The Atmosphere in Motion

Summary

This chapter gives a broad view of how and why the wind blows. Winds are driven by pressure gradients in the atmosphere and it is therefore appropriate to open the chapter with a brief mention of how these gradients in the atmosphere arise from differential heating of adjacent areas. The concept of pressure has been described in early chapters and used already. This is also an appropriate time to cover the measurement of atmospheric pressure. We've all seen pressure charts in the papers and on TV. How are they drawn? Upper level charts are poured over by meteorologists as much as sea-level charts, yet they are drawn in a different way. We shall see how. The hard part of this chapter is a discussion of the forces that control the strength and direction of the wind. We shall finish the chapter by looking at how winds described are shown on charts. The topics here are covered in Ahrens' textbook in chapters 8 or 9, depending on your edition.

Atmospheric pressure

We have met pressure several times as force per unit area. Gravity confines air close to the surface of the Earth, as effectively as the walls of a balloon confine air blown into it. The pressure of air at ground level can be taken as the weight of air in a column above each square metre.

We begin this chapter with an example of how a pressure gradient induces air motion. Consider two places on the Earth at some distance apart where the surface pressures are equal but the temperatures are not. The places could be as close together as Aberdeen bay, where it is cooler in the summer, and Aberdeen city where it is hotter. They could be two places much further apart. Because cold air is denser than warm air, it takes a shorter column of cold air to exert a given pressure than warm air. That's how the textbook puts it. I prefer to say that the reduction in pressure with height is quicker in the colder column than in the warmer column. The consequence of this is that if you look aloft then the pressure at a given height is greater in the warmer column than in the cooler column. The diagram on the slide shows there is more air above a horizontal line in the warmer column than in the cooler column.

The greater pressure aloft in the warmer column starts a flow of air aloft from the warmer to the cooler column. Taking away some of the air in the warmer column reduces its pressure at ground level and the barometer will decrease slightly. Hence at ground level the pressure gradient will cause air to flow from the cooler column to the warmer column. A circulation cell therefore develops. One example of such a cell is the well-known sea breeze. At least it's well known in Aberdeen. As the column of air above the land warms up, it becomes less dense than the air over the adjacent North Sea. Upper level flow starts from the land to the sea, at a height of a few thousand metres. This sets up a circulation cell that brings a lower level flow from sea to land, creating the sea breeze. That's on a local scale. On a huge scale, the warm air over the equator and the cooler air in Northern latitudes are responsible for global air circulation patterns. These will be discussed in chapter 11.

In one sense, the flows mentioned are counter intuitive. If you heat up air in a tyre, then its pressure increases. Yet with the sea breeze effect, the result of the heating is that at ground level the pressure over the land decreases and a wind blows from the cooler sea to the warmer

land. The situation is different because the air columns are not confined, as in a tyre, and the resulting movement brings about a different effect.

Measuring Pressure

- *Mercury barometer*

The gentleman on the slide commemorated in the marble of a statue in Florence, where he spent the last years of his quite short life, is Evangelista Torricelli. Torricelli has already been mentioned in the first chapter of this course. Torricelli came up with the idea of a mercury barometer, though the sculptor hasn't appreciated that the device is typically a metre long. It was left to others to develop the concept into a working device. Indeed it was over a century after that before people realised that the barometer could be a useful device for predicting the weather, so much so that in due course many a household would have one. That, though, is a story for another day.

The mercury barometer readings are in mm of Hg (or inches, with old barometers), a measure of the height of the mercury column. To convert reading *h* to a pressure P in Pascals, the SI unit of pressure, use

$$P = \rho_{Hg}\, gh \ .$$

ρ_{Hg} is the density of mercury in kg m^{-3}. The mercury barometer is the basis of the most accurate measurements of pressure. Electronic and other instruments are calibrated against a precision mercury barometer. Note the apparent similarity of the device to a common thermometer. Both are columns of mercury in a glass tube. (Well, mercury in glass thermometers were common before the advent of the electronic domestic thermometer). You will not be surprised to find that you have to correct the reading for the thermal expansion of mercury. The calibration also depends on the local strength of gravity, *g*, because pressure is a force and the *g* is the constant that converts mass to force. This was also discussed in some detail in chapter 1.

- *Aneroid barometer*

This consists of a sealed, metallic bellows, partially evacuated. It expands or contracts according to the external pressure and the free end of the bellows moves a pointer. The usual domestic barometer, or at least it was the usual kind before the advent of electronic sensors and displays, has a pointer that rotates around a central pivot. The recording *barograph* has a mechanism for moving a small pen up and down a chart that is usually wound around a cylinder. The cylinder rotates once per week and the chart paper is renewed once per week. Even these barographs are becoming consigned to the antique shops now modern electronic datalogging has come of age.

- *Electronic sensors* These have been illustrated in Chapter 1 and briefly described.

- Pressure units - see chapter 1 notes.

Sea-level pressure charts

Before pressure charts are drawn, station readings are reduced to their sea-level equivalent by applying an average pressure reduction correction of 10 mbars per 100 metres altitude. *Contours of constant pressure*, known as **isobars**, are then drawn, smoothing out wrinkles caused by sparse data, poor height correction and local anomalies. Sea level pressure charts are the charts we see in the media, and indeed they are among the charts used regularly by professional meteorologists. If you are going to look at one forecast chart to help you predict the weather, this is the one chart to see. Almost all the charts in the media are predictions based on forecast models, not charts showing actual measurements.

If you own a domestic barometer, it is usual to set it to record sea-level equivalent pressure so that you can compare the reading with the isobaric charts published in the media. For example, if you live at an altitude of 300 m above sea level, then the real atmospheric pressure will be 30 mb less than the published sea-level equivalent. 1010 mb would be an unusually high pressure (equivalent to 1040 mb at sea-level) whereas it is common to see 1010 mb on the charts.

Chart features

Lows are called depressions or *mid-latitude cyclones*. Highs are called *anticyclones*. The isobar charts used in media forecasts are computer calculated from atmospheric models. They are estimates of sea-level pressures. Those published in the papers are usually for mid-day. *Ridges* and *troughs* describe the features illustrated on the slide because of their similarity to contour map features but remember the isobaric chart shows pressure, not height.

Upper Level Charts

It is common in meteorology to plot the upper-level atmosphere using contour lines of height for a constant pressure surface, such as 500 mb. An *isobaric surface* is a surface of constant pressure. For a warm column of air, we have already seen that this will occur at a greater elevation than for a cold column of air. [Fig 9.13]. Such charts can be interpreted as hills, valleys, troughs and ridges. These really are charts showing heights. The 500 mbar map contains altitudes about 5500 m.

At upper levels, the winds tend to blow parallel to the contours; at lower levels, winds tend to blow across the isobars - why? We'll see shortly. What physics determines the motion of anything? It is Newton's laws of motion.

Motion is governed by Newton's Laws

Newton's laws of motion were introduced in the astronomy class but I'm sure most in the class have met them before. The central law, the second law, explains how force causes motion. Force, said Newton, produces acceleration. The greater the mass a given force is applied to, the less the acceleration. In fact the product of mass times acceleration is a constant for a given applied force and this has led to the famous relationship: $F = ma$, where F is the applied force, in Newtons, m is the mass the force is applied to, in kg, and a is the acceleration produced, in ms^{-2}.

A key issue with Newton's laws that distinguished them from the previous physics is that a body moving with constant velocity has no net force acting on it. This is because acceleration is defined as the rate of change of velocity. No force implies no acceleration, whatever the mass. No acceleration implies a constant velocity. That velocity might be zero, in which case the mass stays at rest but, as Newton pointed out, it may not be zero in which case the body travels in a straight line at constant speed. It's not too difficult to accept that if an ice-hockey puck is given a good knock then it will travel up the rink at almost constant velocity since no stick is pushing it and the friction it experiences from the air resistance and the ice is very small. However, it's much harder to believe that a huge cloud scudding at constant speed across the sky has no force acting on it. The key point to grasp is that the cloud is not moving *through* the air. The cloud is moving *with* the air, which itself can't be seen. A good way to think of it is that the clouds are simply visible signs of the flow of air, just as a stick floating in a steadily flowing river shows the water flow. It has no separate force moving it along. What Newton says is that the sum total of the forces on the cloud is zero if its speed is constant. The cloud is simply water droplets carried along by the local movement of the air. The cloud makes visible the local wind. So, what forces act on air to produce the wind?

Forces determining wind

There are potentially 3 sources of force that contribute to the speed and direction of the wind. If the wind is travelling at constant speed, at least 2 of these forces must be present and will balance out. At ground level, commonly all 3 forces will be present but they will act such that they sum to zero. It's curious but true that with a steady wind there is no net force acting on the air.

If clouds scudding across the sky have no force on them and clouds drifting idly along also have no net force, then why do some clouds scud and others drift? The difference is that the scudding clouds are driven up to higher speeds by a stronger unbalanced force, the pressure gradient force, before this strong force is balanced. On a windy day, strong forces balance; in light airs, weak forces balance.

The forces are:

- Pressure gradient force (PGF)
- Coriolis force (CF)
- Friction

These forces are all have physical causes. On top of these we have a name, centripetal force that describes the effect of a combination of forces that makes air travel in a circular path.

Pressure gradient force

Pressure gradient is the force exerted at right angles to isobars because of the pressure difference between neighbouring places. I hope this is pretty obvious. If you want gas to flow down a pipe, then you must inject it at higher pressure than the pressure at the delivery end so that the pressure gradient drives it down the pipe. If there is a leak in the pipe, the gas will escape if the pressure inside the pipe is greater than the pressure outside. Again, pressure gradient is driving the gas.

We saw at the beginning of this chapter that if neighbouring air columns were at different temperatures even though they were at the same pressure at ground level a pressure gradient would exist at upper levels.

Pressure gradient is simply calculated as the change in pressure divided by the distance over which the pressure changes. In words, pressure gradient (PG) = pressure difference (Δp)/ distance (d). In short-hand symbols, PG = $\Delta p/d$. We have seen in the class lots of forecast isobaric charts that plot pressure contours with a standard interval of 4 mbars. Pressure gradients are implicitly shown on these charts by the distance apart of the contours. The pressure change between neighbouring contours is fixed at 4 mbars but the separation of the contours is what the charts show. The further apart the lines, the weaker the pressure gradient and the lighter the winds. The closer together are the lines, the greater the pressure gradient and the stronger the winds. It's that simple.

With just one force acting on the air, the air will accelerate. There must in general be another force and you may be surprised that the second force always present is one you may well not have heard of. It's the Coriolis force, named after Gaspard de Coriolis, a perceptive Frenchman living in the first half of the 19th century.

Coriolis force

There is a piece of background associated with Newton's laws of motion that I haven't needed to mention yet. It would be much simpler if I never had to mention it but unfortunately I do. Newton's laws of motion link real forces like pressure gradient and friction with accelerations, provided the accelerations are measured in an inertial frame of reference. Inertial frames of reference are frames that aren't rotating. Unfortunately, we are living on a rotating sphere. The reference axes we use to measure position are turning in space because of the Earth's rotation. This means that the co-ordinates of an air mass that is acted on by forces doesn't travel through the same points in space and time that it would do in the absence of the rotation of the Earth. If the coordinates are different, the acceleration will be different.

The difference in acceleration measured by an observer in a rotating frame of reference (compared with a non-rotating one) is absolutely real. The convenient sleight-of-hand is to attribute the acceleration to a corresponding force, using Newton's relationship $F = ma$. In fact the acceleration is the result of relative motion caused by the rotation of the observer. Attributing it to a force turns out to make the effect easier to deal with and visualize. The effect associated with the name of Coriolis results when the motion changes the distance of the object from the axis of rotation.

Before looking at the Coriolis force on an air packet on Earth, let's look at a simpler case. The sketch tries to show why the effect comes about in the case of the motion of a ball thrown across a roundabout or rotating table.

1. The table is fixed and the ball is thrown across from point *a* to point *e*. Looking from the outside, the path of the ball is a straight line. Newton's laws of motion say there is no net force on the ball and hence it travels with uniform velocity. (We'll ignore gravity that drops the ball a little). Someone on the table will agree.
2. The turntable is now set spinning anti-clockwise (the same direction as the Earth looking down on the North pole). The ball is launched from *a*.

3. The ball travels across the table but as it does so the rotation moves the table around so that when the ball arrives at the far side it reaches point *d*.
4. What path does the ball appear to take to someone on the table? The path is a curved path that passes across the centre of the table. Someone on the table sees the ball accelerating in a curve. Newton's laws of motion say that acceleration is caused by a force and hence to explain that acceleration the person on the table invokes a force. That force is the Coriolis force.

Maybe the above seems a bit divorced from thinking about the direction of winds on Earth. In fact it's very relevant. Imagine yourself at the North Pole. The pole is stationary. Air descends from above and starts to blow south (it has to go south!). Now if the Earth were not turning the air would just continue to go south and someone on the ground a bit away from the Pole would experience a north wind. However, the Earth is turning. A point only 100 km due south as seen from a stationary point above the Earth is travelling from the west towards the east at a speed of some 26 km h^{-1}. If the wind itself were travelling south at this speed then a sketch should convince you that on Earth it would appear to come from the NE. At 200 km from the pole it would appear to come from even closer to the direction of East. Of course if there were no friction between Earth and wind then by the time you looked at 1000 km from the pole the wind would be travelling at a fearsome speed, because of the rotation of the Earth. Every point on the Earth has to travel a long way around in space in 24 hours. The Earth carries the wind around with it to some extent but the net effect is that in the polar regions the dominant wind is an East wind. It is the Coriolis 'force' that bends the wind around from north to east in the northern hemisphere (and south to east in the southern hemisphere). You can see that there's no real force acting on the wind, the effect is a result of you the observer being on a rotating frame of reference. The effect is very real, though, in that you really do experience an easterly wind. If the Earth didn't rotate, you'd experience a northerly wind.

It's the Coriolis effect that creates the Sahara and Arabian deserts, the Coriolis effect that makes Western European countries agriculturally productive. The Coriolis effect is so important in dictating the world's winds and hence the world's weather systems that I'm going to put the argument above slightly more generally. If you've followed the story above, I hope this doesn't confuse the issue. The following three paragraphs describe in more detail why the Coriolis force is needed.

Look back at the illustrations of the ball crossing the table. First we look at why the ball accelerates when **viewed in a rotating frame of reference**, the table in our example. What is the view in this frame? Remember that "*the velocity of the object relative to the table beneath it* = (*velocity of the object relative to the ground*) – (*the velocity of the point on the table beneath it relative to the ground*)". Why is the track curved? It is curved because the ball constantly changes its position over the rotating table and at each different position the table has a different velocity relative to the fixed reference frame. The second term in the expression quoted above is therefore constantly changing. Remember also that an acceleration is, by definition, a changing velocity. The resulting constantly changing velocity relative to the table produces the curvature and hence an implicit acceleration when viewed from the table. In fact, any straight track over the ground will be seen as a curved track from the table. Some mathematics that isn't part of this course shows that the track of the ball relative to the anticlockwise rotating table always turns to the right. The acceleration is called the Coriolis acceleration ($\mathbf{a}_c$), after Gaspard de Coriolis who first investigated it and published his account as long ago as 1835.

Why talk about a **Coriolis force**? The general conclusion from all this is that if you want to **apply Newton's law of motion** ($F = ma$) **in a rotating frame of reference** then on the right-hand side of this relationship you want the mass times the acceleration in the rotating frame. However, the acceleration in the rotating frame is equal to the acceleration in the inertial frame plus the extra acceleration components introduced by the rotation. One of these components is the Coriolis acceleration $\mathbf{a}_c$. This component is taken to the other side of Newton's equation, multiplied by the object's mass and called a 'force', the Coriolis force in fact. That's it. It takes a little while for what's happening to sink in. The Coriolis force is usually described as 'fictitious', 'imaginary', 'apparent' or 'fake' in that it's not caused by a real material thing pressing on the object, but the resulting effect is not imaginary at all. In fact it's very real. An object moving relative to the rotating frame really does veer to the right in that frame just as if a real force made it do so. Try this in your local park. Sit on a roundabout and get a friend to sit on another part of the roundabout. Set the roundabout spinning anticlockwise and throw a ball straight at your friend. As seen by you on the roundabout, the ball will veer to the right and miss its target. Likewise, when your friend throws to you. It's not an insignificant little effect but quite a big effect.

In our simple example of the ball flying over the table, the track is just the same whatever the mass of the ball. This result comes out of the argument above because we had to multiply the Coriolis acceleration by the mass when we turned it into a Coriolis force. In the equation $F = ma$ the mass on the left-hand side cancels the mass on the right-hand side, leaving a result independent of mass. The Coriolis force's dependence on the ball's speed is even more subtle. You might think that because the track is straighter with a faster ball the Coriolis effect would be less, but that's not so. The track may be straighter but to produce any deflection at all on a fast moving object needs more acceleration because the time available to produce the deflection is less. The net effect is that the Coriolis force needs to be bigger the faster the ball travels to produce the observed apparent deflection. Finally, the Coriolis force depends on the speed of rotation of the table. [For those who would like to see it, the mathematical expression for the Coriolis force is that its magnitude equals $2m\omega v$, where m is the mass of the object, ω is the angular speed of rotation of the table and v is the speed of the ball relative to the table. In addition, the Coriolis force is at right angles to both the axis of rotation and the velocity of the object relative to the moving frame.]

Consequences of the Coriolis effect

For anyone on the rotating table, the Coriolis force seems real enough. We're on our rotating Earth and the Coriolis force must be included to explain the motion of air masses. I've spent some time on this because the Coriolis force is not an easy idea to get hold of yet it's crucial in explaining the winds on Earth, which we'll see do blow in a way you wouldn't really expect, just because of the Coriolis force. As far as meteorology is concerned, one just needs to accept that on any rotating planet or moon with an atmosphere an air packet moving on a large scale will experience a Coriolis force with the properties mentioned above.

Small scale movements like bathwater disappearing down the plughole or creepers twisting around trees don't depend on the Coriolis force and if you see different directions in northern and southern hemispheres, Coriolis isn't the reason. The limerick on the slide, courtesy of the American Physical Society, reminds us that the Coriolis force is responsible for motion to the right, but in the northern hemisphere only. In the southern hemisphere the Coriolis force is responsible for motion to the left.

Coriolis effect on winds

In the Northern hemisphere the Coriolis force always deflects winds to the right, no matter what their initial direction. At the pole, the effect is the greatest. There the situation is much like that shown with the turntable two slides back. At the equator there is no effect because the rotation of the Earth doesn't change the distance of a body from the Earth's rotation axis. Therefore the Coriolis force gradually decreases from pole to equator. In our latitudes it's important.

One final but very important point in relation to the Coriolis force is that it always exerts its effect at right angles to the velocity of the object it affects. This means it can change the direction of the object but it can't slow it down or speed it up. You can only do that with a force that acts at least partly in the direction of travel of an object. The Coriolis force changes the direction of winds but not their magnitude. This make good physical sense because to change the speed of a moving object you have to give it more energy, or take away energy, and that can be done only by a real force not a conceptual force like that of Coriolis.

Coriolis controls the direction of circulation

Remember that in the northern hemisphere the Coriolis force turns the wind to the right. Around a high-pressure system, the combined effects of the Coriolis force and the pressure gradient force produce a clockwise wind. Around a low-pressure system, the wind will be anticlockwise.

The opposite happens in the southern hemisphere. Wind in cyclones over Australia and New Zealand for example rotates the other way from cyclonic wind over Britain. Other 'odd' things happen in the southern hemisphere like the sun rising in the east, moving through the north and setting in the west. Since home base for these notes is Scotland, all the examples are going to be northern hemisphere based.

Nature of the geostrophic wind

For winds aloft, say over 1000 m above ground in altitude, the only forces of significance are the pressure gradient force and the Coriolis force. A wind that begins to blow across the isobars is turned as it picks up to the right. As the wind is deflected, so the Coriolis force keeps changing direction to remain at right angles to the wind. Eventually the Coriolis force is directed exactly opposite to the pressure gradient force and the wind moves parallel to the isobars. It's another 'strange but true' situation. The wind ends up blowing at right angles to the direction you expect. This wind is called the **geostrophic wind**.

The situation is a bit like the case of a falling body reaching terminal velocity. Terminal velocity is reached when the two forces that affect the body, its weight and the air resistance, balance. A packet of air reaches terminal horizontal velocity when the two horizontal forces balance, namely the pressure gradient force and the Coriolis force.

The wind aloft really does closely follow the isobaric contours. At ground level there is the additional factor, the friction between wind and ground. We'll see shortly that this does make a difference but not too much of a difference.

Strength of the geostrophic wind

Remember that the geostrophic wind blows when the Coriolis force equals the pressure gradient force. The wind is driven by the pressure gradient force but the balance condition between these two forces determines how fast the geostrophic wind blows. The textbook shows the result. As you might expect, the answer depends on the latitude you are at. At the top left of all the Met Office synoptic charts I've shown in the class there is a little graphic that enables you to deduce the speed of the geostrophic wind in terms of the separation of the isobars on the chart. You can see clearly that for a given distance between isobars, the wind speed is *less* as you go further North because the Coriolis force is stronger and sets itself at against the pressure gradient force at a lower wind speed.

You can also see from the slide that the wind speed varies inversely as the density of the air. This implies that winds aloft will be faster because air density decreases as you rise. This is true. It is because for a given volume of air the Coriolis force is less at very high altitudes because the mass of air is less. A weaker Coriolis force means that you need a faster speed to balance the pressure gradient force.

Cyclonic flow and the gradient wind

Two slides back the isobars were drawn as straight lines. For both cyclonic and anticyclonic pressure systems, the isobars are often curved in roughly circular contours. The idea that winds aloft blow parallel to the isobars is still true for circular contours but to keep the wind blowing in a circle there needs to be a net force directed towards the centre of the circle. This force is called the **centripetal force**. The centripetal force is just a name, not a new effect, the name given to the difference between the pressure gradient force and the Coriolis force. Take the case of cyclonic flow. The wind goes around the contours anticlockwise, as we've seen, and the net force needed to keep it in circular motion comes from having a stronger pressure gradient force than a Coriolis force. In other words, centripetal force = (pressure gradient force) – (Coriolis force).

Anyone who has studied the basic mechanics of motion in a circle knows that the acceleration towards the centre of the circle is given by the expression v^2/r, where v is the speed of the rotating body and r its distance from the centre of rotation. The acceleration is simply the force per unit mass on a packet of air. The centripetal force is therefore quite noticeable for strong winds (large v). For such winds around cyclonic flow the pressure gradient force noticeably exceeds the Coriolis force.

Anticyclonic flow

For anticyclonic flow, the centripetal force must again be directed towards the centre of rotation. In this case the Coriolis force exceeds the pressure gradient force, as shown.

Buys Ballot's law

Understanding wind flow in terms of the pressure systems around the globe was a discipline that had its roots in the nineteenth century. No-one was more interested in the wind than sailors and Buys Ballot, a Dutch meteorologist, came up with a simple law that any sailor could learn that would help him tell where the pressure gradient lay and where he was in

relation to the centre of the local weather system. "Stand facing the wind", he said, as any sailor normally would do, "and the low pressure is on your right". You can see from the illustrations that he was right. This rule is still very useful, not only for sailors.

Surface winds

Friction between wind and ground (fields, forest, sea, urban landscape, wilderness) slows the wind and introduces another real force into the situation. The requirements of Newton's laws of motion are that when the wind speed is constant, the 3 (vector) forces must all add up to zero. The frictional force is always in the opposite direction to the direction of travel of the wind and the Coriolis force is at right angles to the wind. The diagram shows what happens when all three forces are present. The Coriolis force is no longer at right angles to the isobars and neither is the wind direction parallel to the isobars. For a cyclonic system, there is a net inflow of air towards the centre; for an anticyclonic system there is a net outflow from the centre. Typically the wind may be at some 30° to the isobars and hence Buys Ballot's law need a slight rewording: facing the wind, the low press is about 60° to your right

Summary

The rules given on the slide summarise the key points of the story. Remember these and you've got a good grasp of what's happening on the large scale. The wind that blows because of the current weather system shown on the pressure charts is often called the *gradient wind*, as headlined a few sections back. Superimposed in this may be a *local wind* such as a sea breeze.

If you live in a place where trees and countryside or parkland are visible from the windows you'll know that you can often wake up early, look out of the window and see little wind. As the day wears on the wind will get up and by early afternoon there may be a decent breeze. In the evening, the wind dies down again. This can happen on cloudy days as well as sunny days but it's obvious that the Sun must ultimately be responsible for stirring up the local wind. It's a reminder that the pressure chart and accompanying forecast is a forecast of large-scale behaviour and not a hard and fast statement of what is happening on the scale of a few kilometres. To try to encapsulate local behaviour is a big driving force for forecasting organisations such as the Met Office in the UK to spend tens of millions on large computers. (Of course it's not just local wind that they are trying to predict, but local rain, fog, etc. as well). Particularly if the gradient wind is weak, such as when a large anticyclone is centred over the country, then the local wind will be the one we will experience and this might be in quite a different direction from what gradient wind there is. It's also likely to vary from place to place and from hour to hour. Sailors 'looking for the wind' in light conditions are well aware of the fickleness of local winds.

As well as making the point that local influences are superimposed on the larger scale weather system, I'd also like to say that forecasting isn't just a matter of looking at the weather system now and, knowing how it is moving, predicting that a cloud band will sweep across the country or the band of clear sky will do likewise, etc.. It's partly this but weather systems evolve with time so it's necessary to factor the evolution in as well: depressions fill, warm fronts occlude, anticyclones deflate, clouds rain themselves out, and so on. Getting the timing of these details right is not easy, which is one more reason for needing ever larger computers even though the 'big picture' is reasonably clear.

Wind arrows

Wind is described by the direction it comes from. This is sensible since where it comes from has had an influence on its properties such as its temperature and humidity. For example in our latitude, we expect northerly winds to be cold and southerly winds comparatively warm, though the situation is complicated by the tendency of the wind to move round a cyclone or anticyclone. Wind arrows are drawn on a chart as if the arrows are flying with the wind. Hence they point in the direction the wind is going. The arrow-heads are omitted but the feathers are drawn to represent the wind speed. A whole feather represents a speed of 10 knots; a half-feather a speed of 5 knots and to avoid you needing to count lots of feathers for a really strong wind, a speed of 50 knots is represented by a solid triangle. One **knot** is a nautical mile per hour, showing the nautical influence in the early years of modern meteorology. A nautical mile is north-south distance between lines of latitude one arc minute apart and is a good bit more than the statute mile still in use in Britain for road distances. 1 knot is 1.85 km hr^{-1} or about 0.5 ms^{-1}.

Use of wind arrows

The following two slides show charts with wind arrows reporting the observed wind.

If you live in a town or city, wind isn't much of a concern on a daily basis unless it gets extremely strong. A good breeze whips up papers and dust and when canyoned between high buildings can make itself felt, but on the whole most wind is little more than an inconvenience. At least that's the impression we get until the wind dies away altogether, in which case the atmosphere can get oppressive and hazy and light dust builds up pretty quickly. A little wind in towns is definitely desirable. Out in the countryside, the farmer doesn't spent too much time thinking about the wind either, unless it's strong enough to blow his topsoil off or break branches off his trees. It's the sailor and seamen who rate the wind as the most important weather element. The shipping forecast is mainly about wind, its direction, its strength and likely changes over the next 24 hours; a distant second comes the visibility. Sunshine and rain are hardly mentioned. The farmer is concerned about sunshine and rain, visibility is of no concern and wind a minor issue. The town dweller is mainly concerned about personal comfort: will a coat or umbrella be needed today, temperature and precipitation are the main issues. Spare a thought for the public weather forecaster, who has to cater for everyone, and of course will inevitably please few completely. Forecasters working for specific groups, whether oil service companies in the North Sea, farmers or fishermen, are able to produce a tailored product that should satisfy most of their clientele.

In future, wind may feature more in public forecasts as more and more businesses and individuals install wind turbines to generate some of the electricity they use. People may expect more quantitative sunshine forecasts to estimate their solar panel outputs. When weather elements have a clear cash value then effort put into monitoring and predicting them always increases.

While talking of the effects of weather, I'm reminded that earlier in the course I quoted a passage on the dire effects of freezing rain on woodland in the US. Much nearer home, a passage in the autobiography of the famous geologist Hugh Miller describes his experience of a severe gale in his hometown of Cromarty in Northern Scotland. I have slightly abbreviated his full description. All the words are his own. *At the close of the year 1830, a tremendous*

hurricane from the south and west blew down in a single hour four thousand full-grown trees on the Hill of Cromarty. The vast gaps and avenues which it opened in the wood above could be seen from the town; and no sooner had it begun to take off than I set out for the scene of the ravages. As I approached the wood, I met two poor little girls of from eight to ten years old, coming running and crying along the road in a paroxysm of consternation; but, gathering heart on seeing me, they stood to tell me that when the storm was at its worst they were in the midst of the falling trees. Setting out for the Hill on the first rising of the wind, in the expectation of a rich harvest of withered boughs, they had reached one of the most exposed ridges just as the gale had attained its extreme height, and the trees began to crash down around them. Their little tear-bestained countenances still continued to show how extreme their agony and terror had been. They would run, they said, for a few paces in one direction, until some huge pine would come roaring down, and block up their path; when, turning with a shriek, they would run for a few paces in another; and then, terrified by a similar interruption, again strike off in a third. At length, after passing nearly an hour in the extremest peril, and in at least all the fear which the circumstances justified, they succeeded in making their way unhurt to the outer skirts of the wood.

In getting into the thick of the trees, I was struck by the extraordinary character of the scene presented. In some places, greatly more than half their number lay stretched upon the ground. On the more exposed prominences of the Hill, scarce a tree was left standing for acres together: they covered the slopes; tree stretched over tree like tiles on a roof, with here and there some shattered trunk whose top had been blown off, and carried by the hurricane some fifteen or twenty yards away, leaning in sad ruin over its fallen comrades. What, however, formed the most striking, because less expected, part of the scene, were the tall walls of turf that stood up everywhere among the fallen trees, like the ruins of dismantled cottages.

Nothing relevant has changed since 1830. Trees are still trees, the wind is still the wind. The same disaster could repeat itself in modern times. Miller's description suggests a storm quite as fierce as the famous 'Great Storm' of October 1987 in South-East England that has entered the annals of British meteorology as one of the worst weather events in recent memory.

Beaufort wind scale

It was the British naval captain and later hydrographer to the navy, Francis Beaufort, who brought into use the wind speed system still that is widely employed and reported in every shipping forecast. The Beaufort scale is a simple number that represents wind speeds from 0 for calm to hurricane force 12. For each force there is a short description of what the effect of the wind is. That description is different over land and sea, just because on land you can watch the dust being kicked up by the wind and trees bend in the breeze whereas at sea you have to look at the waves. The slide shows the descriptions on the sea and on land for two of Beaufort's force points.

Francis Beaufort (1774 – 1857)

Beaufort was born in Ireland but came up through the ranks of the British Navy from cabin boy to Admiral. His interest in science was personal but in later life he was in charge of the very important Hydrographic Office of the Navy, the office responsible for producing the official Admiralty navigation charts. He was in a good position to steer the Navy into using more science to back up and improve its practices. One way he did this was to get the Navy

to adopt the simple wind speed scale he had used in his days as a Captain, a scale that he didn't lay claim to inventing but one he improved and found useful over many years. The scale defines the wind speed in terms of the effects it has. In Beaufort's original, the effects were how a man-of-war handled in different winds. Adaptation has replaced the man-of-war descriptions with ones useful to everyone.

Beaufort himself was interested in the measured wind speeds that corresponded to the points on his scale. He commissioned fellow Irishman John Robinson, the astronomer at the Armagh Observatory, to find out for him and the result of this commission was the development of the Robinson cup anemometer and, of course, the wind speeds for the various points on Beaufort's scale. The original Robinson cup anemometer is still extant on the Armagh Observatory.

Measuring wind

The very first slide of the course showed our historic Robinson cup anemometer on the Cromwell tower. The modern version has three cups and you can see on this slide the picture of the one on the Fraser Noble building. It works because the cups rotate faster pretty well in proportion to the speed of the wind. Nowadays a simple electronic signal is generated by the rotating mechanism in proportion to the speed of rotation and that signal is recorded electronically. The early instruments were purely mechanical.

Wind has direction as well as speed and a wind vane shows the wind's direction. Wind vanes are asymmetric, with a largish plate incorporated into the design that orients itself downwind. The other end of the vane, an arrow in the case of the wind vane on the Meston building, points to the direction from which the wind is coming. Again in the modern version the angle at which a wind vane is pointing generates an electrical signal that is recorded digitally. The technique commonly used is actually simple. The wind vane arm operates a variable resistor in the base of the unit, the same sort of component that you turn when you rotate the volume control on the knob of a radio or audio amplifier. The changing resistance as the vane rotates generates a changing voltage that electronics picks up and records.

What use is a barometer?

Much of this section has focused on pressure and pressure changes. Air pressure is of course measured by the barometer, one of the few 'scientific instruments' that it's common to find in people's houses. Why do we at home want to be able to tell what the atmospheric pressure is? Clearly, when the barometer shows a high pressure, like 1030 mb, then there is an anticyclone over us; if the barometer reads a low pressure, like 980 mb, then a depression is passing over. However, that's not the main reason for keeping a barometer in the house.

The barometer has genuine weather predictive capability if you concentrate on the rate of change of the barometer. A quick fall in the barometer shows that an intense depression is on the way. You can expect strong winds and probably heavy rain from the associated advancing front. You can now see why this should be from the underlying fact that the strength of winds associated with a weather system depends on the pressure gradient. If the pressure gradient is large, then the isobars will be packed close together and in only a few hours the pressure will change substantially at one place as the system sweeps across the country.

The barometer is probably the single most useful weather predicting instrument. It's not foolproof because it doesn't actually measure pressure gradient nor tell you directly where the weather fronts are. If by chance the weather system is moving parallel to the isobar that passes through your location, then of course there will be no change in pressure. That won't save you from any accompanying strong wind. The barometer doesn't always get it right then, but it's a useful aid. This was recognised in the early days when scientific meteorology was being established in the first half of the 19th century. The government ran a scheme of establishing public barometers in fishing villages around the country so that offshore fishermen had something more scientific to consult than mere weather lore. Some of these barometers still survive. I saw one in the main street of Stromness in the Orkney Isles when I was last there. You can't get any nearer than this to bringing scientific measurement to 'the man in the street'. If the fishermen (or anyone) observed the barometer almost steady at a high value, then a settled spell of anticyclonic weather was present. The same is exactly true today.

Old aneroid barometers have a blind hand that you set opposite the moving hand when you first look at it. Then a few hours later when you tap the dial to loosen any static friction within the mechanism, the distance that the moving hand has moved from its old position is immediately visible. The gap between the two hands gives you a direct measure of the pressure change. Nowadays, electronic barometers often have a small bar display that shows the change in pressure over the past 12 or 24 hours.

It's several decades since I last saw a fishing boat stranded on Aberdeen beach and if I have remembered the press coverage that followed, inebriation of the crew was one of the contributing factors in this case. However, it wasn't always so. In 1876 from mid-November to mid-December a series of exceptionally bad storms hit this area and carnage was the result. I'll finish my quotations with some lines from this time. *The gale began on Monday, 13th November, and continued intermittently for upwards of a month. The wind, blowing hard from the south-east, speedily had the sea into a tempestuous condition;……*and there follows an account of the first series of disasters that resulted from a combination of high tide and rough on-shore seas that caused serious flooding of low-lying local houses and evacuation of many families. The account continues that on 4th December *flooding again took place and so high was the tide that the waves came dashing against the houses in Fisher Square* [in Footdee], *flowing over the roofs in several instances*. Some sixty people here were forced to evacuate their houses of all their possessions and store them in the Footdee church. Worse was to come. *On the 20th of December the gale rose afresh, and on the succeeding days increased to such a hurricane as was considered almost unparalleled in these regions. Again there was flooding and much damage to the harbour and other property in Aberdeen. All the railway lines in the north were either blocked by snow or flooded, and the telegraph service was for a time at a standstill. A Norwegian barque was driven ashore at Belhelvie, and the master and three of the crew were lost. A Norwegian brig made an effort to enter Aberdeen harbour, but, failing, was driven northward and struck the beach north of Donmouth. Fortunately the seven men forming the crew were got off safely. Another Norwegian brig was driven ashore near Donmouth, and the crew of nine were drowned. A foreign barque foundered off the Black Dog, all hands being lost. On the Belhelvie sands a brig struck, and the crew of eight were drowned – four of them while attempting to get ashore. The crews of two other vessels which struck near Donmouth were got off in safety, except one man, who fell into the sea and drowned. Two vessels foundered in St Coombs, and no trace of their crew remained. Two vessels struck the rocks near Cove, and both foundered at once, carrying their crews with them. A similar fate overtook a schooner at Newtonhill, the crew of eight*

being lost…..In short, it was one long series of frightful disasters along the whole of the East Coast of Scotland. In all sixty nine vessels were known to have been lost, and the number of lives sacrificed mounted up to the appalling total of 294. The fact that such disasters in this part of the world are now no longer within living memory is not on the whole due to better weather; it is due to modern weather forecasting, to modern navigational aids and to a quantification of risk and advance preparation for failure.

A National observatory

The final slide shows the observing towers on the top of Mont Aigoual in the Cevennes in southern France as I saw them a few years ago. It is one of the national observatories run by Meteo France. The array of recording instruments includes a variety of wind gauges and puts our small observatory into perspective!

JSR