VARIATION IN LIGHT INTENSITY AT DIFFERENT LATITUDES AND SEASONS, EFFECTS OF CLOUD COVER, AND THE AMOUNTS OF DIRECT AND DIFFUSED LIGHT

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Thank you for your welcome and introduction. This morning I want to give an overview of some of the key aspects of light. In particular how much the amount of light is influenced by latitude, the time of day, cloudiness, and then a bit about diffuse and direct radiation.

Before we do that it might be worth taking a step back, and asking 'What is the function of light in forestry? What does light provide?'

Light is obviously our key **energy source**. We usually focus on its role in **photosynthesis** and I believe the next speaker is going to cover this in further detail. However solar radiation is also vital for **heating** up the soil and providing energy for processes such as evaporation. Other important effects of light include:
- **Phototropism**: the direction from which the light comes can affect the direction in which plants grow.
- **Photoperiodism**: changes in daylength (i.e. the time between sunrise and sunset), and the associated changes in the ratio of red light to far red light, can affect the developmental responses of trees.
- **Mutagenesis**: some forms of solar radiation such as ultra-violet light, can have a negative effect on trees by causing genetic mutations.

So when we are talking about light there are additional effects beyond the direct photosynthesis effect.

All solar radiation comes from the sun, which has an average surface temperature of about 5,500°C, and it is this temperature that determines many of the characteristics of solar radiation. At a distance of 150 million kilometres the amount of radiation that we receive at the surface of the atmosphere closest to the sun (termed the solar constant) is about 1,370 Watts/m^2. That is 1,370 Joules of energy arriving every second per m^2. If we then assume that we are close to the equator and it is a cloud free day about 13% of that solar radiation may be absorbed by the atmosphere and 13% scattered. Hence the direct radiation that we receive at the Earth's surface close to the tropics in the middle of a cloudless day is about 75% of the level of the radiation at the surface of the atmosphere (Fig. 1). The maximum amount of solar energy on the Earth's surface is therefore about 1,000 joules per m^2 per second.

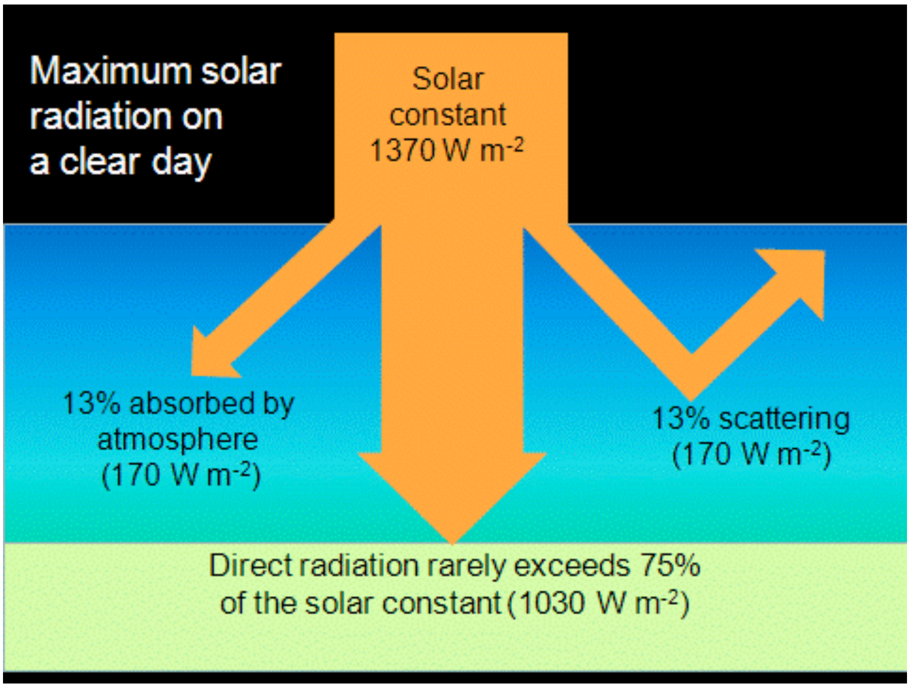


Fig 1. Schematic diagram showing the relationship between the solar constant (at the point in the atmosphere nearest the Sun) and radiation at the Earth's surface.

It is not just the amount of energy that is important, but also the quality of the energy and, because of the temperature of the sun, the radiation coming from the sun has specific wavelength characteristics (Fig 2).

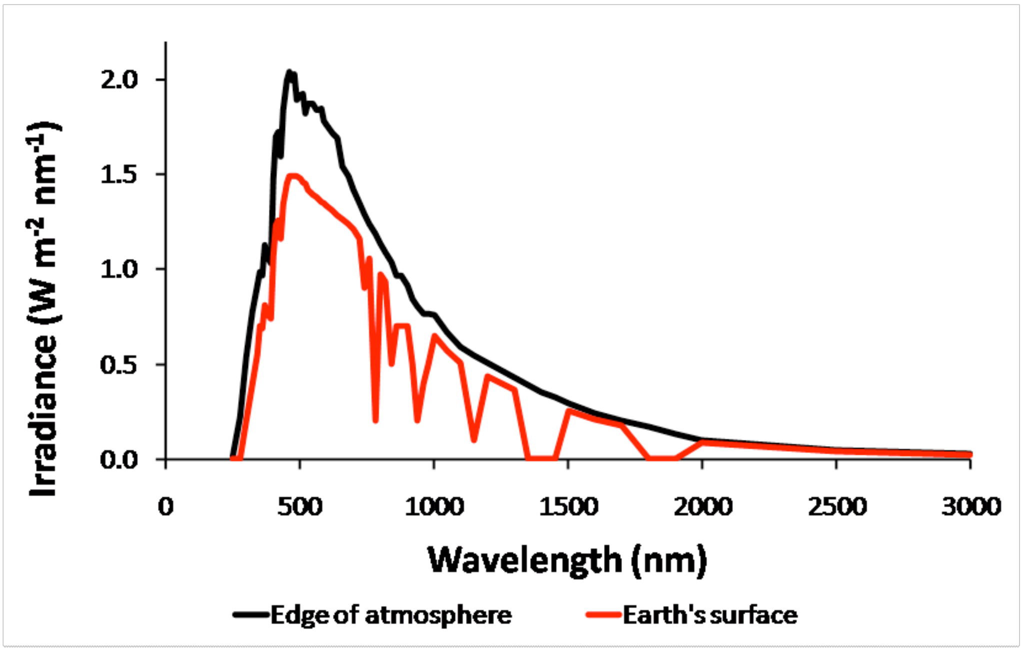


Fig 2. Schematic diagram of the variation in the energy content of solar radiation with wavelength at the edge of the atmosphere and at the Earth's surface (derived from Garg & Prakash, 2000, and NASA, 2008).

For solar radiation the maximum amount of energy per unit wavelength peaks at a value of about 500 nanometres (nm), but ranges up to about

3,000 nm. All of this radiation has relatively short wavelengths and so is called short-wave radiation. There is also long-wave radiation, which is the heat emitted by the earth back into the atmosphere and this has a wavelength greater than 3,000 nm.

If we look at what we actually receive at the surface of the earth, some of the wavelengths are taken out by atmospheric oxygen, water-vapour, and ozone. So there are particular wavelengths that we don't receive, with a significant reduction in the level of ultra-violet and infra-red light. The atmosphere also has the effect of preferentially scattering more blue than red light, and hence on a summer's day we perceive that the sky is blue.

Generally the human eye can see light between a wavelength of 400 & 700 nm ranging from blue through green and yellow to red. These are also the wavelengths that the chlorophyll within plants can use for photosynthesis, and hence solar radiation between 400 and 700 nm is called the photosynthetically active radiation (PAR). When we look at some of the instruments later in the day you will see that they can either measure the total amount of short-wave radiation (0-3000 nm), or the amount of PAR. As a general rule of the thumb 50% of the short-wave radiation energy is within the PAR range.

So far we have assumed no clouds, we have assumed that the Earth doesn't rotate, and that it doesn't go round the Sun. This is not true.

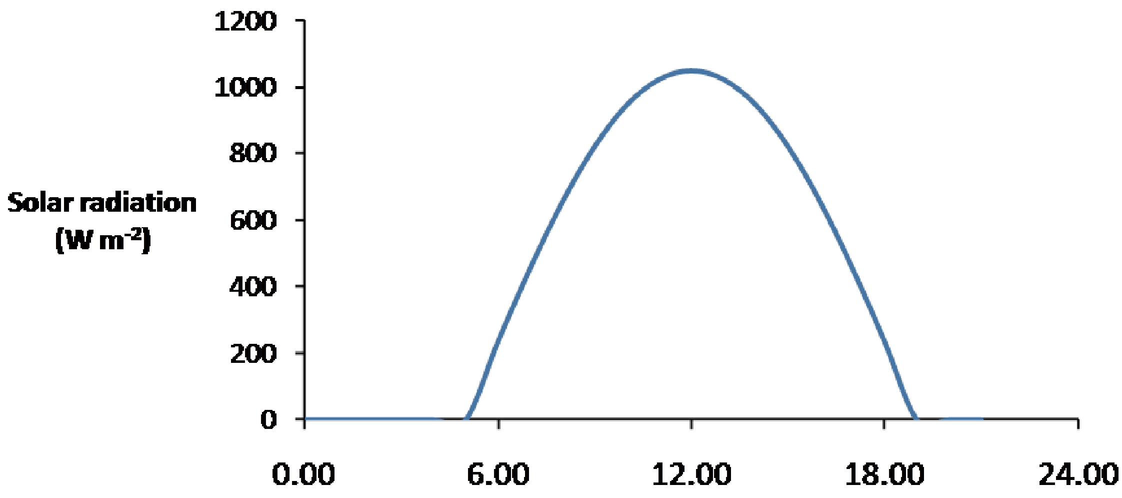


Fig 3. Diurnal pattern in absence of cloud cover in Israel (32°N) in summer (after Monteith and Unsworth, 1990).

Because the Earth rotates, we can only receive the full effect of the 1,370 W/m^2 for a part of each day and, because the area of a sphere is 4 x the area of a disc, the average radiation across all of the Earth's atmosphere at any particular time is about 340 W/m^2. So on a diurnal basis, for a location relatively close to the equator on a clear day we would expect zero solar radiation before sunrise and after sunset and about 1,000 Joules of shortwave radiation (0-3000 nm) per second coming in at noon (Fig 3). The general pattern follows a sine function.

As well as spinning on its axis the Earth goes round the Sun in a counter-clockwise direction as viewed from our north. This wouldn't have a major effect on solar receipts, except that the Earth is spinning at an angle of about 23½° in relation to the sun. Hence although at the autumn and spring equinoxes each part of the Earth will get 12 hours daylight, during the winter in the northern hemisphere the number of hours of daylight will be substantially reduced. Conversely in the summer the hours of daylight will be greater. In addition there is also a slight off-set in the Earth's orbit, so on average during the northern hemisphere winter the Earth receives 6% more solar radiation than in the summer. That means that winters in the northern hemisphere are slightly milder than they are in the southern hemisphere, for a given latitude.

The effect of the above is that the daylength (the period between sunrise and sunset) varies consistently with latitude and time of the year (Fig 4). In Figure 4 day 1 equates to the 1st of January, through to December. Interestingly there are 5 days missing from this graph, so scientists must have holidays as well! If you are on the equator the daylength is a constant 12 hours throughout the year. If you are 50°N, say in southern Cornwall, you go from about 8 hours day length in the middle of winter up to about 16 in the middle of summer. If you are in Shetland, which is about 60°N, the daylength ranges from about 3 hours in the middle of winter up to about 21 hours in the middle of summer.

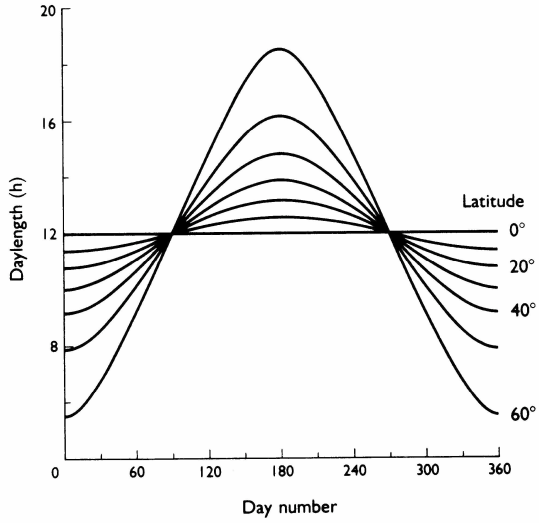


Fig.4 Length of day (sunrise to sunset) in northern latitudes as a function of day of the year (Loomis and Connor, 1996).

The effect of latitude features in a number of ways, as Rodney indicated. Firstly, if we are at a latitude away from the equator the area over which the solar beam is spread increases. For instance at a latitude of about 50°N solar radiation is spread over an area 35% larger than it is at the equator, so the potential receipt at a given unit of time will decrease accordingly. In addition, the solar radiation will also travel through a greater width of atmosphere and that too will decrease the amount of solar radiation, even at midday.

The effect of this can be seen for the amount of solar radiation coming in, for southern England, for 3 days during the year (Fig 5). It is stylised, but during a typical day in September we will experience zero solar radiation before sunrise up to a maximum of about 500 W/m^2 at noon before declining again. At the end of June it is up to about 800 W/m^2, and in December the maximum value may be about 150 W/m^2. If you calculate the area under each of these curves, i.e. multiply the amount of energy coming in per unit time against the amount of time, you can calculate the total amount of energy coming in per day.

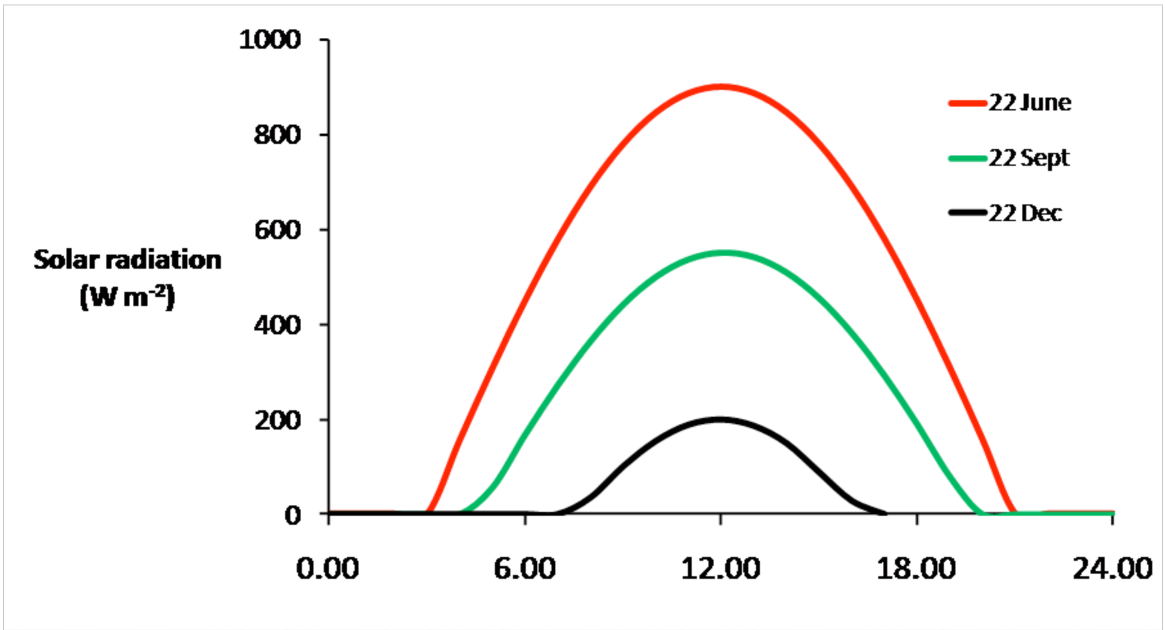


Fig 5. Schematic diagram showing the diurnal variation in the solar radiation receipt on three days with no cloud at a latitude of 52°N. This approximates to a sinusoidal function.

The daily solar radiation receipt therefore follows an annual pattern (Fig 6). At Kampala, in Uganda, which is close to the equator, the amount of radiation coming in is relatively constant throughout the year. At the edge of the atmosphere, there are about 35 MegaJoules coming in per m^2 each day. If you are in Egypt in the middle of the summer you will get about 40 MJ at the edge of the atmosphere, and even in London, as Rodney was saying, on a summer's day you can get as much energy coming in as in a tropical environment. In London the high solar radiation receipt in mid-Summer is achieved over a longer daylength.

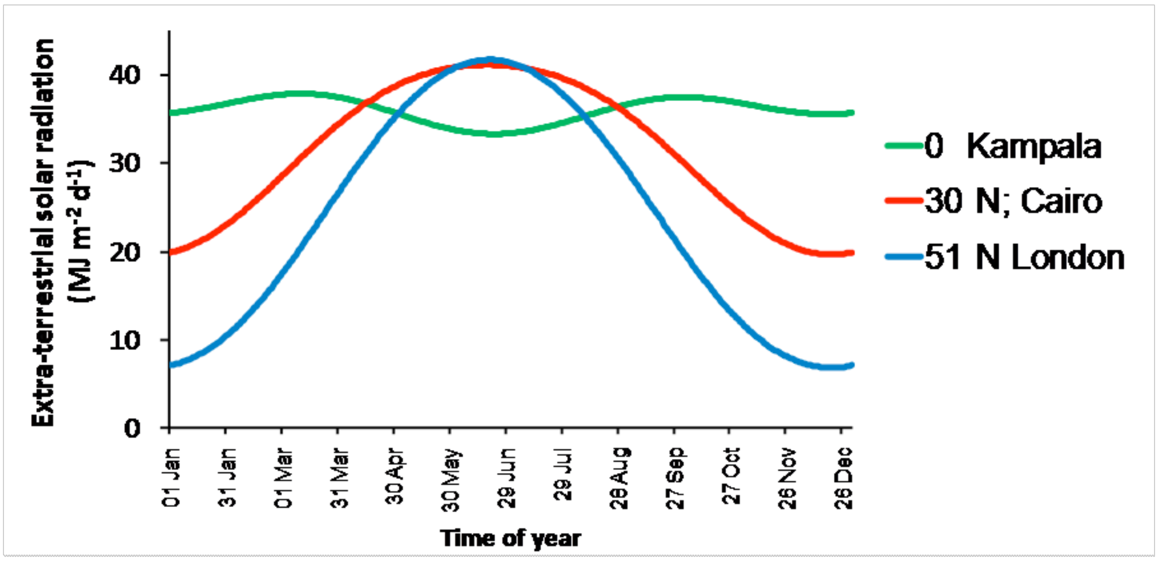


Fig 6. Schematic diagram showing the annual variation in the extra-terrestrial solar radiation receipt at three latitudes.

Within the UK, changes in latitude (50 to 60°N) can affect the daily extra-terrestrial solar radiation receipt, particularly during the winter (Fig. 7). In the summer it doesn't really matter where you are in the UK in terms of the potential daily radiation because although the intensity may be less in the north, this is compensated by a longer daylength. It is when you come to the winter that it gets worse, if you are living in Shetland. In the winter, whereas we have got about 8 MJ/m^2 of radiation at the edge of the atmosphere in Penzance, it decreases to about 2 in Shetland. So if you are suffering from SAD it could make a big difference where you live in the UK.

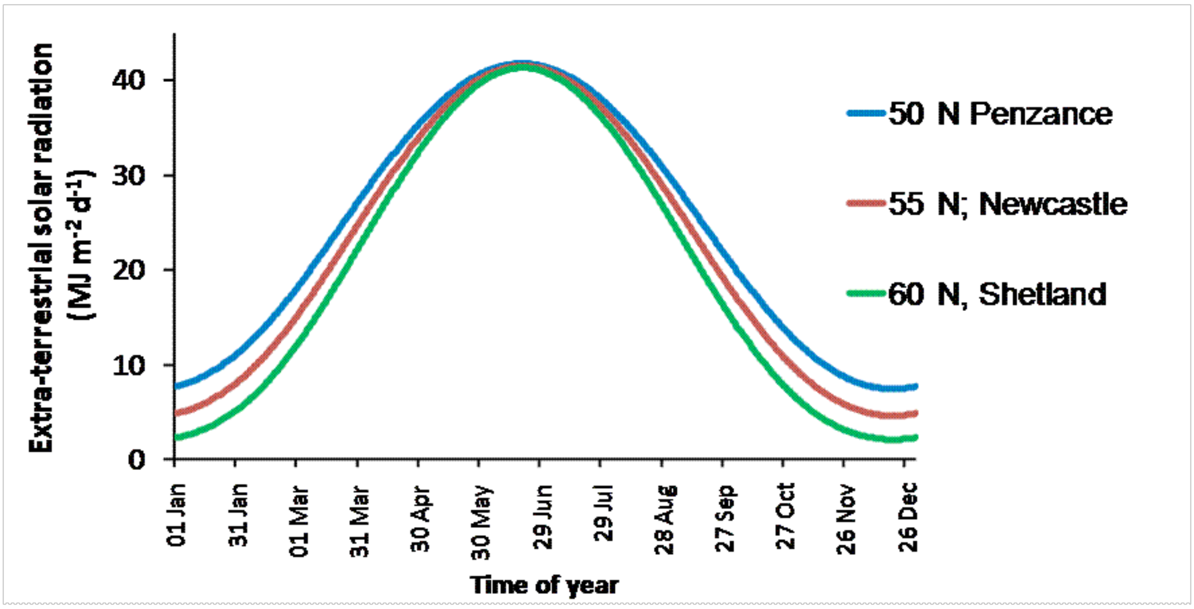


Fig 7. Schematic diagram showing the annual variation in the extra-terrestrial solar radiation receipt at three latitudes in the UK (50°N: Penzance; 55°N: Newcastle, and 60°N: Shetland).

If we now consider the actual solar radiation received at the earth's surface, we also have to include the effect of cloud cover. As I said, even on a clear day we have losses of about 25%, if we have light cloud that could increase to a 50% loss, if the cloud is thicker you may have losses of 75%, and if you have got a dark thundery sky then you may only be receiving 5 – 10% of the potential radiation.

Figure 8 shows some results for the Bedfordshire area: we have a predetermined level of radiation at the edge of the atmosphere determined by the latitude and the day of the year. There is then a potential level of radiation assuming no cloud cover, but the actual radiation indicated in red is determined by the level of cloud cover on a given day.

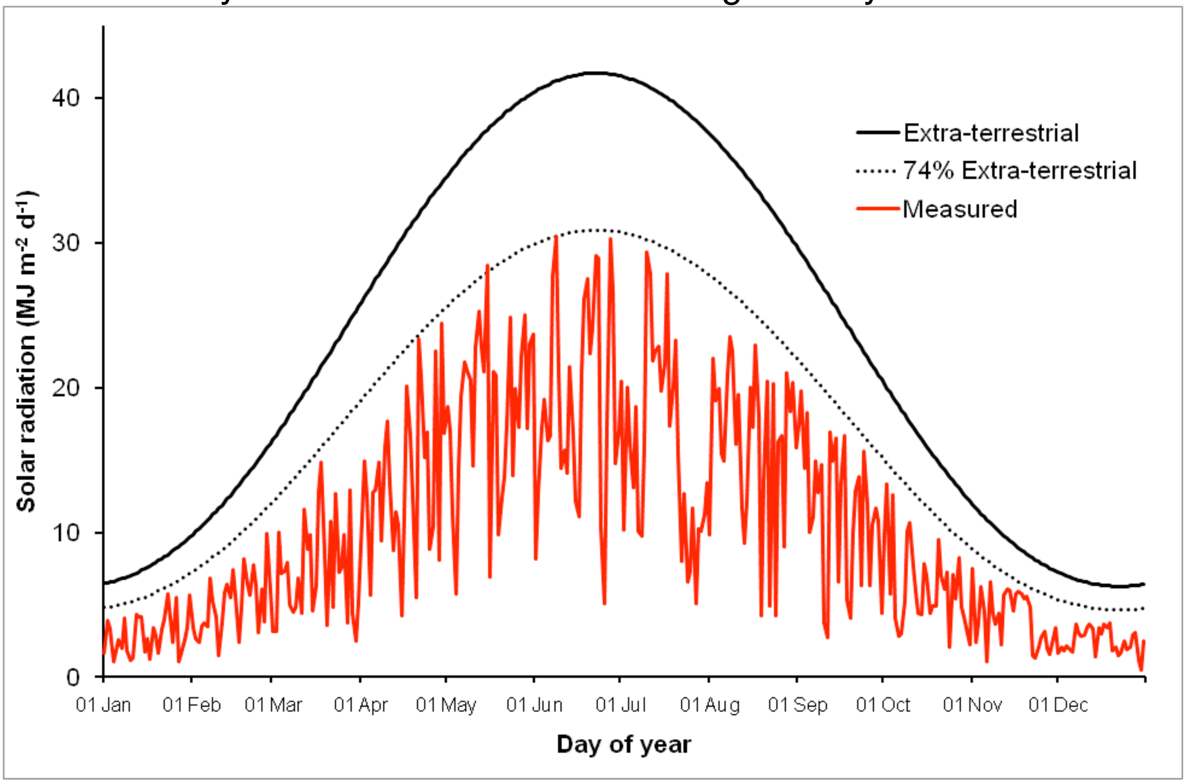


Fig 8. Annual variation in daily extra-terrestrial solar radiation and the measured solar radiation for a location in Bedfordshire in 2005.

There are important geographical differences in the amount of cloud cover, so comparing similar sorts of latitude, if you are on the Essex coast you might be expecting an annual average about 4 hours of sunshine per day whilst in the Welsh mountains you will be receiving on average 1 hour per day less sunshine. And if you live in the Scottish Highlands then you would lose another hour's sunshine a day on average (Met Office, 2009). So then if we express that in terms of the amount of energy coming in per day we have a spread across the UK ranging from max levels (averaged over the year) of 10 MJ/m^2 in the South West down to about 7 MJ/m^2 in the Shetland area (JRC, 2009).

Rodney asked me to say a little bit about diffuse and direct radiation: that is that a certain proportion of the radiation comes directly from the sun and a proportion is scattered on its ways to the Earth's surface. A general rule of thumb is that the greater the amount of solar radiation then the higher the proportion of direct radiation. Various authors have established relationships that show that the proportion of diffuse radiation as a proportion of the total radiation follows a relatively consistent relationship with the actual level of solar radiation compared with the extra-terrestrial solar radiation (Fig. 9). So if you know how much radiation you are receiving compared to the extra-terrestrial radiation, you can estimate the amount or proportion of diffuse radiation.

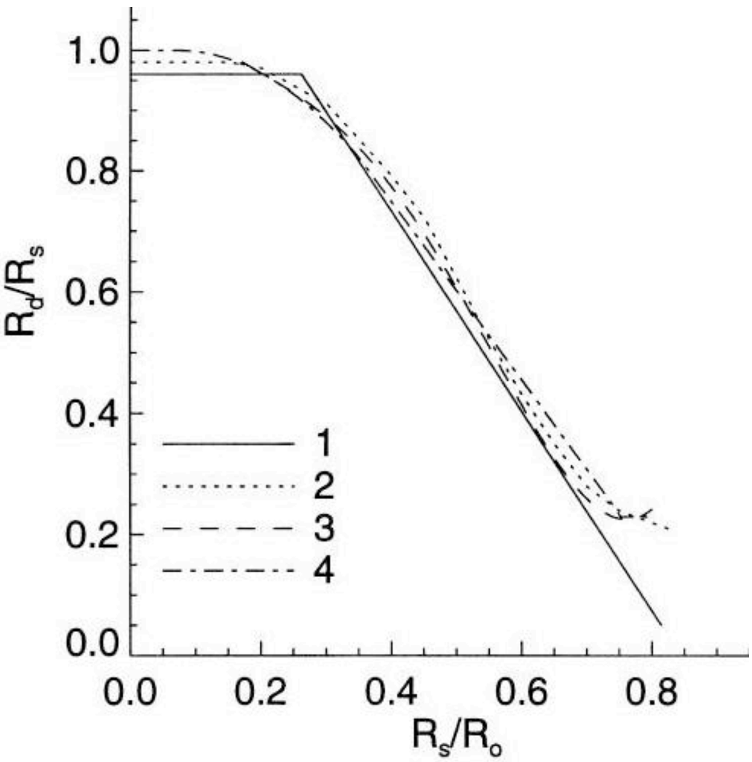


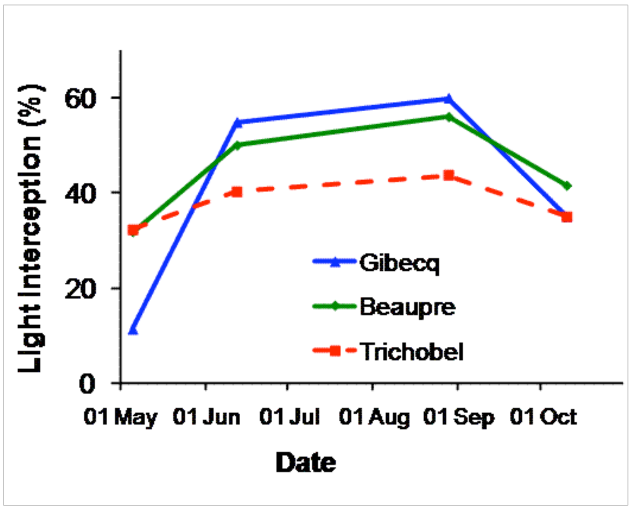
Fig 9. Relationship between the proportion of diffuse radiation and the incident radiation as a proportion of extra-terrestrial radiation (Roderick, 1999). As the incident radiation expressed as a proportion of the extra-terrestrial radiation (R_s/R_o) declines, so the proportion of diffuse radiation increases (R_d/R_s)

A few years ago we took some measurements at Cranfield University using a hemispherical camera similar to the one that Delta-T is displaying at the back of the lecture theatre. This was for widely-spaced 11-year-old poplar and we used the camera to estimate the amount of direct radiation and the amount of diffuse radiation coming in each day. We took a picture of the canopy from the ground, looking up. Once you have a photograph like this you can trace the direction of the sun during the day, make calculations of how much direct radiation will be received at that particular location, and also the amount of diffuse radiation.

Fig 10. Example of a hemi-spherical photograph taken below an eleven-year-old widely-spaced poplar plantation (10 m x 6.4 m spacing)

In these 11 year old poplar stands we had three hybrids. The amount of light being intercepted by the tree changes through the year as they come into leaf. There are significant differences between different hybrids of poplar, but generally we can see that Beaupré and Gibecq were the two hybrids that intercepted the most radiation during the middle of summer (Fig 11a). Then if we look at the proportion of diffuse radiation below the canopy, it was higher when measured under those hybrids (Fig 11b).

a) Light interception by trees



b) Proportion diffuse radiation at soil surface

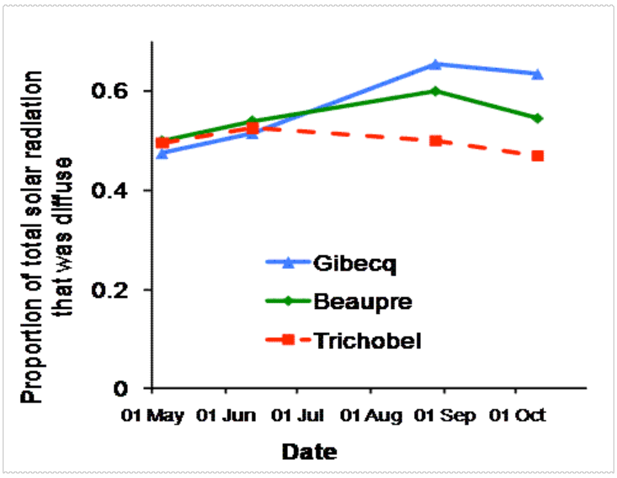


Fig 11. a) Total light interception by three poplar hybrids on four occasions between May and October 2003 (n= 45) and b) the proportion of solar radiation at soil surface that was diffuse (Pascal, 2004).

So I hope this whistle-stop tour has been illuminating. We started on a clear day, then incorporated the rotation of the earth on its axis, the rotation of the earth around the Sun, and then the effects of cloud cover. It is primarily the interaction of these three factors that determine the amount and quality of solar radiation that is received at any instance at any location in the UK.

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REFERENCES

Garg, H.P. & Prakash, J. (2000) Solar Energy: Fundamentals and Applications. New Delhi: Tata McGraw-Hill.

JRC (2009). Yearly total of horizontal global radiation. http://mappery.com/maps/United-Kingdom-Solar-Radiation-Map.thumb.png

Loomis, R.S. & Connor, D.J. (1992). Crop Ecology. Cambridge University Press. 538 pp.

Met Office (2009) UK mapped averages. http://www.metoffice.gov.uk/climate/uk/averages/

Monteith, J.L. & Unsworth, M.H. (1990). Principles of Environmental Physics. 2nd Edition. Edward Arnold. 291 pp.

NASA (2008) Man-Systems Integration Standard Volume 1. http://msis.jsc.nasa.gov/sections/section05.htm#_5.7_RADIATION

Pascal, P. (2004). Light and water use in a poplar silivoarable system. MSc by Research Thesis. Cranfield University. 143 pp.

Roderick, M.L. (1999). Estimating the diffuse component from daily and monthly measurements of global radiation. Agricultural and Forest Meteorology 95: 169 – 185.