Seasonal & Daily Temperatures

Introduction

In this section we shall concentrate on how variation in energy input to the Earth's atmosphere controls the fluctuations in temperature that occur daily, seasonally and in the long term, namely over millennia. The Sun drives the weather system and hence the relation between the Earth’s surface and the Sun is critical. The long time scales are the concern of climate change, and we’ll see why climate must change in the long run without any help from mankind. I shall end up saying a little about how temperatures are measured. The topics here are covered in Ahrens’ textbook in chapters 3 and 16 of recent editions.

Cause of Seasons

The joke in Scotland is that summer is defined as the best day of the year. Be that as it may, the seasons are conspicuous here. Even so, some of the class may have forgotten the basic cause of seasons. Anyone who lives near the equator can be forgiven for having done so because seasons are not a big deal there. Annual temperature changes and all that follow from them are comparatively small. Life goes on much the same throughout the year. Where people live it is a hot, lush, moist life. The stability of the environment engenders a steadiness in life and ways of doing things. It is a fact of recent human history at least that people living in tropical regions have not been the drivers of change in global society. Why change what works steadily all the year round? The seasons aren’t simply a matter of changing personal experience throughout the year; they have affected the course of history. The lack of strongly defined seasons in the tropical regions of the world also has a big impact on environmental issues relating to climate change. The tropics are trumpeted as a huge resource of bio-diversity. This is true. However, many tropical species of animals and plants have evolved to survive in a very narrow range of temperature and rainfall conditions. There is evidence that they cannot cope with the kind of seasonal change that ecosystems further north or south experience annually. In short, there are strong fears that many tropical species will not adapt to ‘climate change’ that will include temperature rises of several degrees and significant rainfall changes. Species everywhere, both animals and plants, have always faced the ‘adapt-or-perish’ scenario and global climate changes will put species in the tropics particularly to the test. I’ve no doubt we’ll hear more in the future about this implication of climate change.

In Aberdeen, seasonal change is very obvious. The winters are pretty cool; they are damper and windier than the summers. The sun is low in the sky and hours of darkness well exceed the hours of daylight. In summer the sun is comparatively high, the days are light, warmer, drier and indeed a more cheerful air pervades everyday life. The season isn’t just a statement about the weather, it’s a statement about our physical and mental environment. How confused would we Northerners be if the Sun was highest in the sky in late March and late September, as it is on the equator?

The basic cause of the seasons is physical. The seasons are caused by the tilt of the Earth's axis with respect to the plane of the Earth's orbit around the sun. If the Earth's axis through your hemisphere is tilted directly towards the Sun, it is mid-summer. The key point, and this isn't obvious but is due to some fundamental physics about conservation of angular momentum, the Earth's axis remains the next best thing to fixed in direction in space throughout the year. What moves in space throughout the year is the direction of the Sun relative to the Earth's axis, by virtue of the Earth's orbit. Hence 6 months later, the Earth's axis points away from the Sun and we have mid-winter. In short, between the spring equinox and the autumn equinox, the North pole of the Earth's axis is pointing in some degree towards the Sun. In the Northern hemisphere the days are longer than the nights as the Earth spins and we experience the second part of spring, the summer and early autumn. Over the next 6 months, the North pole of the Earth's axis is pointing in some degree away from the Sun, the nights are longer than the days and, loosely speaking, the weather is worse! There are, though, some complications you may not know about.

One complication, which is very significant, is that the Earth's path around the Sun is elliptical, with the Sun off centre. The distance from the Earth to the Sun varies both because of the elliptical shape of the path and because the Sun is off centre. The path brings the Earth closer to the Sun in mid-winter in the N hemisphere, increasing the amount of radiation per unit area by a maximum of about 7%. This has a significant global effect. It gives hotter summers in the S hemisphere and milder winters in the N hemisphere.

Sun's View of the Earth

See the slide for how the Earth appears during the four seasons.

The Tropics

Why does the tilt of the axis produce the seasons? Simply because it alters the height of the Sun in the sky at a given time of day (this height is called the Sun's altitude) and the actual energy that falls on unit area of the Earth's surface depends on the tilt of the surface to the Sun's rays. Rays falling perpendicularly on the surface deliver their full energy. If the Sun's energy is 1300 W m^{-2}, then 1300 W m^{-2} is delivered on 1 m^2 of surface held perpendicular to the rays. The tropics represent the latitude furthest away from the equator where the Sun is overhead at noon some time during the year. The tropics are at latitudes nearly 23.5° N & S.

The Sun Shining Obliquely

Oblique illumination reduces the energy spread over a given area because it spreads the given energy over a bigger area. The increased spread of a beam of light over the area it would illuminate if it fell perpendicularly is $1/\cos\theta$, where θ is the angle that the perpendicular to the tilted area now makes with the light beam. When the area is perpendicular, this angle is zero and hence the cosine is just unity. We'll see the effect of this spreading factor at Aberdeen in a minute.

Another way of saying the same thing is that the energy per unit area is reduced by the factor $\cos\theta$.

Aberdeen's Position on the Globe

As we know, Aberdeen's latitude is about 57° N, which is 33.5° from the Tropic of Cancer. The Sun is never going to be directly overhead, even at noon. Its maximum altitude is (90° (overhead) - 33.5°) = 56.5° in mid-summer and only (56.5° - 2 x 23.5°) = 9.5° in mid-winter. The increased area that 1 m^2 of the Sun's rays are spread over at Aberdeen is

for noon at mid-summer: $\frac{1}{\cos 33.5^\circ} = 1.2\ \text{m}^2$, which not much loss.

For mid-winter: $\frac{1}{\cos 80.5^\circ} = 6.1\ \mathrm{m}^2$ which corresponds to a huge spreading out of the sunlight. At other times of the day, the spreading factor is even larger than the figures above.

[Another example of the spreading effect of tilt is the lengthening of shadows as the Sun drops down in the sky. The shadow on the ground covers the area that would be illuminated by the sunlight striking you and it gets bigger as the Sun sinks. The factor involved is different from the factor calculated above but we needn't go into the details.]

Sun's Track at Different Latitudes

The illustration from Ahrens' textbook shows how the track of the Sun across the vault of the sky varies over the year at places with different latitudes. Even in the tropics, it's only shining straight down onto the land at most twice during the year. At all other times it's shining at an angle. In Aberdeen, it's always at an angle so the $\cos\theta$ spreading effect is always at work.

Inverse Square Law of Radiation

See the slide. This law is essentially a statement of conservation of energy. All the energy that propagates through an area 1 m^2 at unit distance, is spread over 4 m^2 at double the distance, 9 m^2 at triple the distance, and so on. Hence the illumination per m^2 falls off as the inverse square of the distance away from the source one looks or measures.

Irradiation in Summer

Angle is one thing, but there is more to it than angle. In Northern latitudes like Aberdeen, the Sun is above the horizon a lot longer in summer than the 12 hours it is at a tropical latitude where the Sun travels overhead. Do the extra hours make up for the lower altitude of the Sun? In another context, are solar heating panels any use in Aberdeen? Briefly, yes! At the top of the atmosphere above us, we receive more solar radiation per long summer day than the Berbers receive in mid-summer in the Sahara desert. Difficult to believe ("strange but true"). However the sloping path through the atmosphere brings in more absorption over Aberdeen than through the atmosphere above the Sahara and the net result is that we receive at ground level a bit less radiation. Not enormously less though. Cloud interruption is another matter.

Irradiation in Winter

The slide shows the equivalent solar energy received in winter. As we've seen, because of the shallow angle the Sun's rays make to the ground at Aberdeen, even at noon there is only at most 1/6th of the normal incident flux here. On top of this there is a much longer atmospheric path and a short day. Forget about your solar panels in November, December and January in Aberdeen.

One consequence of the changing solar irradiation over winter and summer that is 'obvious' once it's pointed out but which you mightn't have thought about is that daily variations in temperature during the winter in this part of the world are noticeably smaller than daily variations in summer. 3 or 4 degrees Celsius is a typical range in winter over 24 hours, whereas in summer over 10 degrees is common. In winter the biggest factor determining the outside temperature is the mass of air that the current weather system brings with it. This point is taken up much later in the course.

Seasonal temperature variations are driven by the Sun's energy input but because of the stored energy in the oceans and the atmosphere, seasonal average temperatures rise and fall about a month behind the solar changes. [Analogy with the time delay in heating a saucepan on the electric ring].

Energy Balance over the Globe

Over a year, higher latitudes receive less solar energy than the tropical belt. You might expect that average temperature would drop substantially as you go towards the Poles. In fact it drops modestly. Put another way, in Scotland we are warmer than we should be by virtue of the solar radiation we receive. We are not in radiant energy balance - more energy is radiated from Scotland than we receive in radiation. This is radiant energy deficit. We give away more than we receive. In fact all latitudes above 35° are in radiant energy deficit. By contrast, tropical regions are in radiant energy surplus. You don't need a degree in physics to work out that energy must therefore be transported by means other than radiation from tropical regions to higher latitudes. This is done in 3 main ways, each roughly accounting for 1/3rd of the energy moved.

See the slide.

Global Climate

Global climate is driven by the Sun, and only the Sun. The Sun, though, is not a fixed object a fixed distance away. Sure, its output is apparently constant, within about 1 part in a thousand when measured over the timescale that has been available to us. Aspects of the Earth's orbit, though, are known to vary on a timescale measured in terms of thousands of years. I want to say some more about this in the next 10 minutes.

Global climate is also influenced by all effects on Earth that influence energy balance. Since the circulation of oceans and atmosphere are crucial, as we have seen, global climate is therefore a complex, interactive system. Summarising one of the messages from the last chapter, global climate is influenced by atmospheric and ocean circulation patterns, by cloud cover, land cover (snow, forests, deserts) and other factors and in turn determines these factors. Meteorologists, environmentalists and all of us, really, have a complex problem on our hands trying to predict changes that might occur, both natural and as a result of mankind's activities.

Why is the Earth always partly cloudy? If the cloud cover significantly evaporated, much more sunshine would reach the Earth's surface, evaporating enough water to make a lot more cloud. If the cloud cover gets greater than usual, then the Sun is blocked out, evaporation reduced and less cloud produced to replace that which rained away. This is one example of a mutually interactive process at work. This particular example shows “negative feedback” that tends to maintain stability.

One important point to make is that there does not appear to be any 'law of averages' in relation to climate. In so much as the law of averages means anything it means that averaged over a long period, climate is constant. In that period there will typically be as many hot summers as cold summers, and so on. For climate, though, it seems that no matter how long you average over - a decade, a century, longer - climate does not stay constant. In short: expect changes. Some 'green' factions try to sell the picture that mankind has jumped onto a finely balanced see-saw and upset the equilibrium. A better analogy is that Man has jumped into the sea and created more waves, but there were a lot of waves there already.

I want to look in a bit more detail at seasons. At present, the seasons occur as shown in the next slide.

Earth Receives the Same Solar Radiation in Each Season

The eccentricity of the Earth's orbit introduces complications in the seasons. At present winter is shorter than summer in the N hemisphere. The closer the Earth is to the Sun, the faster it travels. You can see from the figure that in Winter the length of the arc is shorter *and* the Earth travels faster. Winter is shorter than summer by about 7 days. You may say "long may it continue", but it won't. However, because the Earth is nearer to the Sun in our winter the whole Earth receives more radiation. Do the two effects balance? Yes, they do. It is a quirk of geometry. In every astronomical season, the whole Earth receives the same input of solar energy, though the input is spread over a different number of days.

N & S Hemispheres don't Share their Radiant Energy

The classic view in meteorology is that energy that falls on the N hemisphere more or less stays in the N hemisphere; likewise for the S hemisphere. This view is based upon an appreciation of atmospheric circulation patterns, which we'll cover in a later lecture. When the Sun is overhead at the equator (at the equinoxes) each hemisphere receives, equally, half the radiation. When the Earth's axis is tilted, one hemisphere receives more, up to a factor $(1 + \sin 23.5°) = 1.40$ at midsummer (0.7 at midwinter). The extra energy received in summer stays mostly in the hemisphere concerned, due to good mixing within each hemisphere.

Changes Past and Future

Although the whole Earth receives the same solar radiation in each season, because of the tilt in the Earth's axis, the radiation is not distributed uniformly across the hemispheres. Averaged over the whole summer, the ratio of energy received in the summer to that received in the winter is about 5:3, for the present orientation and tilt of the Earth's axis. Hence the average daily input of energy in summer (in either hemisphere) is substantially larger than in winter and in the N hemisphere the summer lasts longer. We would expect conditions *unfavourable* for glaciation (which is where all this is leading to).

However, times will change. The direction of the Earth's axis is *very slowly* changing in space, due mainly to the influence of the gravitational fields of Sun and Moon on the slightly ellipsoidal shape of the Earth. This change takes place over about 23,000 years and is called the *precession of the Earth's axis*. [Astronomy texts give a figure nearer 26,000 years]. In about 5500 years time (1/4 of the precession period), summers and winters will be of an equal length. More particularly, winter in the N hemisphere will be longer for the same amount of radiation received. The average daily radiation received in winter will drop. There is worse to come. In another 5500 years the winter will be 7 days longer than the summer. Is that long enough for glaciation to be on the increase? Probably 'yes'.

Changes in the Earth's Eccentricity and Obliquity

There is even worse to come. The difference between summer and winter depends on the eccentricity in the Earth's orbit, which is changing with a basic period of about 100,000 years, with additional longer period influences as shown on the slide. At present the orbit is pretty circular (e = 0.0167). At its maximum the eccentricity is about 4 times greater and there is a 33 day difference between summer and winter. That difference, repeated year after year, would seem to be enough for glaciation. The cause of the change in eccentricity is the very small influence of the gravitational pull of Venus, our nearest neighbour, and Jupiter, our biggest neighbour. The astrologers have got it all wrong about the planets. They don't make a blind bit of difference to our luck on a daily basis but in 50,000 years time they can bury Aberdeen under a km of ice. That's real influence!

Another aspect of the Earth's motion is that the Earth's axis inclination varies from 22° - 24.5° over a period ~ 40,000 years. The tropics are moving at a rate 10 m yr^{-1} as a result of this. At present the angle is a bit less than 23.5° and decreasing, hence the tropics of Cancer and Capricorn are moving towards the equator. One of the lessons that climate change studies have shown is that the response of the climate system to all the influencing factors is complex. Even for the very long timescale astronomical influences, the response signal, in terms of global temperature changes, doesn't follow the driving forces in a sufficiently straightforward way that you can say how much each influence contributes to the overall result.

Daily Temperature Changes

Back to normal life. Daily temperature changes are controlled by the Earth spinning on its axis, i.e. the Sun rising, travelling across the sky, setting at dusk. During the day the energy input varies continuously; at night the Sun's input is constantly zero. The variations in temperature are dominated by the Sun but the average temperature on any day is largely controlled by the air mass passing over (which in turn depends on the Sun elsewhere on the globe). A warm wind from the South produces warm air and a warm day. A cold wind in winter from the NE produces a cold day no matter how brightly the Sun shines.

Just as there is a delay in seasonal temperatures compared with the yearly changes in solar radiation - the temperatures you'll remember lag about a month behind changes in the Sun's energy - so, too, on a daily basis. On a daily basis, the temperature lag can be about 3 hours. Maximum daily temperatures are not reached on a sunny day until mid-afternoon. Quite simply, the air continues to heat so long as the incoming energy exceeds the outgoing radiation (which is controlled only by the temperature). This simple statement is complicated by cloud cover. Clouds significantly reduce the Earth's radiant energy loss but, even more significant in daytime, they cut off the Sun's rays reaching the ground. At night they are effective in keeping the ground warmer; in daytime they keep the ground cooler.

Temperature Changes with Height

The normal state of affairs is for temperature to decrease with height. We'll discuss this in a lot more detail later. On a calm day there is a big change just a few metres above ground [see the slide]. Lying on the beach, you are hotter than standing up. Meteorological thermometers are normally placed a good metre or two above ground. If the temperature gradient is very big, such as above a tarred road, then a mirage can be seen, which is effectively the reflection of the sky in the hot air [see Chapter 4]. Ground loving plants experience a hotter day than you or I. On windy days, the change with height is a lot less, due to the mixing of the air by the wind.

Temperature Changes at Night

On calm nights the reverse happens. The temperature is colder very close to the ground [see the slide]. Dew, or even frost, forms on the ground itself first. Ice forms on the road when the temperature 1 m above ground may still be a couple of °C. This increase of temperature with height is called a *temperature inversion.*

Daily Temperature Range Decreases with Height

During the day, temperatures decrease quite quickly with height - perhaps 10 C° per 1000 m. By night there might be an inversion near the ground but typically temperatures will decrease with height, though not so fast as during the day. See the schematic on the slide.

It's Warmer under the Ice

- Snow and ice are poor thermal conductors. If you're trapped in a snow storm - stay well dug in.
- Snow and ice also have large specific heat (see later) compared to most solids. It takes a lot of heat loss to cool them down so they tend to stay warmer than the ground.
- Snow and ice are white and hence poor heat (IR) emitters. They tend to hold on to their energy longest and cool down slowest.

Sea-level Isotherms

Isotherms are lines of constant temperature. Only 2/3rd of the globe is sea. Over the remaining 1/3rd, an allowance is made to convert average temperatures at the height observed to average sea-level temperatures. Not all meteorologists use the same correction factor so you have to be careful what has been used if you're really going to study the details of the results. Ahrens shows the results for January and July. Scotland is in a lobe of warm temperature that pushes north in January - warmed by a combination of southerly and SW air and ocean currents. By rights at 57°N there should be ice covering the Dee in January and deep snow and ice over the town. There usually isn't - see the picture of Aberdeen in January. The charts in Ahrens repay further study. See the next two slides.

Daily, Monthly & Yearly Temperatures

The daily diurnal temperature range varies, as we've seen, with height. It also varies with distance from the sea. Water is a great reservoir of thermal energy and evaporation is the means of transferring that energy to the surroundings. The Sun can't quickly warm water in the daytime. Water is some of the hardest stuff in the world to heat up by radiation [it is a bad absorber of IR, especially at shallow angles, and a good reflector]

- wave motion stirs up water, constantly bringing cooler water to the surface and taking warm water from the surface
- evaporation cools the surface
- water is a poor thermal conductor

- water has large specific heat
- you don't heat your bath water by shining a radiant heater on it.

The slide shows some effects of water.

Seas and large lakes not only affect daily temperatures. They have sufficient energy capacity to affect annual temperatures. Temperature ranges during the year for a given latitude are greatest well away from the sea and less near the sea, as we know in Aberdeen. Temperature variation also tends to increase with latitude.

The Met Office follows the WMO (World Meteorological Office) standard of using 30 year averages for climate data. You can find on-line regional averages under UKCP09 for the periods 1961 - 1990, 1971 - 2000 and 1981 - 2010.

Two Measures of Heat

As we approach the end of this chapter, I should give good definitions of two concepts I've already mentioned briefly. See the slide for:

Specific heat capacity - usually quoted for 1 g of material.

Specific heat pays a crucial role in global warming. The specific heat of the sea is some 4 times greater per gramme than the specific heat of the atmosphere. In addition the sea is about 1000 times as dense as the atmosphere. With global warming, the energy input to the Earth is increased, as was discussed in the last chapter, because the atmosphere radiates more infrared towards the surface. If this extra input of energy just had to heat the atmosphere, then air temperatures would rocket but because the energy has to heat both rock and sea, it takes a vast amount more of energy to increase the temperature of the sea than the air. Without this effect, global temperature rises would not be as small as a few degrees per century.

Latent heat - the energy required to change state at *constant temperature* - see the presentation. It was the eighteenth century Scots chemist Joseph Black who introduced the concept of *latent heat*, and realised its importance. Latent heat is a remarkable property of matter that was unanticipated in its day. You pour heat energy into ice at 0° C, melting it in the process but the resulting liquid water is still at 0° C; you keep the heat under a pan of boiling water for a long time, far longer than it took to boil the water in the first place, and the water gradually turns to steam but is it any hotter than 100° C? No it’s not. Surely heat makes things hotter? Black pointed out that it didn’t always do so. Before Black’s discovery of latent heat, people did not appreciate what was going on when matter changed from one phase to another, solid to liquid and liquid to vapour.

To see how important latent heat really is, it’s worth imagining for a moment what the world would be like if it didn’t exist. Catastrophe would ensue. Suppose boiling water had no latent heat. As you heated a kettle of water the temperature would rise by a degree every few seconds, as it does: 96° → 97° → 98° → 99° → 100° → then in the next few seconds the entire kettle full of water would be turned into steam. Your breath would be taken away. As for cooking anything in boiling water – forget it. A saucepan of boiling water could scarcely exist. As it is, you have to put many times the energy into the water to boil it away as you did to heat it up from room temperature to 100°; that’s what latent heat is all about.

At the other end of the temperature scale, if there were no latent heat of melting ice, catastrophe would also follow. Imagine a mountain-side in your favourite ski resort covered in snow. Imagine that the latent heat of melting ice didn't exist. A mass of warm air comes in with changing weather. The temperature of the ice rises at half hour intervals from -3° → -2° → -1° → 0° and then in minutes the entire snowfield becomes water at a fraction of a degree Celsius, cascading down the hillside in an almighty deluge. Houses would be swept away, lives lost, nature could scarcely survive if ice did that. Fortunately it doesn't, thanks to the big latent heat of melting ice. It takes a lot of energy to turn ice into water and, if I can put it this way, persistent cold to turn water into ice, because latent heat works both ways, in melting and in freezing, in evaporating and in condensing. Melt or boil something and you need to supply lots of latent heat; freeze liquid or condense vapour and the latent heat that comes out must be taken away. With water, in particular, there is lots and lots of heat to be taken away.

Wind Chill

Our skin heats up the air next to us, which helps to keep us warm, both because air is a bad conductor and because the air next to us is therefore a little warmer than the farther surroundings. Wind does two things:

1) it sweeps away this insulating blanket
2) it sweeps away evaporated moisture, making room for more to evaporate. Each gram of evaporation carries away 600 cal of energy, such is the size of the latent heat of water.

The result is that we lose heat as fast in a wind as if it were many degrees colder. That is what is meant by *wind chill.* See the table in Ahrens (reproduced in the next slide).

Measuring Temperatures

Liquid in glass thermometers - the most common liquid is alcohol (which has a typical low point of -30°C) with an added dye.

Maximum thermometers can be like medical thermometers, with a constriction in the bore, or they may contain an index pointer in the bore that is pushed up by the mercury meniscus as the temperature rises. The later works very well with mercury-in-glass (invented by Fahrenheit, you remember). *Minimum thermometers* have an index marker that is pulled down by the alcohol meniscus and left there as the temp rises.

Platinum resistance thermometers (as used in our first year lab) give readings directly related to the international temperature scale (ITS-90) and are much the preferred electronic sensors. They simply use the highly accurately known and reproducible change in resistance of a fixed length of platinum with temperature. Platinum resistance thermometers are the *international standard thermometers* for meteorological temperatures.

Measuring Enclosures

The purpose of an enclosure is to shield the instruments from direct sunlight and precipitation. Enclosures also tend to trap air-borne and rain-borne particles on the outside, providing some protection from dirt for the instruments within. An enclosure should allow a free flow of air through. They are always painted white, to minimise the absorption of energy from the Sun that could heat the air within.

The *Stevenson screen* (and similar housings in other countries) provides standard shelter for thermometers, humidity measures and barometers. It has standard dimensions, to try to make weather recording enclosures standard up and down the country.

JSR