Global Circulation

Global influence

Standing in a field and looking around, it is not obvious that there's any difference between N, S, E & W. On an overcast day it can be difficult to tell which direction is which. Now look at the wind rose for Aberdeen on the slide. It is strongly asymmetric. The 'obvious' asymmetry at Aberdeen is the North Sea. That is not the reason for the asymmetry of the wind rose. You need to look at our environment on an even bigger scale to find the cause. There's a strong temptation to think that weather is just a local phenomenon. It's not. Our weather is part of a world circulation pattern.

Global circulation models

Weather systems that affect Britain typically come from the West, from the Atlantic [the picture on the slide is of the island of Eigg on the West coast of Scotland]. Our weather is part of the global circulation pattern for our latitude. Our climate is not a product only of local conditions but is very much part of the climate of the world. To predict tomorrow's weather, we 'simply' need to know some detail of the air mass that is coming our way, how its properties may change 'en route' and what conditions are like here and now. When I was on holiday in France I noticed that the 'meteo' on one of the TV channels usually showed a computer animation of the 'masses d'air' predicted to sweep across the country. I thought this was helpful.

One doesn't need to collect meteorological observations over many years to be convinced that the wind rose anywhere in Britain is asymmetric. In British towns the 'west end' is established as the upper-class part of town with its expensive houses and fine gardens. The reason is meteorological. More often than not the wind blows from west to east and hence the air pollution from chimneys and perhaps odiferous industry is blown towards the east end of town, leaving the west side as the sweetest place to live. Why does the wind blow more often from the west in our latitudes? You need to understand global circulation to answer that.

To predict future climate, or the influence of natural causes and human activities on future climate, we need to model the climate of the whole world. "There is no other way forward", to quote a much-used phrase. The same is true even if you only want to predict next week's weather. To do this in detail, meteorologists need to establish the physics behind everything that contributes to the weather and how the different ingredients interact. It's quite a challenge and, as you know, the physics behind the weather is one of the themes of this course. A full global circulation model requires accurate representations of the atmosphere - all its layers and its clouds (clouds are the key to global modelling) - the oceans and the land surfaces, and how all these interact. Meteorologists have a long way to go before they have a finely detailed computer model of the global weather system and all that influences it properly accounted for. Current attempts are called General Circulation Models, aka GCMs. If they incorporate modelling of ocean currents and the ocean/atmosphere interaction, they are called Atmosphere-Ocean General Circulation Models (AOGCMs) or sometimes just Coupled General Circulation Models (CGCMs) as described in chapter 16 of Ahrens' textbook.

This is an appropriate introduction to pause for a moment and reflect on our understanding of the weather. Suppose today is wet and windy. You look at tomorrow's forecast and see it will be dry, sunny and pretty calm by lunchtime. Tomorrow's forecast is usually right these days. Why is it right? It's because the complex weather system with its changing pattern of winds, of clouds, of sunshine, of humidity and rain may seem never to repeat itself exactly but in fact obeys the laws of physics. These laws we know. It turns out to be a tough call to use these laws to predict what will happen in days to come but that is being done with increasing success. Tomorrow's forecast in this part of the world not only gives a general overview but the best forecasts (e.g. the Met Office) predict detailed conditions with timings and get them right to within an hour or so. Their public forecasts are now given for 7 days, whereas they used to be for 5 days (and before that typically only for 2 days). OK, the forecasts are increasingly less reliable with increasing number of days ahead but nowadays reliable enough to be worth giving. In short, we understand the weather system. We can't control it (almost certainly 'fortunately', for who could be trusted to do so?); we understand it enough to know there are limits on what we can predict and I'll expand on this aspect of forecasting.

It's also worth saying explicitly that meteorologists have discovered the holistic nature of the weather system, which is often not appreciated by the public. Extended drought in California or storms in South China may arouse our sympathy for humanitarian reasons but it's easy to think that as far as the weather is concerned they have nothing to do with our weather in Scotland. These events may not signify any particular disaster for Scottish weather but the weather we experience will be different from what we would have had if the disasters hadn't happened. It may be unusual, it may not. To take an analogy – think of injuring your big toe. You can't walk properly so your legs feel it; you spend much more time sitting; your social life is affected and your diet changes, as well as your mood. The whole of you is affected, a reminder that your toe is part of a whole system, all of which normally works together. The weather is a whole system, which is what global modelling attempts to catch. One implication is that no-one should be allowed to control the weather even locally, for any alteration will in some way affect everyone in the world. There is no such option as local weather control.

Lewis Fry Richardson

General Circulation Models aim to predict the future state of the atmosphere by recognizing that the atmosphere is a physical system obeying known laws of physics. The mathematics describing the relevant laws is coded into a computer and the equations solved. It's not really that easy, however. It's true that the laws are known, laws such as the equations of motion, the properties of the atmospheric gases and the 'thermodynamics' describing the relationship between pressure, temperature and volume. In mathematical form most of the laws are written as 'non-linear differential equations' and they have the unfortunate property of not being exactly soluble. Moreover, what the future looks like depends on what the present is, so the equations for the evolution of local properties of the atmosphere such as its density, temperature, speed of motion, etc. need fed with the values of all the variables now. Of course we don't know precisely the state of everywhere in the atmosphere now. There really are some very good reasons why weather forecasts aren't 'spot on', but we're jumping ahead of the story a bit.

It was the astronomer R S Ball in the 1890s who pointed out in a popular book that the story of trying to model complex environmental behaviour goes back at least to the tide predicting machines of Sir William Thomson (later Lord Kelvin) in the 1870s. These were quite complicated but pretty successful, enabling graphs of water height with time to be prepared in advance for a chosen station on the coast. The devices were entirely mechanical but were based upon a mathematical analysis of the repeating components in the pattern of tidal changes. Ball suggested that perhaps one could do for the atmosphere in general what

Thomson had done for the tides, namely build a machine that will mimic the variations in atmospheric behaviour. After all, he argued, the atmosphere is driven by the Sun in a predictable way, though he recognised that its response was more complicated than the response of the sea to the tidal forces of Sun and Moon. Ball never set out to do the job but the idea that future weather might be calculable was 'in the air' from no later than the end of the 19th century. Even if anyone had had the inspiration to think of this much earlier, they wouldn't have been able to conceive how to do it because some of the necessary physics and the accompanying mathematical tools to handle the physics were only discovered and invented in the second half of the 19th century.

Weather modelling in practice was pioneered by Lewis Fry Richardson (1881 – 1953) who published his book *Weather Prediction by Numerical Processes* in 1922. Although he tried to make numerical predictions (for a small area of England, not the whole world) he was still ahead of his time in that the human and mechanical calculators of his day were far too slow for the task. It is said that with his first attempt he took two years to predict the next day's pressure at a point, and he was far out with his figure when he finally arrived at a result. This might sound a very unpromising start to the concept but his science was good, it was just the implementation and interpretation that needed much more work.

Even today's computers have difficulty and this is the reason some of the world's fastest machines have been built for atmospheric modelling. Japan's "Earth Simulator" was the fastest of them all when it was switched on in 2002, capable of 35 teraflops (one teraflop is 10^9 floating point operations per second) thanks to its 5104 central processors. It's used for climate modelling and other environmental simulations. It was still the top Japanese machine reported in November 2009 to be running at 122 teraflops, but the top American Cray cluster in 2009 ran at more than 14 times this speed – impressive! Of course yesterday's impressive computer becomes today's no-news item. Updating this paragraph in July 2012, I see that the fastest machine is now credited as IBM's Sequoia, with a peak performance of just over 20,000 teraflops (20 petaflops), knocking Japan's Fujitsu machine in Kobe off its perch. A more than 500-fold increase in computing power has been achieved in one decade and climate modelling is one of the main driving forces behind this advance. Updating these notes again at the beginning of 2016, I see that the Met Office has just installed a new 23 petaflop IBM machine, with 2 terabits of memory and almost half a million processors. Serious kit to tackle a big problem.

As a minor comparison I can relate my own very small experience of climate modelling. In 2005, through the BBC, a climate modelling programme became available as a screen saver. Each person who used it ran one model with one set of parameters. The model started near the beginning of the twentieth century and ended near the end of the 21st century. It took my fairly new PC over a year to complete this. Of course it didn't calculate the model when I was using the PC for other things or when I switched it off but it still took some 2900 hours of calculation time for this one run. I didn't benchmark my PC in Mflops but I suspect that the Earth Simulator would have run through in less than a minute the almost two centuries of climate modelling that my PC covered.

By way of another digression, a couple of quotations indicate that it has taken about 50 years of serious development of computer-aided forecasts to reach the level of reliability we now expect. The *New Scientist* of 30th May 1957 under the heading "*Computer Weather Forecasts?*" reported "*It seems that the Russians have made considerable progress towards a reasonably successful prediction of a weather map 24 hours in advance……In the Russian* *experiment pressure calculations were made for some 450 points in Europe and western Siberia. The total calculation took about 40 minutes to complete using the very high-speed BESM computer based at the Academy of Sciences of the USSR.*" What the Russians achieved in 1957 was a pressure calculation, not an automated forecast. 50 years later, the magazine *Weather*, the Royal Meteorological Society's popular monthly publication, opened its June 2007 issue with an article "*The end of weather forecasting at Met Office London*". This reported the demise in September 2006 of what used to be the London Weather Centre, an institution that could trace its origins back to 1854. The main reasons for its closure were "*Vast improvements in the accuracy of numerically produced forecasts combined with big changes in communication methods.*" It's argued these days that computers can even effectively incorporate local knowledge, the prime reason for setting up a spread of Met Office Weather Centres across post second-world-war Britain. There used to be seven in Scotland. Only one remains, the one in Aberdeen. Not everyone agrees that computers are as good as local forecasters.

The message worth getting across is that **computer modelling works**! A millennium ago the prediction of extreme events at least was the realm of astrology and incantation. It didn't work. Weather lore, essentially sayings encapsulating past experience and hoping it will repeat, does at times work better than chance. Weather lore is localised experience that fails to take account that the weather systems are huge in scale. Measuring weather properties like rainfall, temperature, air pressure and so on and constructing large-scale charts to follow the evolution was the basis of forecasting from the mid-nineteenth to the mid-twentieth century. This was a much better attempt to use the 'it's happened before so may happen again' strategy. In parallel with this there was a huge increase in understanding the physics that governed the behaviour of the atmosphere. Add this in to an increasing database of daily world-wide measurements and the computing power to make use of the physical understanding and forecasting now works a lot better than ever before. Even better, it predicts its own uncertainty, estimating how likely the forecast is to be right. As said elsewhere in these notes, forecasting is and always will be a probabilistic activity. We've never had it so good in terms of accurate weather forecasts, thanks to computer modelling.

The following two slides are good graphics produced by the IPCC to illustrate the improvements in climate modelling over the past three decades.

The world in global climate models

The complexity of climate models has increased over the last few decades, with additional physics progressively incorporated into the models as shown pictorially on the slide. I'm not going into the details here but you'll recognize various aspects of the models from the discussion in the earlier section of the course on 'climate change'.

Geographic resolution of climate models

This second IPCC slide illustrates the geographic resolution characteristic of the generations of climate models used in the IPCC Assessment Reports: FAR (IPCC, 1990), SAR (IPCC, 1996), TAR (IPCC, 2001a), and AR4 (2007). AR5 (2013/14) are now published but the slide gets across the message. The illustrations show how successive generations of these global models increasingly resolved northern Europe. They are representative of the most detailed horizontal resolution used for short-term climate simulations. The century-long simulations cited in IPCC Assessment Reports after the FAR were typically run with the previous generation's resolution. The vertical resolution in both atmosphere and ocean models isn't shown, but it has increased comparably with the horizontal resolution, beginning typically with a single-layer slab ocean and ten atmospheric layers in the FAR and progressing to scores of levels in both atmosphere and ocean. Updating this paragraph in 2014, for weather forecasting the Met Office's numerical weather prediction (NWP is the jargon) will in the near future be based on a global model with a spatial resolution of 17 km and a vertical resolution of 70 layers; a regional model covering the UK and extending over Western European countries with a horizontal resolution of 4 km and a local model for the UK with a resolution of 1.5 km. Improved models are not only about finer resolution but also about better implementation of the physics. In 2018, the Met Office now use their global coupled model GC3.1, a further improvement on all counts. It is results from this model that will feed into the Coupled Model Intercomparison Project Phase 6 (CMIP6), an important contributor to IPCC's 6th report, due in 2021. The area is awash with acronyms.

Vertically, the Met Office's so called 'Unified Model' is being extended beyond the mesosphere into the thermosphere. This introduces new chemistry and new physics into the model. Meteorology is meeting astronomy, for the astronomical community has long recognized that the outer atmosphere is strongly linked to the behavior of the Sun. In the UK, astronomers interested in this aspect form a large and active body known as MIST – **M**agnetospheric, **I**onospheric and **S**olar-**T**errestrial Physics. The linking of the Met Office's powerful modelling capabilities with MIST interests may well solve the riddle of whether there is a genuine correlation between climate and the sunspot cycle.

The direction of progress with computational meteorology in recent decades is clear. To return to our topic of global circulation: global circulation of air represents the average winds around the world. You don't need a full computer-based general circulation model to say something worthwhile about global circulation.

The Hadley Cell

George Hadley (younger brother of the more famous John, who invented the octant, a navigational instrument that was the pre-cursor of the sextant), lived through the first half of the 18th century. He took a particular interest in trying to understand the Trade Winds and began with a model that that took the equatorial regions as hot and the polar regions as cold. This is clearly very reasonable! He surmised that there should be a general convective circulation driven by this temperature difference. His basic convective cells - one per hemisphere - take no account of any difference between land and sea, or any influence of the Coriolis force (Coriolis lived a century later). The idea that such convection exists is correct but Hadley's idea on its own is too simple.

3 cell (or 6 cell) model

The Earth's rotation makes a big difference and breaks up Hadley's circulation pattern into 3 cells per hemisphere. From equator to ~30°, the circulation looks very like Hadley's cell. On this model there tends to be permanent areas of low pressure at the equator and also in sub-polar latitudes - that's us - and permanent high pressure areas in the sub-tropics and at the poles. The Coriolis force deflects winds from the N-S direction. It has a larger effect nearer the Poles than near the equator.

The influence of the Coriolis force

See the slide. The Coriolis force received a lot of attention in the last 'chapter' of these notes so I'll be very brief here. Warm air aloft rising up at equatorial latitudes is diverted eastward in the northern hemisphere sufficiently that by 30º N it is not travelling north any more. At ground level the returning air is again deflected to the right, defining the trade winds, as shown in the next slide. In brief, the Coriolis force is responsible for the climatic bands around the Earth. If you pause to think about, influences don't get much bigger than this. The climate structure of the Earth determines where people live, how people live and why people migrate, all factors central to the evolution of civilisation. The pattern of human history has been determined by the effect of the Coriolis force on the atmosphere. Maybe you'll now excuse the length that I went to try to explain this effect.

The weather affecting the UK is mainly brought to us by cyclonic circulation (depressions) that, broadly speaking, form on the front between the polar cell and the ferrel cell. This is discussed in more detail in the next chapter but the point is that our location on the Earth is such that our weather is not brought to us by the steady behaviour of one cell but by the variable interaction of two cells. The cell's themselves are driven by the Sun and the overhead position of the Sun moves between the tropics over the year, increasing the variability of the cells and hence of our weather. All these factors make predicting the UK weather a tough job.

In a wider context, the Coriolis effect is responsible for the banded atmospheres of Jupiter and Saturn, and the very slow rotation of Venus is the reason why there are no corresponding bands on Venus to those on Earth, although Venus has more atmosphere and is comparable in size to Earth.

Global Winds

If you look at the general circulation of air around the world (and it took generations of sailors to establish what this pattern is) then you'll see they bear some resemblance to the winds in the 6-cell (or 3-cell per hemisphere) model. In the northern hemisphere, the Hadley cell would produce N winds (blowing in a southerly direction) on a static Earth but they are deflected to the right by the Coriolis force to produce the NE trades. These are the winds that took Columbus to America. You can see why he landed in the Caribbean, given that he largely sailed with the wind 'abaft the beam', i.e. generally behind him. Likewise, the Coriolis force produces the SE trades in the Southern Hemisphere. Where these meet is called the Intertropical Convergence Zone (ITCZ), informally recognised as the meteorological equator. Here the trade winds run together and peter out. The area is hot, wet and generally calm. Sailors called it the doldrums. Warm air rises up, taking up lots of moisture and forming clouds. You'll see this zone clearly on geostationary satellite pictures.

The doldrums is often portrayed as a region of little wind. This isn't quite true. There may be little pressure gradient wind but there can be quite strong local winds produced by the strong convective activity. Ocean sailing in this region, I'm talking about sailing with sails and not motoring, it's best to avoid being right under a cloud, where you can be becalmed. The strongest wind is near the edge of the clouds and it can be squall force at times. The following account comes from one of the Volvo Ocean race crew in 2009, sailing near the equator in a multi-leg round-the-world race. "*Sailing along through the Micronesian Islands of the South Pacific, I got a nasty awakening this morning as I was rolled out of my bunk without warning. Fortunately I landed in the stack below me* [folded sail] *but the boat was* *tipped over at such an angle that if you didn't know what was going on you might think the boat was about to capsize. We'd been hit by another line squall; they appear to be quite prevalent in this part of the world and seem to have some teeth as well. Once the call has been made that we are about to get hit, the crew has to react quickly to make the boat safe - wind speeds in a squall can easily double or increase by 20 knots.*

I could hear the guys on deck running around as they got the big jib down and put up a smaller sail, then a minute later the reef starts to go in, I can feel the boat accelerating and then go quiet as the helmsman turns downwind so that the guys can make the maneuver safely. The squall has generated a sloppy wave pattern and boat starts to crash and bump because the waves are disorganized and random. This particular squall was a real beauty and lasted about two hours.

The first indication that you are going to get nailed by a line squall will be a general darkening and thickening of the clouds to weather. Therefore if you're reaching [i.e. not sailing with the wind behind you] *and you see some activity at about 45 degrees off the windward bow you need to start getting prepared. The leading edge of the squall comes with a pretty high probability of a significant wind-shift, you will observe high black cloud above you and light rain will start to fall, this lasts for about 5 minutes and is generally followed by a short pause in the rain which may be accompanied by a possible clearing of the clouds. This break will only be for a few minutes before the large drops start to fall from the puffy nimbus clouds that make up the body of the squall.*

Once in the squall the rain will be torrential and I mean torrential. It's really quite fun because the water is so cool and clean it provides a great chance for a shower and generally speaking the on-deck watch has to work around the off-watch guys streaming out of the hatch clutching shower gel."

Returning to the illustration on the slide; like intersecting gear wheels, adjacent cells of the global weather pattern circulate in opposite directions. In our latitudes, the prevailing winds become Westerlies. Remember that the Coriolis force increases towards the poles and hence can twist the winds more strongly. At both poles, we get Easterlies.

That's the global picture. Notice the point that I made when discussing long term climate change, namely that there is little mixing of the atmospheric circulation patterns in the two hemispheres, North and South.

Global View

Composite images from geostationary and other satellites give both cloud and temperatures. The picture on the slide is produced at 6 hour intervals by the University of Wisconsin - this image is amazing. Look at it closely. Today's image is shown in the next slide.

The World Today

Remember the IR view of clouds: high clouds are white, low, warm clouds are grey. The whole Earth is shown.

Winds from Satellite Measurements

The simple patterns of the 6-cell model are average winds. The actual wind pattern at any given time is much more complicated. By picking out fine detail in clouds and watching it move, wind directions and speeds can be deduced automatically from satellite pictures. It is impressive technology. The slide shows part of a much larger region of the Western Atlantic. At the foot, the NE trades, almost Easterly, blow in to the Caribbean. At the top, Westerlies blow away from the Eastern seaboard of the US. By looking at cloud features in different wavebands, winds at different heights can be deduced. It is impressive technology.

Ocean Surface Winds

Winds just above the sea surface were available for a wide area including all around Britain from the 'QuikSCAT' radar project. This was another example of impressive satellite remote sensing. QuikSCAT has now retired but is due to be replaced in 2014 by 'RapidScat', launched from the International Space Station.

Real World Winds

Average winds are modified from the simple model by the distribution of land and sea. This introduces semi-permanent highs and lows around the world. See Figs 11.3. In winter our weather is dominated by the Icelandic low - not that there is simply an area of low pressure static over Iceland. What happens, as we'll see, is that areas of low sweep across the Atlantic, generally moving around or towards Iceland, creating on average a low in that region. We get snow and bad weather in winter; better weather in summer, because of northerly movement of the Azores high. When this high pressure area moves north for an extended period and the Icelandic low weakens, the effect is known as part of the North Atlantic Oscillation. It is a hot topic in climatology today.

January Winds & July Winds

Illustrations from the text book, referred to above.

Global Precipitation

Global rainfall patterns are strongly influenced by global pressure systems which, after all, drive the winds. You would expect areas of high rainfall in the tropics and in latitudes 40° - 55° (depending on the time of year) where mid-latitude storms and the polar front force air upwards. Areas of low rainfall are where the sub-tropical highs are, and in the polar regions where the air is cold and dry. The monsoons are a direct result of the reversal of pressure between south central Asia and the seas to the south.

Wind Aloft

The wind aloft has a very substantial influence on the weather. The slide summarises three influences, all of which we shall meet again later.

Jet Streams (4 slides)

What's going on aloft has a significant impact on the weather and one aspect of the atmosphere on high that at first came as a surprise to meteorologists is the jet streams. It turns out that the jet stream has an important influence on steering depressions and anticyclones as they come across the Atlantic. High flying planes in the 1940s found that **near the top of the**

troposphere there were some very fast moving air streams - now called jet streams. The slides show the nature of these.

As we'll see in the final section of our course, the jet stream influences whether the mid Atlantic cyclones that sweep across the UK turn into deep and powerful weather systems or just fill and peter out over us; the jet stream determines in which direction 'depressions' cross the UK. The jet stream isn't a stable system of upper air circulation but on a time-scale of days it moves around by up to thousands of kilometres. It is this variability of the jet stream that underpins the variability of weather we experience in the UK.

Let me expand on this for a moment. The underlying reason for the jet streams is the difference between cold arctic regions of the Earth and the warmer Earth near the equator. In the Northern hemisphere the Arctic is warming substantially in the current phase of global warming. One result of this is that the jet stream that influences our weather in Britain is likely to become more variable in its location relative to Britain. Greater variability of the jet stream implies greater variability of the weather, not just over a year but in any given month. In 2012, for example, we had high summer heat in March and early May, followed by one of the coolest Junes on record. In recent years there has been significant snowfall in mid-April on more than one occasion. Isolated examples don't make a trend but there is good reason to think that the characteristics of the jet streams are a feature of global climate and a changing global climate means changing jet stream behaviour. If the meanderings of our jet stream are likely to become more pronounced in future, we'd better get used to more variable weather, and hence more extreme weather, in any given season.

In meteorology on the TV these days, in dedicated programs or just in the forecasts, the jet stream is increasingly mentioned. The story given, which agrees with what I've just written, is that a reduction of the speed of the jet stream occurs with a reduction of the temperature gradient between arctic and equatorial air. Reduced speed increases the meandering of the jet stream and that of itself increases the variability of the weather. A large meander taking the jet stream south of the UK can bring cold artic air over the country. With a slowly moving jet stream, the meanders change less quickly so a weather pattern can 'get stuck' over the UK, increasing the persistence of bad weather. Different bad winter weather is associated with a fast flowing jet stream heading directly for the UK. Fast jet streams allow deep (lower pressure) cyclones to develop over the Atlantic. These sweep across the UK each bringing strong winds and heavy rain. A succession of such 'depressions' one after the other makes for extended unpleasant winter weather that brings flooding and storm damage to the worst affected areas.

Ocean Currents

One of the features that has made the present generation of General Circulation Models (the GCMs) much better than their predecessors is the inclusion of ocean circulation over a range of depths and ocean-atmosphere interaction. The most conspicuous ocean currents are the tides. For a global pattern of the ocean currents, see fig. 11.14 etc. *Gyres* rotate clockwise in the northern hemisphere, anticlockwise in the southern hemisphere. This is the real 'bathplug effect', though no water is draining anywhere, caused by our friend the Coriolis force acting on the ocean currents.

Oceans are huge bodies. They contain an enormous amount of heat energy. Water has a specific heat capacity many times that of rocks; there is vertical motion of water that can bring warm or cool water to the surface, this doesn't happen with rock; there is a horizontal motion of water that transports enormous amounts from one latitude to another, which of course doesn't happen with rock, apart from continental drift on a time-scale of hundreds of millions of years. As an example of the importance of the oceans, I'll mention in advance an issue connected with *El Niño,* which is a topic near the end of this chapter. *El Niño* directly affects the weather of Chile and Australia. What can it possibly have to do with Europe? *El Niño* involves warming over a million square km of Pacific Ocean surface. Sufficient extra heat is fed into the atmosphere by this that there is some effect on global climate, and global temperatures. The final slide in this chapter shows that there are *El Niño* effects very far from the source of the disturbance. The influence of oceans on our atmosphere and hence the weather and climate is very important but it is not straight-forward to model.

To get an ocean moving up to speed, albeit a slow speed must take a lot of time. To stop it, if that were possible, would also take a lot of time. The simplest approach to ocean modelling is to put into a climate model the ocean currents as they are measured to be. However, that isn't completely satisfactory. If the oceans can affect the atmosphere, so the atmosphere can affect the oceans (for example by controlling the amount of solar heating through the distribution of clouds and the rate and direction of water motion through winds). Ocean currents are known to change. The first bad news is that there is no satisfactory model that enables meteorologists to predict the natural variability of ocean currents. The reason why it is bad news is that the oceans affect climate on a timescale of months to years, a timescale longer than 'weather' but shorter than 'climate'. It's the kind of timescale we would like to be able to predict generalities such as 'Are we going to get a hot summer?', 'Can we expect drought this summer?', 'Will the winter bring more snow than usual?' If questions like that could be answered months in advance then the economic benefit of being able to plan in advance would run to billions of pounds in the UK alone. You know of course that questions like that can't be answered at the moment with any worthwhile reliability. Meteorologists feel that understanding the detail of the ocean/atmosphere interaction and being able to predict ocean variability is a key to being able to answer such questions.

So, how much of the ocean circulation system is a permanent feature of the Earth and how much is variable? Is it intrinsically different from atmospheric circulation which is fickle and unpredictable in detail on a timescale longer than a couple of weeks? That is a very important question. We've all heard it said that 'the Gulf Stream warms Scotland and W Scandinavia' even though in fact it's not the Gulf Stream that comes past us but a current that starts in the Bay of Biscay. Wherever it comes from, it's good for us and we don't want it to go away. Is there any essential reason why the ocean currents must be exactly what they are today? If there is, no-one's thought of it - so there probably isn't.

Digression on Chaos (no slide)

The atmosphere is the archetypal chaotic system. This doesn't mean it doesn't play by any rules, far from it. The weather system is controlled by just those physical laws that the forecasters use. The situation is more subtle, though, than it seemed to the early forecasters. In a chaotic system:

1) small, very small, changes in one part of the system will over a period of time affect the whole future behaviour of the system. (The "butterfly effect").
2) The long-term evolution of the system is intrinsically unpredictable in detail. That unpredictability is made worse, as far as computer models are concerned, by

a) lack of data on a fine scale of the weather *now* or, in many parts of the world even on a coarse scale.
b) An imperfect understanding of the physics affecting all aspects of the weather. The ocean-atmosphere interaction is one important subject in this category near the top of the agenda in modern meteorological research.
c) The ability to put current physical understanding into operational forecasting programs. One example is modelling the complex structure of cloud layers, some of which cool the Earth's surface while others warm it.

Starting with (c), money is the essential ingredient in providing the computing needed to model the atmosphere on a fine scale. Already the most powerful computers in civilian use are employed and only national and international organisations can afford these. As I'm updating these notes in 2014, the Met Office's current supercomputer is an impressive 140 terraflops IBM, purchased in 2009. It has computing power to allow it to model fine scale weather in an effort to increase the accuracy in both space and time of precipitation forecasts, particularly from cumulonimbus rainstorms. Now the Met Office is spending £97 million on its successor, a Cray XC40 that will have 480,000 central processing units and operate at 16 petaflops when fully installed in 2017. Take my word that these are impressive statistics in today's computing world, as you would expect for that kind of money. Something can be done in the long term to improve the problems of imperfect physical knowledge (b) and many Universities and forecasting institutions are working on this. Not much can be done without spending a lot of money on weather monitoring to improve (a).

With present day knowledge and techniques, we can't predict the atmosphere, and hence weather, more than 1-2 weeks ahead. Broadly speaking, you can see clearly what the problem is. The pressure systems that will bring us our weather in two weeks time haven't yet been born. Is the birth of a depression that could bring gales across the country in three weeks time a necessity arising out of the current weather pattern? Probably not. Chaos means that the system itself is un-determined in the long run. It can't even predict itself, if you like. I don't know what the ultimate limit on predictability of the weather is, and neither does anyone else, but I doubt if it's more than a month.

As an aside, imagine the same sort of situation in another context. Britain could have a Prime Minister in 100 years time whose actions result in civil anarchy and a disintegration of the UK. Can anyone predict this? Of course not; the person who will be Prime Minister in a century isn't yet born. Are social conditions in the UK such that the birth of this person is inevitable. Again, of course not. The birth of no individual is inevitable. So it is, to some extent, the same with the weather.

3) Another feature of chaotic systems is that they can have a tendency to show large, rapid shifts of behaviour not linked to any large cause. If all this sounds dire news for those who are trying to predict climate change, it's not quite as bad as it sounds. Climate is average weather and although we can't predict, and won't be able to predict at Easter whether the middle days of your summer holiday will be sunny or rainy, we believe we have a hope of predicting climate change that could occur in response to natural and artificial changes in the environment. That's what GCMs are all about. At this stage, no-one knows what aspects of climate should in principle be predictable [quote from Edward Lorenz at 'The Physics of Climate' conference].

4) There is a feature of some chaotic systems that actually helps in the business of predicting weather. Chaotic systems can show scale independent behaviour. Fractal patterns are the 'classic' example. For example some aspects of the pattern of pressure or rainfall fluctuations are the same on a scale of 1000s of kilometres as they are on a scale of 1 km. Now computers haven't got the power to model atmospheric processes in detail on a scale of 1 km but there is the possibility that one can find out on the large scale what the fluctuation patterns are and then feed these in at the small scale, so that the model does have valid information at the smallest scale. This idea is, as far as I know, just being talked about at the moment and isn't a regular feature of weather forecasting models. It shows, though, that one needs every bit of cleverness available to model the processes in the atmosphere and sometimes a problem can be turned into an asset.

In summary, it is chaos that makes meteorology very different from much of astronomy. In astronomy one can predict the position of asteroids, recurring comets and planets in the solar system to high accuracy in a couple of century's time. The predictability of astronomy allowed William Thomson to build his machines that could predict the tide months, even years, in advance. The meteorologists can only look on in envy. Predictions of the weather in a couple of week's time have only a low accuracy. [Astronomy does run into prediction problems but only on a time-scale of tens of millions of years].

In chaotic systems one can create a narrative of past events but not extend the narrative much into the future. I.e. one can hind-cast a long way back but not forecast far into the future. How far in time one can predict depends on the timescale at which change tends to happen. In this context it's important to remember the difference between climate and weather in discussions of chaos. The timescale involved in weather is about an hour. Forecasting the weather to quite good accuracy can be done for a couple of days, say 50 hours, and gets less and less reliable beyond then. The timescale for climate is about a decade. On that analogy, we might hope to forecast climate changes when the climate system has been well modelled to, say, 50 decades, or 5 centuries. It's not at all unreasonable to expect that good climate modelling will be able to predict climate changes until the end of this century, even though we can't predict the weather at any one spot a month ahead.

Back to the oceans. My previous question was essentially: "are ocean currents determined or chaotic?" Of course the time-scale of chaos would be much longer than with the atmosphere - perhaps decades, centuries or millennia, but it will be short compared with mankind's intended occupation of the Earth. A forefront issue in oceanography has been the World Ocean Circulation Experiment (WOCE), which was a large scale international ocean measurement programme, coupled with oceanographic satellite observations (ERS-1, ERS-2, Topex/Poseidon, Jason 1 and 2) and a computer modelling programme which is showing turbulent motions taking place on every scale in depth and in time. This suggests that the oceans are as chaotic as the atmosphere. However, even intrinsically chaotic systems show short timescale patterns. [E.g. planetary positions in the solar system are chaotic in the long term but have stunningly good predictability on a timescale of centuries]. So looking for patterns of years or decades is still worthwhile and the prospect of 'long-range' forecasts for a few months ahead is still a worthwhile goal.

Continuing the theme of ocean currents, I'll just say that the UK's comparatively warm climate for a northerly country is often attributed to the Gulf Stream, as mentioned above.

There's more to it than that. The entire Atlantic Ocean is responsible for transporting heat from the tropics to the solar energy deficit regions poleward of 40°. Poleward of 40° much of this heat is passed from the top level of the ocean to the atmosphere, helping to power the cyclones and anticyclones whose winds are a distinctive part of our climate. As a result the UK's climate is some 5° to 9° warmer than other countries at a comparable latitude, not as a result of warm water lapping our shore but as a result of warm, vigorous air. Indeed the temperature of the water off Aberdeen beach struggles to get into double figures. There is even another factor that highlights how global influences affect our weather. The transport of heat by the Atlantic Ocean northwards (about 1.3 PW at 26° N, if you would like a figure) is substantially greater than that of the Pacific Ocean because the Atlantic is also fed by heat from both the Indian and Pacific Oceans. This additional heat ultimately affects our climate. What effect will global warming have on our privileged position? It's not obvious. Since heat flow is ultimately driven by the temperature difference between equatorial and polar regions, then as global warming heats the poles more than the equator, which it is already doing, then the heat flow northwards is likely to decrease. This could result in cooling Britain. Global climate is complicated.

See the textbook for notes on the following topics covered in the slides.

Global Ocean Currents

Ekman Spiral

El Niño

Normal & El Niño Circulation

Monitoring the Atmosphere and Ocean

The Atmospheric Connection

El Niño and La Niña

Sea Surface Temperatures Recorded

The Wider Effects of El Niño

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