

4.2 The solar declination angle

The solar declination angle depends on the date:

$$\delta_s = \varphi_r \cos \frac{2\pi(j_t - j_r)}{J} \tag{5}$$

where:

φ_r : latitude of the tropic of cancer (23.45° = 0.409 rad)
j_t : time of the year (= day[0-364] + hours[0-23]/24 + minutes[0-59]/(24*60))
j_r : day of the summer solstice (173)
J : no. of days in the year (365)

5 Emitted radiation

The emitted short wave radiation depends simply on the albedo α at the site:

$$K \uparrow = -\alpha K \downarrow \tag{6}$$

6 Long wave radiation

Many different simple models have been proposed for the net flux of long wave radiation in the atmosphere; here we present some of the simplest.

6.1 Burridge and Gadd (1974)

$$L^* = L \downarrow + L \uparrow = -97.28(1 - 0.1\sigma_{CH} - 0.3\sigma_{CM} - 0.6\sigma_{CL})\mathrm{W \cdot m^{-2}} \tag{7}$$

6.2 Swinbank (1963) and Paltridge and Platt (1976)

$$L^* = -\sigma T^4(1 - 0.94 \times 10^{-5} T^2) + 0.3\varepsilon_{cb}\sigma T_{cb}^4\sigma_c \tag{8}$$

where:

σ : Stefan-Boltzmann constant (5.67×10^{-8} W · m^{-2} · K^{-4})
T : air temperature at the ground
ε_{cb} : emissivity at the cloud base
T_{cb} : temperature at the cloud base
σ_c : cloud cover (0-1)

Work

Work in groups of two or three (maximum).

1. Write a program to compute the daily variation of radiation fluxes, for a position anywhere on the earth's surface, for any given date. The input parameters for the program should be:
   – the coordinates (longitude and latitude) of the site;
   – the albedo for the site;
   – the date;
   – cloud cover data.

   The output from the program should be:
   – the hourly variations in the incoming shortwave radiation, the outgoing shortwave radiation, the net longwave radiation and the net radiative flux for the site, for a period of 24 hours.

   The program could be written using Excel, Matlab, Python or any other language of your choosing.
2. Use your program to compute radiation budgets for the 5 cases provided in §8, and compare your results with the measured data for those cases. The data can be downloaded from *Moodle*: `23_ING_S09_MOD806_5/BE/BE1/Radiation_profiles.xlsx`. Comment on the differences between your simulations and the measured data. How sensitive are the simulations to the different assumptions that you have had to make to model the different cases?
3. Use your program to investigate different situations, and the influence of different parameters. The results of your calculations should be plotted.

7 Report

1. This activity will be marked, and the mark will count for a proportion of the final mark for the module.
2. Reports should be written by group of two or three students.
3. The report should be written in English. Maximum 10 pages.
4. The report should be deposited on Moodle as a machine-readable pdf file.
5. The deadline for submitting the report is 23h59 on Monday 8th January 2024.

8 Measured data

This section provides some examples of measured radiation fluxes, for different locations around the world, with different types of surface cover, at different moments during the year.

Saskatchewan Figure 1 shows the radiation flux profile for Matador, Saskatchewan (50 °N) on the 30th July 1971. The land cover consisted principally of grass, 0.2 m high. The sky was cloudless in the morning, with cloud cover increasing from late afternoon until evening.

Antarctica Figure 2 shows the radiation flux profile for Mizuho Station, Antarctica (70 °S) on the 13th November 1979. The land was covered in snow.

Lake Ontario Figure 3 shows the radiation flux profile for Lake Ontario, near Grimsby (43 °N) on the 28th August 1969, on a day with cloudless skies.

Washington Figure 4 shows the radiation flux profile for Cedar River, Washington (47 °N) on the 10th August 1972. The fluxes were measured above a forest of Douglas fir trees, 28 m tall.

Rothamsted Figure 5 shows the radiation flux profile for Rothamsted, England (52 °N) on the 23rd July 1963. The fluxes were measured above a field of barley.

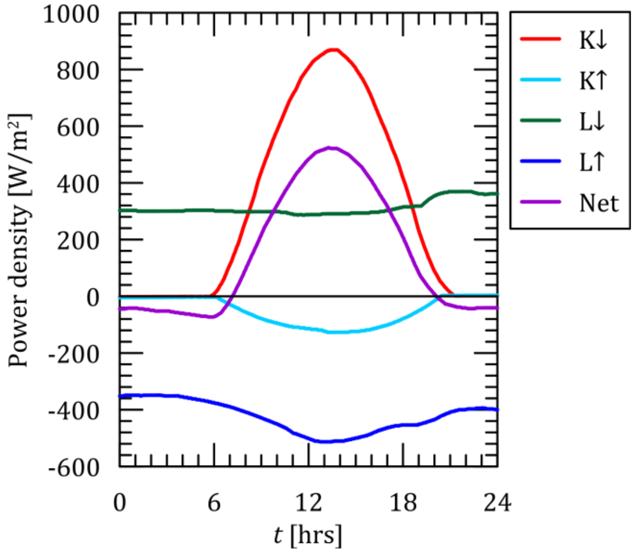

FIGURE 1: Matador, Saskatchewan

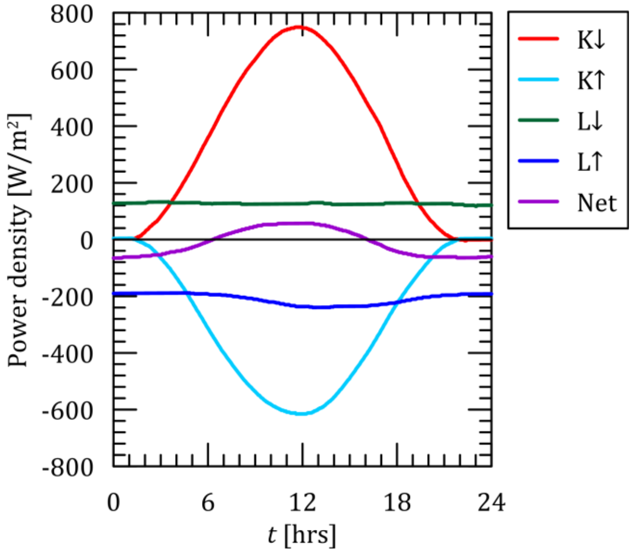

FIGURE 2: Mizuho Station, Antarctica

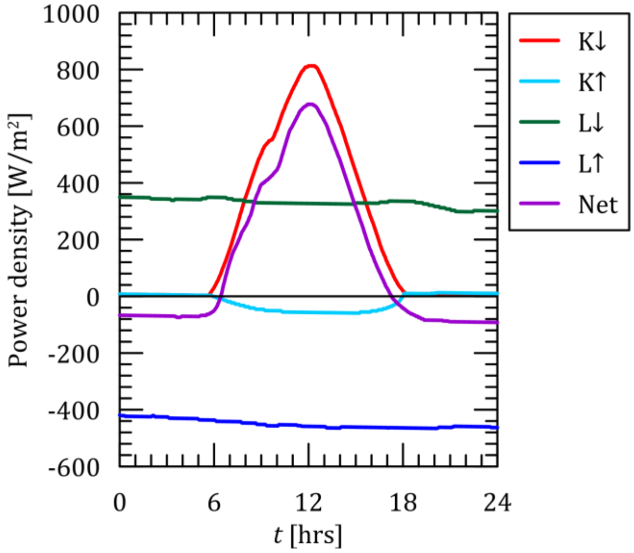

FIGURE 3: Grimsby, Lake Ontario

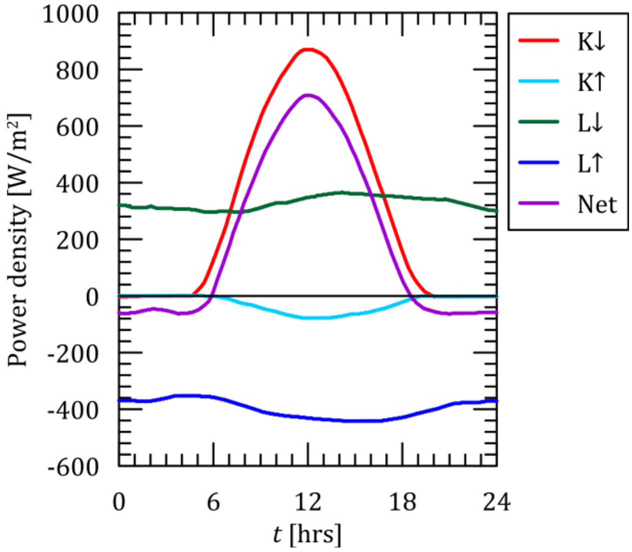

FIGURE 4: Cedar River, Washington

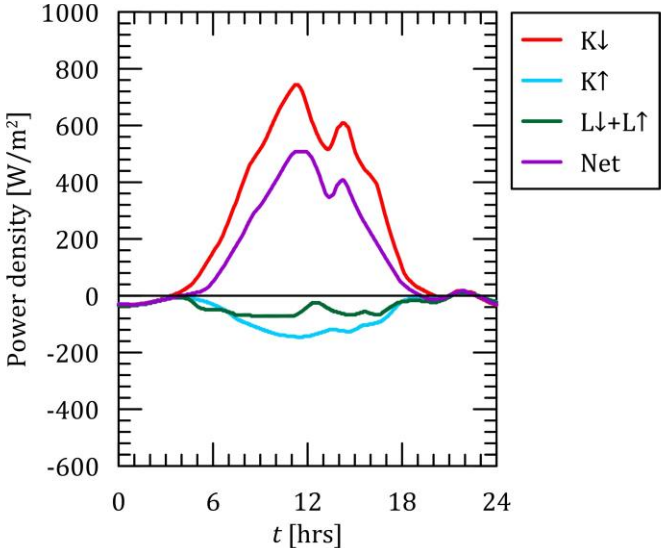

FIGURE 5: Rothamsted

References

BURRIDGE, D. and GADD, A. (1974) *The Meteorological Office Operational 10 Level Numerical Weather Prediction Model (December 1974)*. Tech. rep. 12 and 48. Brit. Met. Office Tech. Notes.

PALTRIDGE, G. and PLATT, C. (1976) *Radiative Processes in Meteorology and Climatology*. Elsevier.

SWINBANK, W. (1963) Long wave radiation from clear skies. *Quart. J. Roy. Met. Soc.* **89**, pp. 339–348.

Appendix A
Coordinated Universal Time

A1 Introduction

If we want to relate calculations of solar radiation to observations at a particular location and time, we have to be able to relate the local time system to that of the sun, which is determined by its position relative to the location concerned. To understand this, it is convenient to work in terms of the solar noon, which is defined as the moment at which the sun is at its highest point above the horizon on its daily trajectory, relative to an observer on the surface of the earth.
We can then identify three distinct timescales:

- solar time – the time measured relative to the local solar noon;
- *UTC* – Coordinated Universal Time, which is the time relative to the solar noon at the prime meridian (Greenwich, in London);
- civil time – the time shown on local clocks.

Any measurements of solar radiation are likely to be presented in terms of the civil time at the measurement location, so we need to be able to relate civil time to solar time, and it turns out that the easiest way to do this is using the *UTC*.
The civil time at any place on the earth's surface is essentially defined by political and cultural considerations, and is therefore largely arbitrary. Most societies prefer to have more daylight hours after midday than before, so the local time of midday is usually offset relative to the solar noon. For example, in London in September, the solar noon occurs at 1pm (as shown on local clocks), meaning that there will be as many daylight hours before 1pm as after 1pm. (In January, with winter time, the solar noon in London will occur at midday, so there will be as many hours of daylight before midday as after midday.)
The biggest difficulty that we have when we try to link solar time to civil time is that there is no general objective link between them – the relationship between solar and civil time varies as a function of local cultural and political choices.
The solution to this is in two parts – firstly, we use a timebase that is the same everywhere, independent of location and local political and cultural considerations. This is Coordinated Universal Time – *UTC*. (The abbreviation *UTC* was chosen as a compromise between the English – *CUT* – and the French, Temps Universel Coordonné – *TUC*.) *UTC* is defined as the time on the prime meridian (Greenwich, in London) relative to the solar noon. So 12h00 *UTC* will always give the time at which the sun is at its highest position in the sky, on the prime meridian. (*UTC* is therefore similar to Greenwich Mean Time – *GMT* – except that *GMT* is now defined as a timezone, whereas *UTC* is just a standard reference time.)
The relationship between civil time and *UTC* can be found from various websites, for almost any location and any date. A good source of information is: `www.worldtimebuddy.com` which will allow you to enter a town or city, and a date, and it will then provide the *UTC* time corresponding to the civil time at the specified location. The site takes into account factors such as Winter and Summer time, so it is important to use the full date (day, month and year) rather than just the day and the month, since the changeovers between Winter and Summer time do not occur on the same date every year.
Once we know the *UTC* we can calculate the local solar time because this only depends on the longitude of the location of interest – for every 15° West, relative to the prime meridian, solar noon is delayed by 1 hr.

A2 Some Examples

A2.1 Lyon, 20th September 2017

Lyon has a longitude of 4.8357° East, and `www.worldtimebuddy.com` shows that the time in Lyon on that date is 2 hours ahead of *UTC* (Fig. A1). So, when the sun is overhead at the prime meridian (Greenwich) it will already be 14h00 in Lyon. At what local time, then, will the solar noon occur in Lyon? Since Lyon is 4.8357° to the East of the prime meridian, solar noon will occur $4.8357°/180° \times 12$ hrs $= 0.3228$ hrs $= 19.34$ mins before solar noon on the prime meridian. So solar noon in Lyon will occur at about 13h41 local time.

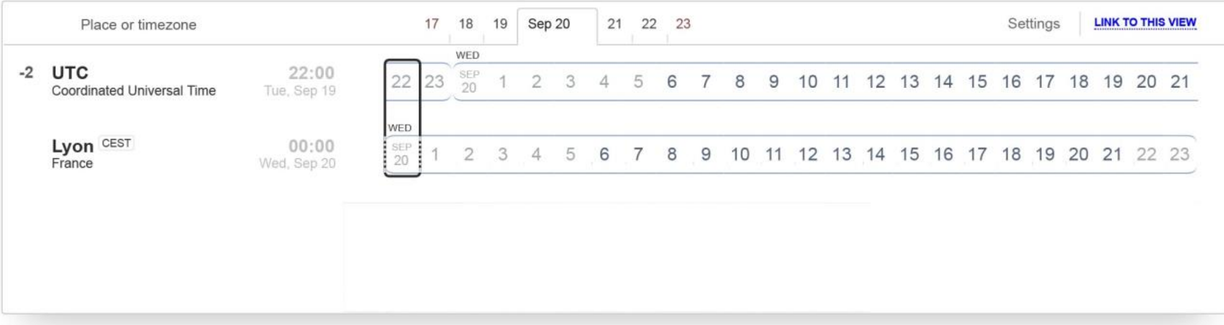

FIGURE A1: World Time Buddy *UTC* for Lyon, 20/9/2017

A2.2 Matador, Saskatchewan, 30th July 1971

In order to use www. worldtimebuddy. com we have to find a town or city near to the measurement site that is included in the database. Looking at a map of the surrounding area (Fig. A2) we can see that Saskatoon is probably the nearest large settlement likely to be registered in www. worldtimebuddy. com but we could also check for North Battleford and Medicine Hat.

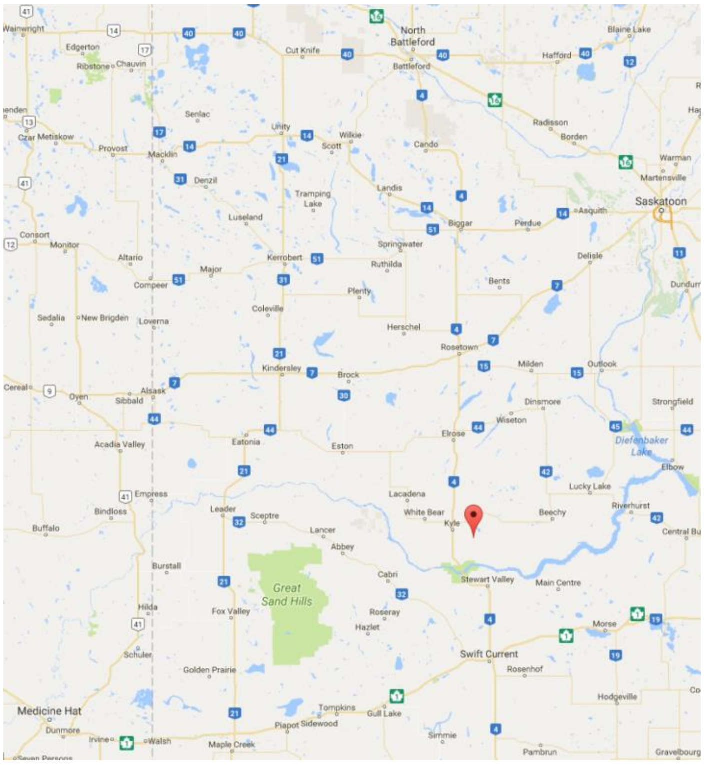

FIGURE A2: Map of the area surrounding Matador, Saskatchewan (*Google Maps*)

The results are shown in Figure A3; we can see that the local time at both North Battleford and Saskatoon is 6 hours behind the prime meridian, whereas Medicine Hat is in a different time zone and the local time there is 7 hours behind the prime meridian.

FIGURE A3: World Time Buddy *UTC* for Saskatoon, North Battleford and Medicine Hat, 30/7/1971

Now since Matador is located 107.951° to the West of the prime meridian, solar noon will occur $107.951°/180° \times 12\,\text{hrs} = 7.1967\,\text{hrs} = 7\,\text{hrs}, 12\,\text{mins}$ after solar noon at the prime meridian. When it is solar noon at the prime meridian it is 06h00 at Matador, so the local time for solar noon at Matador will be 13h12. Consulting the Excel data for Matador, the maximum incoming solar radiation is measured at 13h20, so this agrees well with the measurements.