

Understanding and Interpreting Radiosonde Ascents

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1. Introduction

The vertical temperature, humidity and wind structure of the atmosphere is absolutely fundamental to determining the weather conditions experienced at the ground. Meteorologists have long realized that in order to be able to understand the hour-by-hour variations of the weather and to make weather forecasts, we need to be able to observe the vertical structure of the state of the atmosphere not just the weather at the surface. The first attempts to measure this vertical structure were made during the mid nineteenth century with instruments attached to kites. The first balloon-borne measurements of the temperature of the atmosphere were made in the 1890's at the meteorological observatory at Trappes near Paris, and led to the discovery of the tropopause and the stratosphere. Trappes is still the location of a meteorological observatory and provides operational balloon borne measurements twice a day (upper air station number 07145).

During the 20th century, and particularly during the 2nd World War, the development of aircraft flying at increasing altitudes led to a demand for even better measurements of the state of the wind, temperature and humidity through the depth of the troposphere. Instruments were developed which could be attached to helium or hydrogen filled balloons, measure pressure, temperature and humidity every few seconds as the balloon ascended, translate these measurements into variations in voltage or current in an electrical circuit and then transmit the readings back to a ground station in real time. In addition, tracking the balloon's position by radar, and more recently by GPS, allows the calculation of wind vectors at different levels of the atmosphere. This is the modern radiosonde, and all around the globe approximately 1000 of these instruments are launched twice a day, of which between 600 and 800 are used to help set the initial conditions of the numerical weather forecasts run by the world's major meteorological agencies.

Despite the advent of high resolution Numerical Weather Prediction computer models, providing increasing levels of forecast accuracy, the data from radiosondes are still of a great deal of use to weather forecasters, beyond just being used in the data assimilation process to set the initial conditions for NWP forecasts. Particularly for forecasters working with both civil and military aviation, radiosondes can provide very useful information about the vertical structure of clouds and winds and the position and intensity of weather fronts and convective storms. In addition, radiosonde data are a fantastic tool for learning about the atmosphere and understanding how the weather which we experience at the Earth's surface is determined by the 3-dimensional structure of the atmosphere. Being able to interpret a radiosonde sounding in terms of cloud layers, vertical motion, position and intensity of fronts and the likelihood of convection is a very useful skill for any meteorologist.

2. The Tephigram

Once instruments had been devised which could measure the temperature and humidity of the atmosphere in the vertical, a new challenge was set for meteorologists – what was the best way to represent this information in a useful graphical format? A number of different solutions to this problem were devised including the Skew-T log-P diagram commonly used in the USA, but the version we shall focus on here is the *tephigram*.

The tephigram was devised by the British meteorologist William Napier Shaw in about 1915. Its name comes from the fact that it is effectively a graph of temperature (T) against entropy (which was at the time usually denoted by the Greek letter ϕ) – hence T- ϕ -gram. Nowadays we use the letter s to denote entropy but the name tephigram remains in use.

The tephigram is nothing short of a work of genius. It is both exceptionally clever and very easy to use, although at first look it seems rather complicated. And indeed the way it looks is a result of a complex series of transformations. However, so well designed is it that it has not changed in its fundamental structure since its inception.

Perhaps the obvious thing to do when presented with some information about the variation of the temperature of the atmosphere with height is to plot a graph of temperature against height. However because temperature falls quite rapidly with height in the troposphere such a graph would show a rapid decrease with height and all the small, subtle variations would be lost in the general decreasing trend – see figure 1.



Figure 1. A schematic graph of temperature (T) against height (z).

Another disadvantage of simply plotting temperature against height is that the area under the temperature curve does not represent any thermodynamic quantity of the atmosphere – i.e. this graph is not a *thermodynamic diagram*. In classical physics we are used to seeing a P-V diagram which plots the pressure of a gas against its volume. On such a diagram the area under a curve which represents a change of state of the gas is proportional to the work done on the gas during the transformation. Napier Shaw was looking for something similar but clearly volume is not a quantity that is measured by a radiosonde, or has much utility for meteorologists. Instead Napier Shaw decided to plot temperature against entropy (s). The entropy of a parcel of air is proportional to the natural log of its potential temperature (θ) and potential temperature is a function of the temperature and pressure of the parcel - see equations 1 and 2.

$$s = c_p \ln \theta \quad 1$$

$$\theta = T \left(\frac{p}{p_0} \right)^{R/c_p} \quad 2$$

Where p_0 is usually taken to be 1000 hPa.

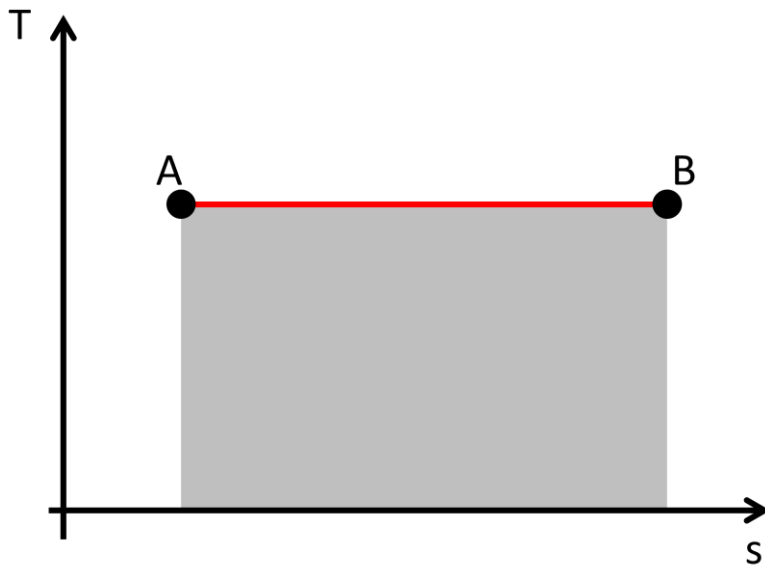


Figure 2. a schematic plot of temperature T against entropy s . The red line from A to B represents an isothermal process acting on an air parcel with initial thermodynamic state A. The grey shaded area under the line is equal to the heat added to the air parcel during this process.

Figure 2 shows the result of plotting T against s . The red line from A to B represents an isothermal process whereby an air parcel increases its entropy without changing its temperature. The grey shaded area beneath the red line is equal to the heat added to the parcel during this process (dQ), since $dQ = T.ds$.

Figure 2 doesn't look much like a tephigram, and the really clever thing that Napier Shaw did to transform this fairly standard thermodynamic diagram into a meteorologically useful way of displaying radiosonde soundings was to transform the orientation of the diagram.

The first thing he did was to draw onto the diagram lines of constant T , lines of constant s (or θ) and lines of constant p (the green curves on figure 3). Higher pressures occur in the top left-hand corner of figure 3 (i.e. $p_3 > p_2 > p_1$).

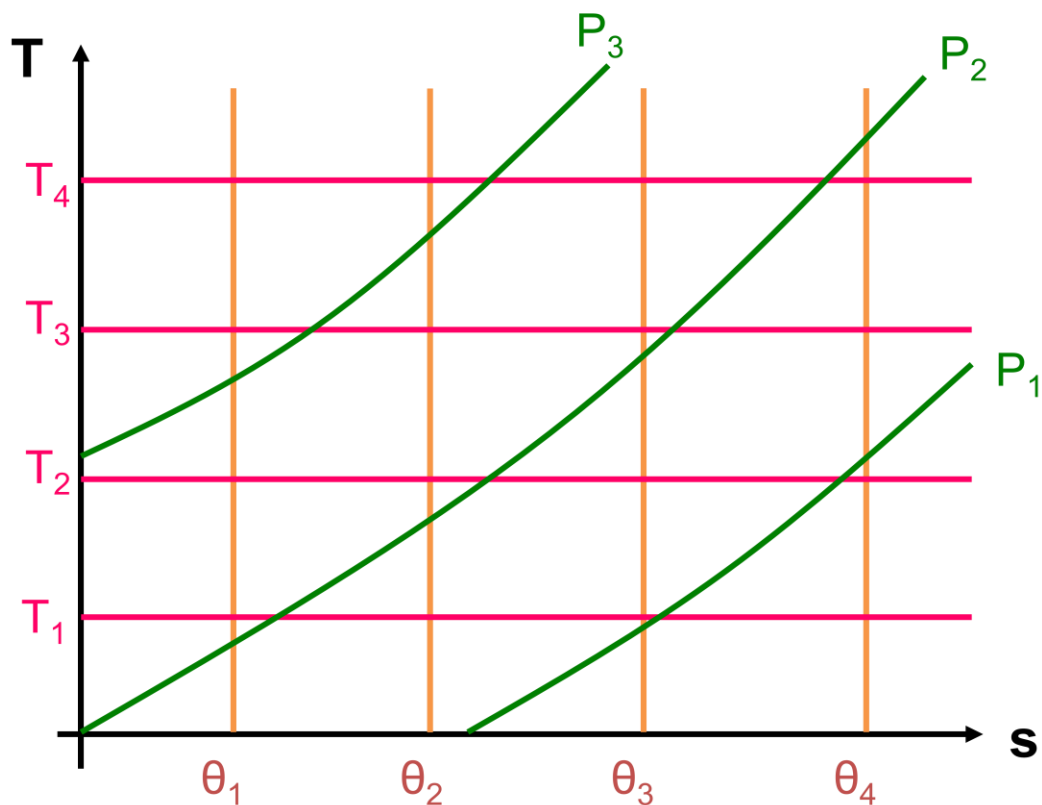


Figure 3. A T versus s thermodynamic diagram with lines of constant T (red), constant θ (yellow) and lines of constant p (green) superimposed.

Next he rotated the whole diagram through 45° so that the T and θ lines slope across the diagram at 45° instead of being horizontal and vertical lines – see figure 4.

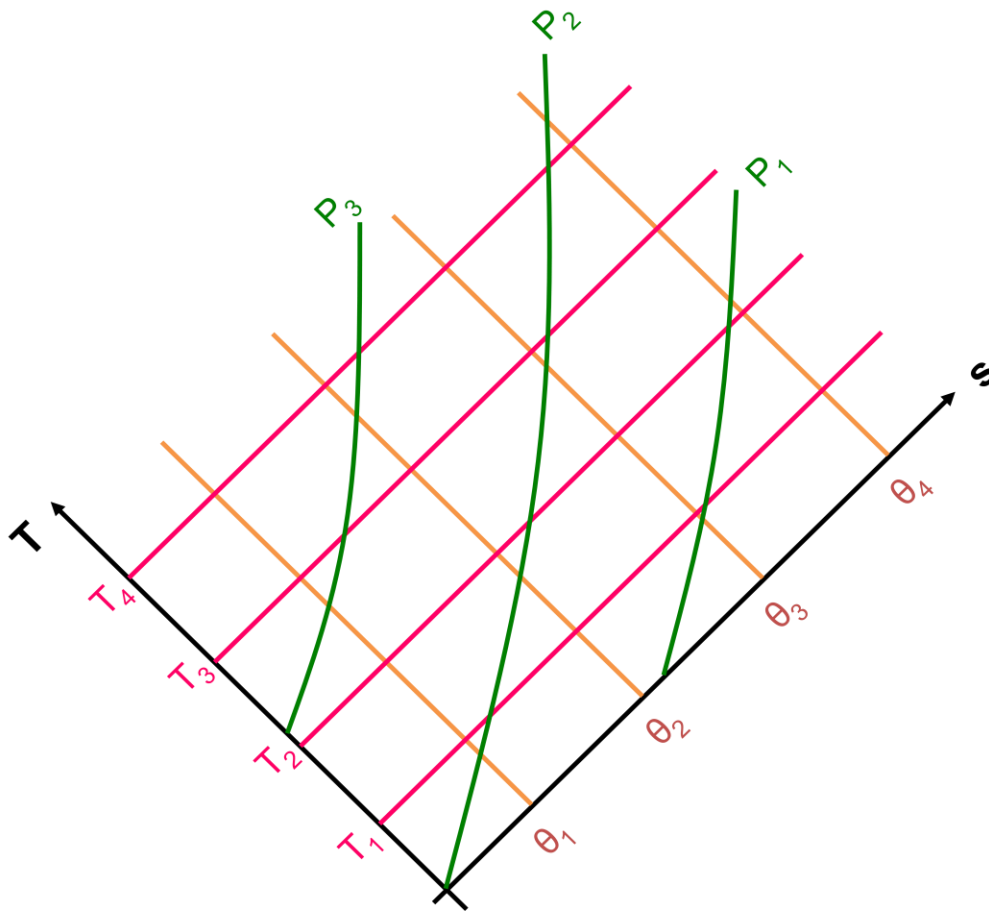


Figure 4. The T versus s thermodynamic diagram rotated through 45° .

Finally the whole graph is reflected about the s axis (imagine standing a mirror with its bottom edge on the s axis and then plotting the reflection). The result looks like figure 5.

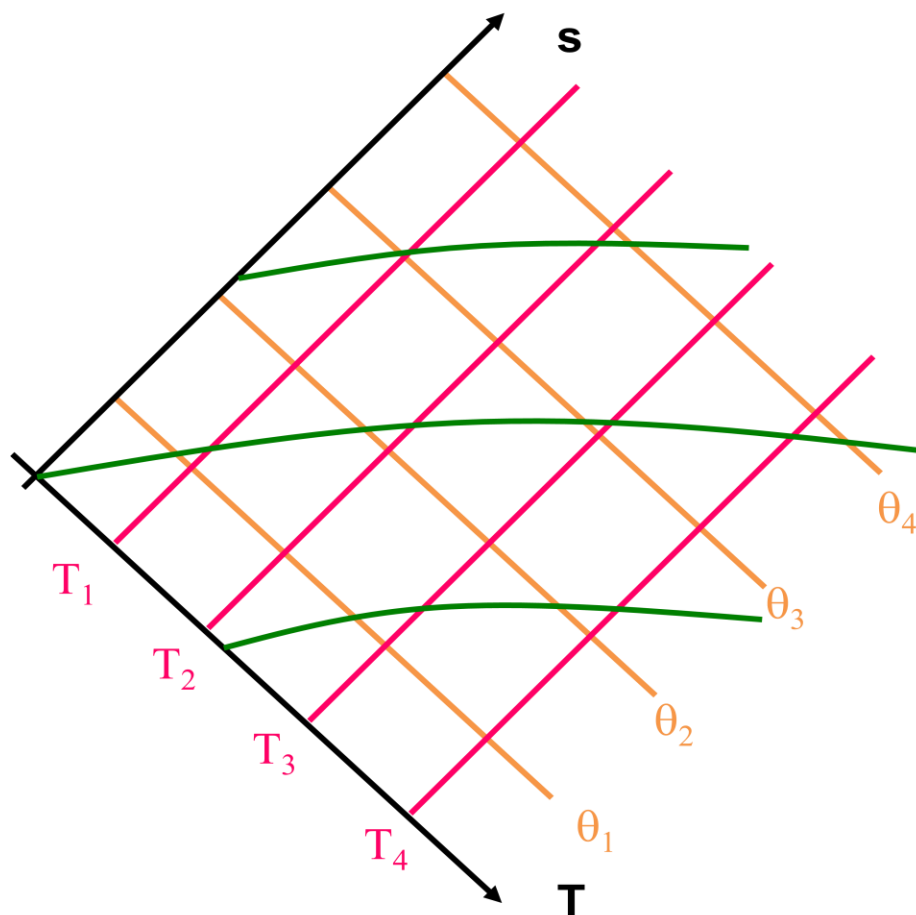


Figure 5. The T versus s diagram rotated through 45° and then reflected about the s axis. This is now oriented like an operational tephigram.

Figure 5 shows the layout of the tephigram as we actually use it. Note that a consequence of the reflection about the s axis is that now pressure decreases as we move from the bottom of the diagram towards the top, just as pressure decreases with height in the real atmosphere. Potential temperature is higher at the top of the diagram than the bottom (in the atmosphere θ nearly always increases with height or is constant with height) and T is lower at the top of the diagram than at the bottom (in the real atmosphere temperature almost always decreases with height – at least in the troposphere). So now, not only is this a useful thermodynamic diagram but it is also oriented in a way that makes intuitive sense for plotting graphs of temperature measured by a radiosonde. A version of the operational tephigram is shown in figure 6.

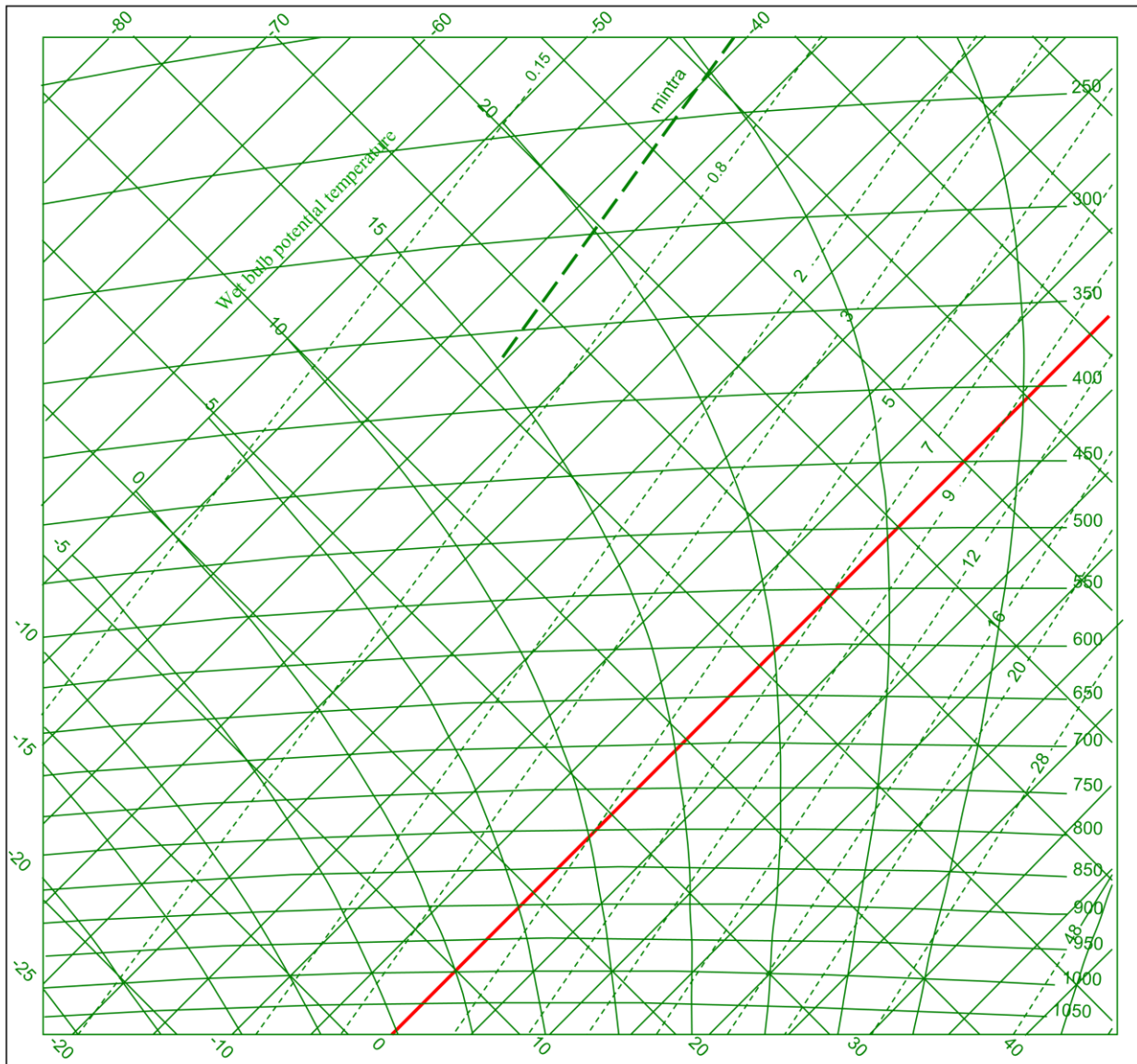


Figure 6. An operational tephigram. The red line shows the 0°C isotherm.

One thing that is immediately apparent on figure 6 is that there are more lines on the operational tephigram than on the schematic version in figure 5. In particular there are 2 sets of lines that do not appear in figure 5. The first of these is a set of dashed lines running from bottom left to top right of the diagram, which are not quite parallel to the lines of constant temperature. These are lines of constant *water mixing ratio* and are labelled in units of grams of water per kilogram of dry air (g/kg). These are used for displaying information about the humidity of the air and will be discussed later. The other set of new lines is a set of curves which appear almost vertical near the bottom of the diagram but gradually lean more towards the top left corner as pressure decreases until, towards the top left corner they become parallel to the lines of constant potential temperature. These lines are labelled as lines of constant *wet*

bulb potential temperature and their meaning will be discussed later. The other line that appears on this operational version of the tephigram which is not on the schematic version in figure 5 is the long dashed line labelled “mintra”. This line is of little relevance to today’s meteorologists, giving as it does an indication of the likelihood of the formation of condensation trails from a Rolls-Royce Merlin engine (as used on WWII Spitfire aircraft).

3. Plotting Radiosonde Data onto a Tephigram

Having obtained a usable version of the tephigram, both as a thermodynamic diagram and a piece of graph paper which is appropriate for atmospheric sounding data, radiosonde ascents can now be plotted onto it.

Figure 7 shows an example of a radiosonde sounding, in this case the ascent from Albermarle, a location in the north-east of England at 00UTC on the 12th of September 2012. The red line on this figure shows the variation of temperature with pressure as measured by the sonde. Clearly temperature is generally decreasing with height up to about 300 hPa, but because of the 45° slope of the constant temperature lines this now means that the temperature line measured by the radiosonde is much more “upright” than the example shown in figure 1 where temperature was plotted as a function of height. The humidity information measured by the radiosonde is translated into *dewpoint temperature* prior to plotting, and the dewpoint temperature is shown as the blue line in figure 7. The dewpoint temperature (T_d) is defined as the temperature a parcel of air would have to be cooled to, at constant pressure, in order for the water vapour in that parcel to start condensing. In very dry air, the dewpoint temperature will be much lower than the actual temperature whereas if the air is saturated, temperature and dewpoint temperature will be equal. So the gap between T and T_d on a tephigram is an indicator of the humidity of the air – a big gap means dry air, a small gap means moist air and no gap at all means saturated air. Of course the dewpoint temperature can never exceed the actual temperature and so the dewpoint curve will always appear to the left of the temperature curve on a plotted radiosonde ascent – unless the air is saturated at which point the two curves will coincide. The water vapour mixing ratio can be read off the tephigram by looking at the dewpoint curve. For instance, in figure 7 the dewpoint curve at 850 hPa crosses the 3 g/kg mixing ratio line, meaning that the air at this level contains 3g of water vapour for every kilogram of dry air.

The wind vectors calculated by tracking the position of the balloon by GPS are plotted up the right-hand side of the tephigram using standard meteorological plotting symbols whereby the orientation of the wind arrow indicates the direction from which the wind is coming and the number of barbs on the arrow indicates the wind-speed. Hence at 700 hPa the wind is coming from about 300 degrees at 25 knots.

with respect to water may be less than 100% and so there still appears to be a gap between the temperature and dewpoint curves. At temperatures below freezing it is probably safe to assume that if the difference between the temperature and dewpoint curves on a tephigram is less than 5°C then the balloon has probably passed through a cloud.

2. Due to instrument errors the humidity sensor on a radiosonde sometimes does not record 100% RH even if it passes through a water cloud. So at temperatures above freezing, if the temperature and dewpoint are within 1°C of each other then the balloon has probably passed through a cloud.

4. Using the Tephigram as a Vertical Motion Calculator

As well as its use as a piece of graph paper on which to plot radiosonde ascents, the tephigram is also an extremely useful *calculator* for determining what happens to the thermodynamic properties of air parcels as they move around in the atmosphere. In particular it can be used for calculating the thermodynamic effects of vertical motion. Vertical motion in the atmosphere occurs on a whole range of different time and space scales. Some vertical motion is pretty well directly vertical and can be rather rapid (e.g. a few metres per second) whereas some vertical motion can be slantwise and *almost* horizontal with ascent (or descent) rates of a few millimetres per second. However, regardless of the nature of the motion, the laws of thermodynamics which determine the changes in temperature and humidity as air moves to higher or lower pressures are always the same and they are embedded into the design of the tephigram.

As a parcel of air rises in the atmosphere it will experience decreasing atmospheric pressure and so will expand. The First Law of Thermodynamics states that, as long as no additional heat is added to or taken away from the parcel, it will cool and that cooling will take place at a well determined rate called the *Dry Adiabatic Lapse Rate* (DALR). However, by definition the *potential* temperature (θ) of the parcel will remain constant. Hence the lines of constant potential temperature on a tephigram are also lines showing the DALR for a parcel of air as it rises or descends. The parcel temperature will change at a rate which can be found by following a constant potential temperature line. So for an air parcel initially at 1000 hPa with a temperature of 10°C, if forced to rise (by whatever means) to 800 hPa, its temperature would decrease along the potential temperature line (or DALR) through its initial state, so at 800 hPa its temperature would be about -7°C.

This example above will only be true if the air parcel remains unsaturated throughout its ascent to 800 hPa. If it should become saturated then some of the water vapour in the parcel will

condense, releasing latent heat. This latent heat will then be absorbed into the parcel, increasing its temperature slightly, meaning that when the air parcel reaches 800 hPa it will be warmer than it would have been if it had remained unsaturated. This means that in order to perform a lapse rate calculation we need to know whether the parcel will become saturated during its vertical motion. Fortunately there is a line on the tephigram which allows us to find that out. As a parcel of air moves vertically it will conserve its *water vapour mixing ratio* unless water is added to it (unlikely unless the parcel is directly above a moist surface) or taken out of it (unlikely unless some precipitation occurs). This means that the dewpoint temperature will change during vertical motion along the *mixing ratio line* through the parcel's initial dewpoint. So by drawing a constant θ line through the parcel's initial temperature and pressure, and a constant mixing ratio line through the parcel's initial dewpoint temperature and pressure, the rate of change of the temperature and the dewpoint with height can be calculated. If the two lines intersect (i.e. the temperature and dewpoint become equal) then we know that saturation will occur at the level that the two lines meet. This is illustrated below in figure 8.

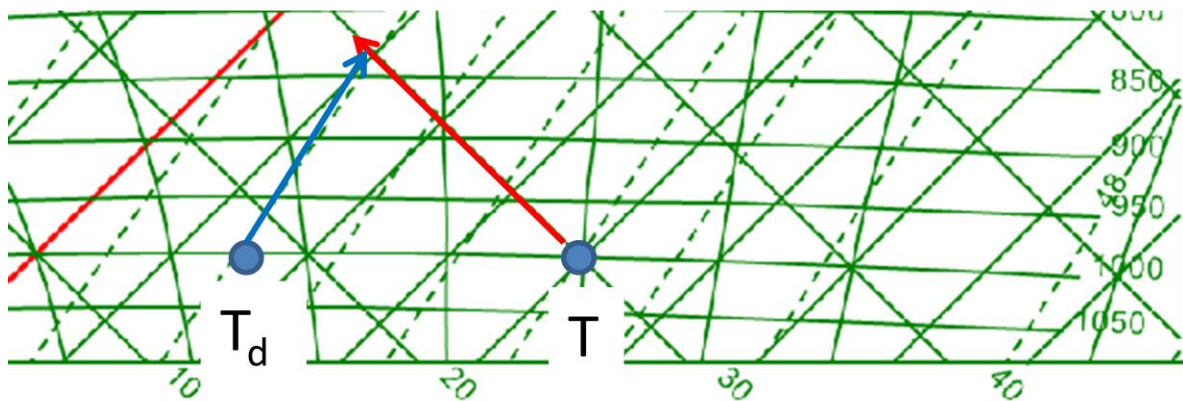


Figure 8. An example of how to calculate whether a parcel of air will become saturated if lifted vertically. The temperature will change along a DALR line (red arrow) and the dewpoint will change along an HMR line (blue arrow). The point at which these two meet is the point at which the parcel will become saturated. This is known as the *Normand's point*.

The blue circles represent the temperature and dewpoint of a parcel of air initially at a pressure of 1000 hPa. If that parcel is lifted, its temperature will decrease following the DALR through its initial state, shown by the red arrow. At the same time its humidity mixing ratio (HMR) will be conserved so that its dewpoint will change following the HMR line through its initial state, shown by the blue arrow. The red and the blue lines meet just above 850 hPa, telling us that the parcel will become saturated at this level. At this point condensation would start to occur and cloud would start to form. The point at which this occurs is known as the *Normand's Point*, and for air at the surface it is often referred to as the *Lifting Condensation Level* (LCL).

If the parcel continues to rise above the LCL its temperature will no longer follow the constant θ line due to the release of latent heat of condensation. This means that the calculation of the rate of change of temperature with height becomes much more complicated. However, the tephigram can do this calculation for us. Once a parcel becomes saturated its temperature will change at the *saturated adiabatic lapse rate* (SALR). This rate is given by the curved lines labelled wet bulb potential temperature in figure 6. Simply put, for a saturated parcel the conserved quantity is not the potential temperature θ but the wet bulb potential temperature θ_w . figure 9 shows a continuation of the case in figure 8 where the parcel now continues to rise above its LCL. The temperature will now follow the SALR curve through the LCL and because the parcel is saturated, its dewpoint will be equal to its temperature so that the dewpoint too will follow the SALR.

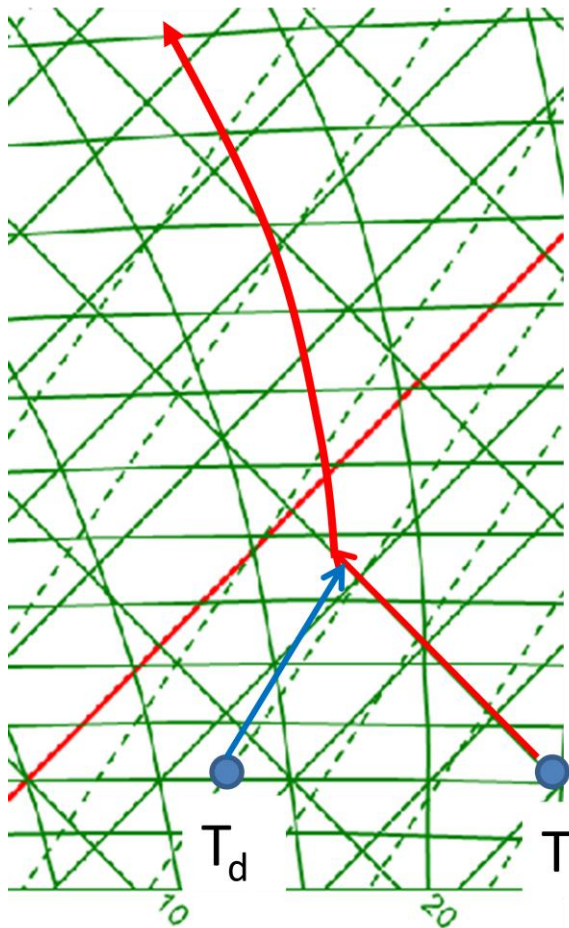


Figure 9. A parcel of air which is saturated will cool at the SALR if it continues to rise. This is shown by the red curved arrow above the Normand's point.

As well as understanding what happens to the temperature and humidity of a parcel that is ascending, the tephigram also allows us to consider what happened to these quantities in a

parcel which is undergoing *descent*, perhaps in an area of high pressure. Consider a parcel of air at an initial pressure level of 600 hPa which is close to saturation. As it descends it will warm (due to the higher pressure) but will conserve its humidity mixing ratio. This means that even if it was initially at 100% relative humidity its RH will decrease instantaneously on descending and warming. Hence the air parcel will warm at the DALR. Its dewpoint will change along a constant HMR line and so its relative humidity will continue to decrease. If this parcel descends to 850 hPa (which would take about 1.5 days for a parcel descending at 2 cm/sec in the centre of an anticyclone) then by the time it gets to this level it will be very dry and relatively warm, as shown in figure 10.

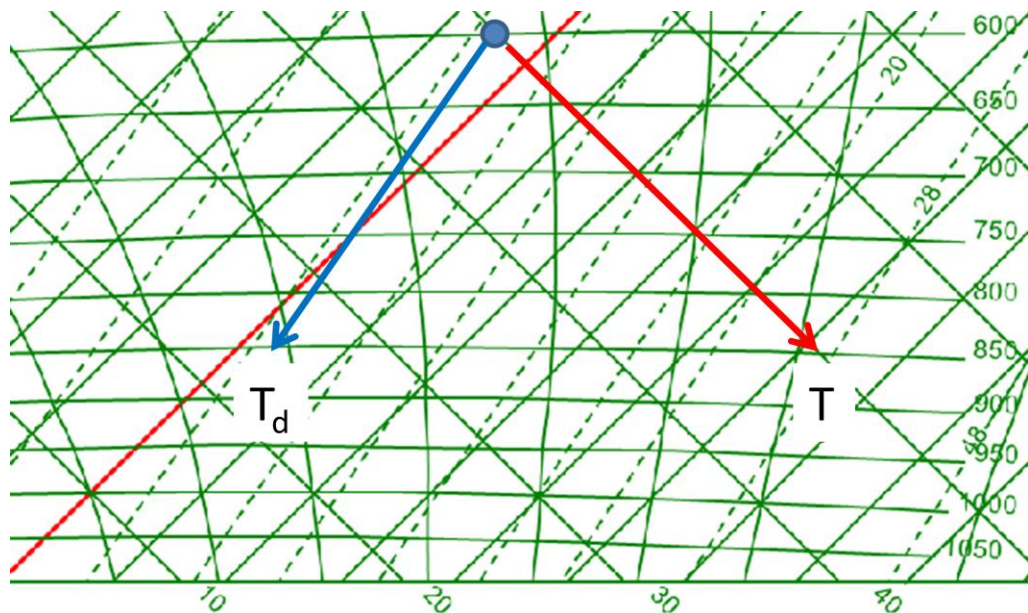


Figure 10. An initially saturated parcel of air descending from 600 hPa to 850 hPa. Its temperature will change following the red arrow (a line of constant potential temperature) and its dewpoint will change following the blue arrow (a line of constant water vapour mixing ratio).

Another extremely useful calculation to make on a tephigram is the determination of the wet-bulb potential temperature (θ_w) of the air at any given level of the atmosphere. Because θ_w is a conserved quantity for both dry and saturated adiabatic processes it is an excellent marker for an airmass as it doesn't change much as air moves around in the atmosphere. θ_w at any level in the atmosphere is calculated very simply by performing a Normand's point construction through the observed temperature and dewpoint at that level and then following the SALR line through that Normand's point back down to 1000 hPa. Figure 11 shows an example of this, for a sample of air at 800 hPa. The value of θ_w read off at 100 hPa is about 23°C.

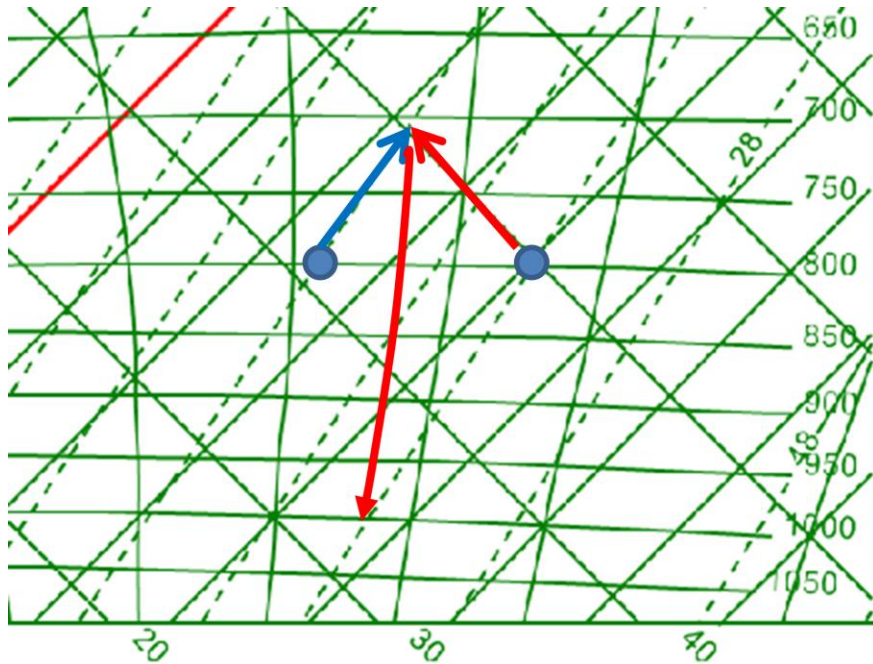


Figure 11. The calculation of wet-bulb potential temperature (θ_w) for a sample of air at 800 hPa whose temperature and dew-point are given by the blue dots. The Normand's point for the sample is calculated and then the SALR through this point is followed back down to 1000 hPa where the θ_w value is read off the temperature axis.

There are many other calculations we could perform using a tephigram but we can get quite a long way by just being able to use the methods described above.

5. Stability

The real utility of a tephigram comes when we combine its functions as a piece of graph paper and as a thermodynamic calculator. One very common use of the tephigram, in association with a radiosonde sounding, is to determine whether convective clouds and possibly precipitation are likely to form within the airmass which the radiosonde has sampled. Convection is simply vertical motion driven by buoyancy differences between a parcel of air and its surrounding environment. If an air parcel is in an environment where its temperature is higher than the surrounding air it will be less dense than its environment and will rise. On the other hand if the parcel is cooler than the environment it will be denser than its environment and so will sink. If air parcels which have been forced to rise for some reason continue to rise due to buoyancy then the environment may be described as *unstable* – a small vertical displacement leads to further rising motion. However, if a parcel which has been lifted slightly is negatively buoyant compared to its surroundings it will sink back to where it came from and the environment may be described as *stable*. Convection occurs in environments which are thermodynamically unstable.

Figure 12 shows an example of how a radiosonde ascent can be combined with a calculation of the change of temperature of an air parcel with height. The calculation of the change of an air parcel's temperature with height has been duplicated from figure 9 where the parcel temperature changes along the DALR until saturation occurs, and changes thereafter along the SALR through the Lifting Condensation Level. Now the temperature of the environmental air as measured by a radiosonde has been added to figure 12, shown by the orange curve. It is immediately apparent that, at every stage of the parcel's ascent, its temperature will be colder than the environment. This means that the buoyancy force will always be acting to push the parcel back down again towards its initial position and so the environment is stable and convection would not be occurring. If however, the temperature of the parcel were always warmer than the environment temperature measured by the radiosonde, the environment would be unstable and convection could occur.

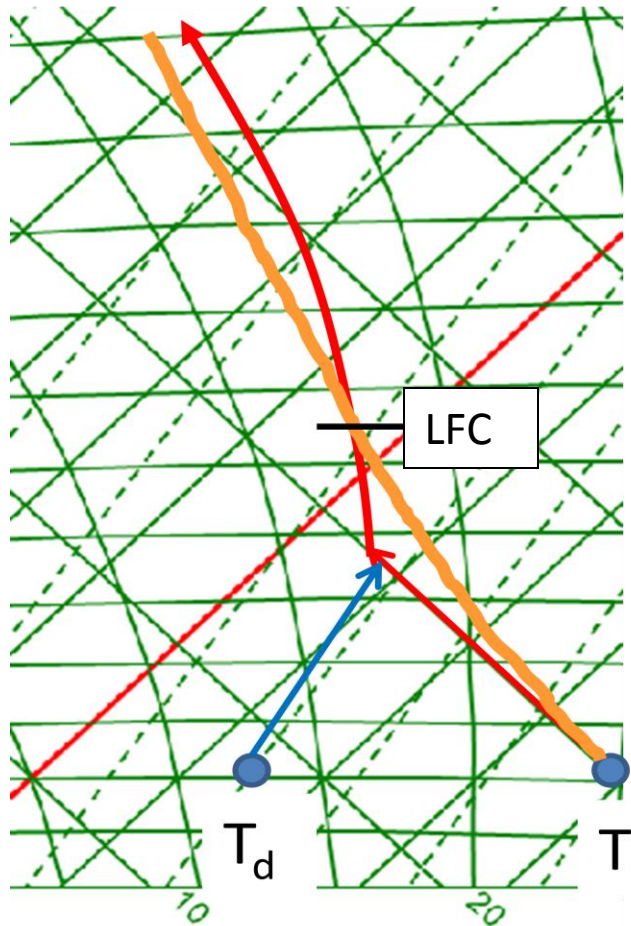


Figure 13. A tephigram showing a situation where a parcel which has been forced to rise from the surface in an initially stable environment. The red line shows the parcel curve and the orange line shows the temperature of the environment. At the level of the horizontal black line the parcel becomes warmer than its environment and convection will occur. This level is known as the Level of Free Convection (LFC).

6. Interpreting radiosonde ascents

As well as being useful for calculating atmospheric stability, a radiosonde ascent plotted on a tephigram can tell a meteorologist a lot about the state of the atmosphere. The location of cloud layers, positions of any fronts and the moisture content at any given level can all be determined by inspecting the profile. Additionally it is possible in some cases to work out where the air in the profile has actually come from – both in the vertical and horizontal senses. Particular air-masses can be traced by looking at a series of sondes at one location or a set of sondes for one time over a given area and the gross nature of those air-masses (warm or cold, moist or dry, stable or unstable) can be rapidly determined by visual inspection.

The first thing to remember when studying radiosonde profiles is that the air in the atmosphere does not move around uniformly in vertical columns which extend from the surface to the tropopause. A column of air as sampled by a radiosonde may include layers from several very different origins, both in the horizontal and the vertical. A layer of relatively warm moist air near the top of a sounding may have had its origins somewhere near the surface over a sub-tropical ocean region. A layer of relatively warm dry air just above the boundary layer may have originated from much higher up in the atmosphere and due to large scale descent (such as in a ridge of high pressure) it will have warmed and dried over the course of many hours or even days as it descended. So when examining a radiosonde profile it may be necessary explain the structure of the profile by considering several different distinct layers which may all have come from different places. One good indicator of changes or airmass or air origin on a radiosonde profile is to look for places where the wet-bulb potential temperature (θ_w) changes rapidly over a small vertical interval. Generally, within a single airmass θ_w increases very slowly with height. A sudden jump in θ_w usually indicates a change in the origin of the air in the column at that level.

Most of the examples we shall look at here all come from the period of the joint Leeds University/Reading University field trip to Lochranza on the Isle of Arran in September 2012.

6.1. Example 1. A Single Polar Maritime Airmass

The first example we shall consider is a simple case where all the air in the column *is* composed of a single airmass with a characteristic single area of origin. The radiosonde is from Lerwick in the Shetland Isles at 1200 UTC on the 12th of September 2012 – see figure 14. At this time the surface winds at Lerwick were northwesterly and, as the profile shows, this was the case right up through the profile with very little windshear in the vertical.

6.2 Example 2. A Ridge of High Pressure in a Tropical Maritime Airmass.

The next example we shall consider is a profile from Lochranza obtained 4 days prior to the previous example, at 1200 UTC on the 8th of September 2012 (figure 16). On first inspection this profile is very different indeed from the previous example but they do have one characteristic in common – they both show that all the air in the column originated within a single airmass, albeit a very different one.

Although temperature and humidity in this profile have some very distinct and rapid changes with height, calculation of θ_w values at 100 hPa intervals gives fairly consistent results - values of about 12°C right through the depth of the profile.

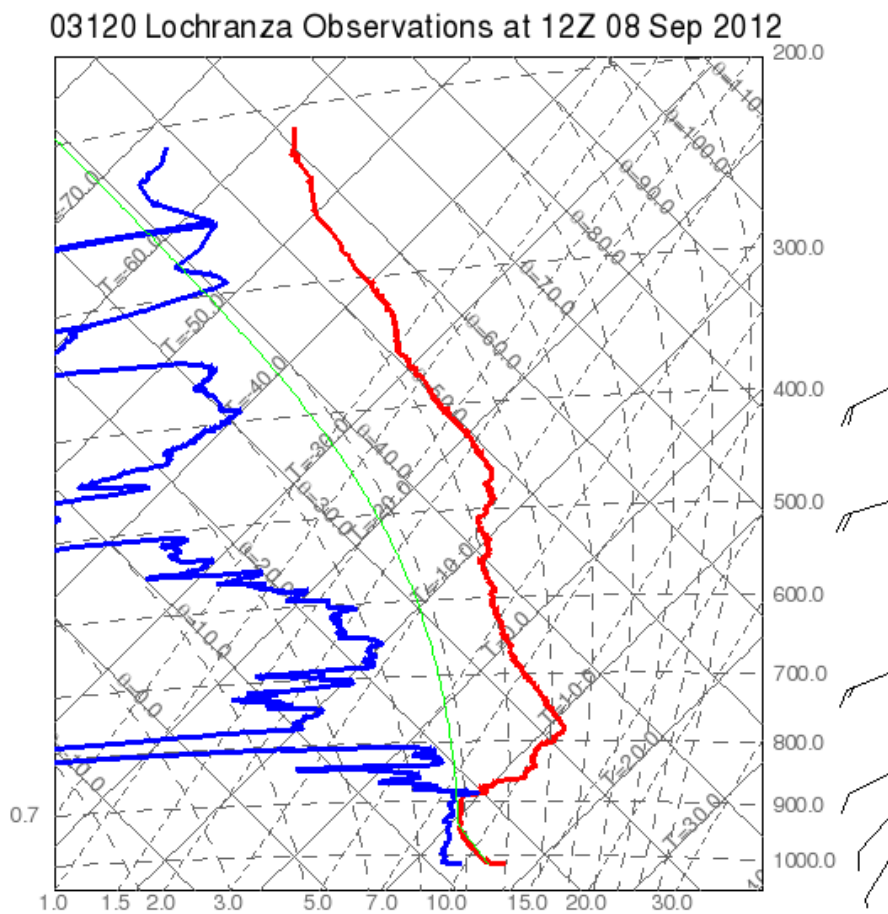


Figure 16. The radiosonde profile from Lochranza at 1200 UTC on the 8th of September 2012. The inversion just above 890 hPa is due to large scale subsidence in a ridge of high pressure.

The boundary layer in this profile extends up to about 890 hPa, is quite moist and is almost certainly capped by a thin layer of cloud. The temperature profile near the surface is close to a dry adiabat, and above about 940 hPa is close to a saturated adiabat indicating a well-mixed

boundary layer capped by a layer of stratocumulus cloud about 40 hPa thick. Above 890 hPa there is quite a sharp temperature inversion (T increases with height) which is in turn capped by an isothermal layer extending up to just above 800 hPa. Above 890 hPa the air becomes rather dry, and above 800 hPa it becomes even drier. Above this level there is a lot of variation in humidity with height, but this variation is generally between dry air, very dry air and extremely dry air. The balloon ascended to almost 200 hPa before it burst, but there is no sign of the tropopause in this ascent. This high tropopause indicates air with a sub-tropical origin, probably a Tropical Maritime airmass.

Despite the fact that all the air in this profile has its origins within the same airmass, it certainly hasn't just been sitting still in its column over the previous few days. The dry temperature inversion just above the boundary layer is absolutely characteristic of large scale descent. Descending air will warm at the DALR, even if it was initially saturated, and so air which has descended from the mid-troposphere can be very warm by the time it gets down to just above the boundary layer. The presence of the air in the boundary layer itself, with the solid Earth below, prevents air descending all the way to the surface, hence the characteristic presence of this *subsidence inversion* at about 1km or so above the surface. As air descends it will conserve its humidity mixing ratio value, and since air higher up in the atmosphere holds very little moisture a very dry mid-troposphere is very characteristic of a region of large scale descent.

The boundary layer is quite moist indicating that the air here has been fed with a source of water vapour (the ocean surface) over the past few days, but the presence of the subsidence inversion has trapped this moisture in the lowest kilometre of the column since there will have been very little mixing of air across the inversion. Inversions are very stable, so apart from a little bit of turbulent mixing across the top of the inversion there will have been no convection to take air parcels from near the surface into the mid-troposphere, in contrast to the previous example.

The rather large fluctuations in dewpoint throughout the depth of the profile reflect the nature of the air motion within an area of high pressure. As well as undergoing large scale descent air is also moving around horizontally on anticyclonic trajectories. At some levels moister air from the flanks of the system is being advected in towards the centre, and at other levels drier air from the centre is being advected out towards the flanks, all whilst also swirling around anticyclonically. This horizontal motion accounts for the filaments of drier and moister air encountered by the radiosonde as it ascends through the weather system.

In summary this profile, with a moist boundary layer capped by a dry subsidence inversion, indicates the presence of large scale descending motion, probably over a period of several days. The high tropopause and high θ_w values indicate that the airmass is probably Tropical Maritime in origin. The synoptic chart for the same time as this ascent is shown in figure 17 and confirms

the presence of an area of high pressure centred near southern UK which accounts for the large scale subsidence of air seen in the profile.

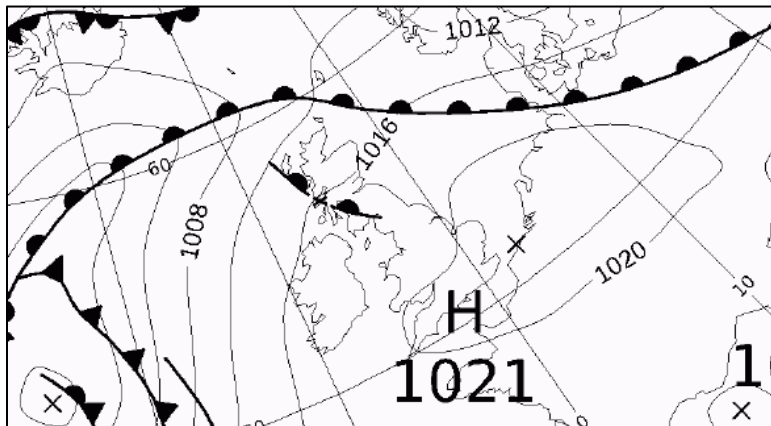


Figure 17. the synoptic chart for the same time as the radiosonde profile in figure 16. The area of high pressure over the UK accounts for the large scale subsidence seen in the profile.

6.3. Example 3. 24 Hours After Example 2

Having a sequence of radiosonde ascents makes interpretation easier. It is much easier to explain changes to a profile over a 24 hour period during which you have been monitoring the weather than it is to examine a profile with no prior knowledge of what the synoptic conditions have been.

Figure 18 shows the radiosonde profile from Lochranza at 1200 UTC on the 9th of September 2012, 24 hours after the profile shown in figure 16. The first and most obvious difference is that the profile on the 9th is much more humid throughout its depth than that recorded 24 hours earlier. Secondly the temperature inversion/isothermal layer is much less marked now, and slightly higher up (at about 830 hPa as opposed to 890 hPa previously).

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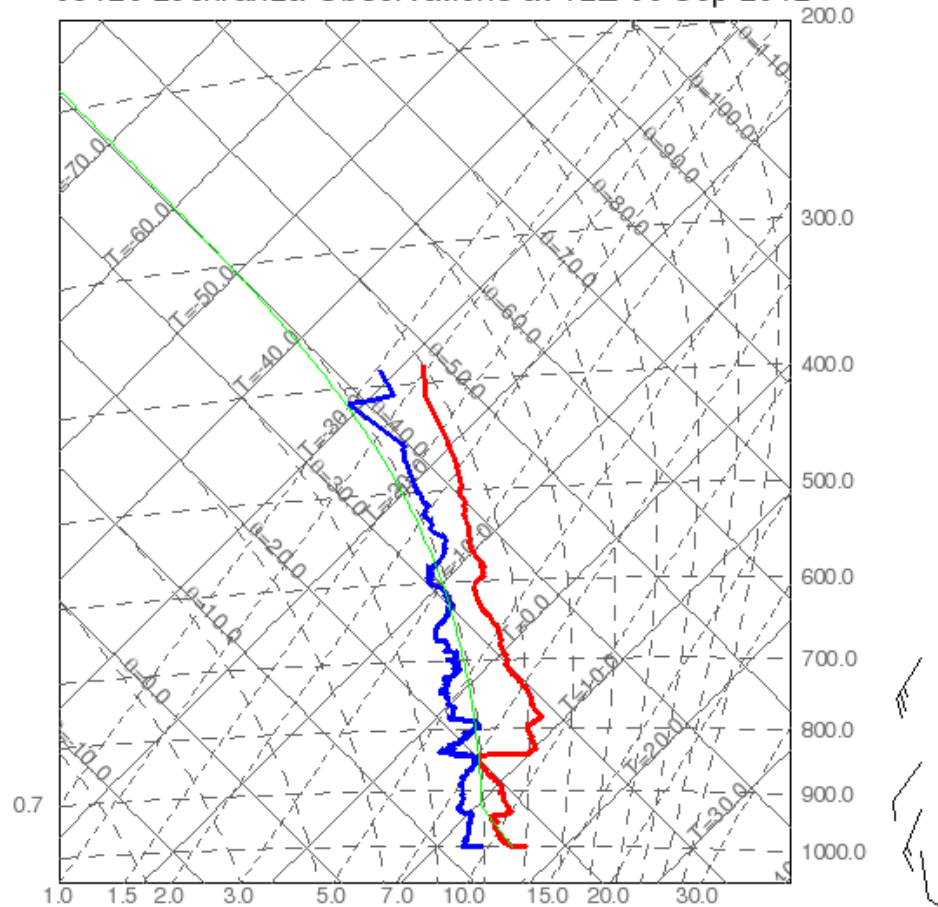


Figure 18. The radiosonde profile from Lochranza at 1200 UTC on the 9th of September 2012.

The erosion of the subsidence inversion points to a cessation of the large scale subsidence that formed it, and the moistening at all levels above the inversion indicates the advection of moister air throughout the depth of the tropopause. However, θ_w values throughout the depth of this profile are similar to those of the previous day (about 12°C) and there is no indication anywhere on the profile of the presence of a frontal zone which would be shown by a rapid increase of θ_w with height. Hence the conclusion is that this profile is still in the same airmass as the previous day, but no longer in an area of large scale subsidence – i.e. the ridge of high pressure has decayed or moved away. This conclusion is borne out by the synoptic chart for 1200 UTC on the 9th of September shown in figure 19. The area around Lochranza is now dominated by the cyclonic flow on the flank of a depression centred near Iceland and a cold front is approaching from the west. However, because of the rearward sloping nature of the front it does not appear on the radiosonde profile, although it is clearly responsible for the advection of moister air into the area.

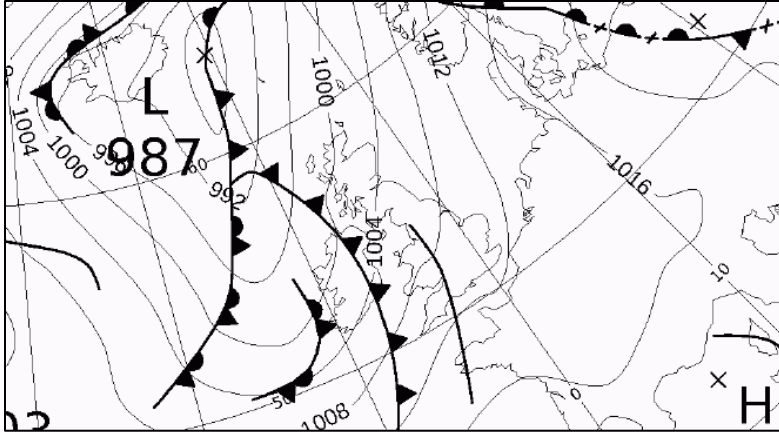


Figure 19. The synoptic chart for 1200 UTC on the 9th of September 2012, the same time as the Lochranza radiosonde ascent shown in figure 17.

6.4. Example 4. An ascent which has intersected a frontal surface

By 1200 UTC on the 10th of September 2012, 24 hours after the chart shown in figure 19, a cold front shown is now situated approximately 150 km to the south-east of Lochranza, as shown in figure 20. This is most likely the same front analysed as an occlusion 24 hours earlier (see figure 19). One might wonder how an occluded front can “unocclude”, but in this case the front marks the boundary between true Polar Maritime air to the northwest and returning Polar Maritime air that has had a longish track over the warm Atlantic Ocean south of 60°N, and so the front will have the characteristics of a cold front.

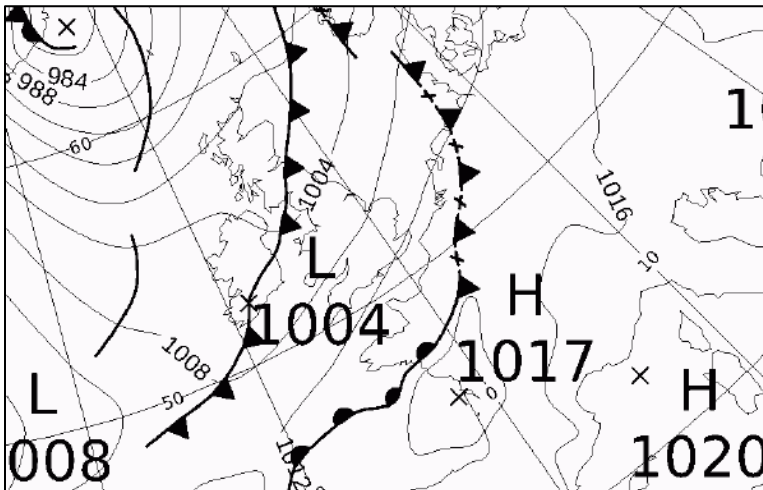


Figure 20. the synoptic chart for 1200 UTC on the 10th of September 2012. A cold front is now shown to the south-east of Lochranza.

The radiosonde ascent from Lochranza at the same time as the synoptic analysis in figure 20 is shown below in figure 21. The rapid decreases of temperature and humidity at the surface are just an artefact of the sonde having been prepared indoors and then moved outdoors prior to launch, and so can be ignored.

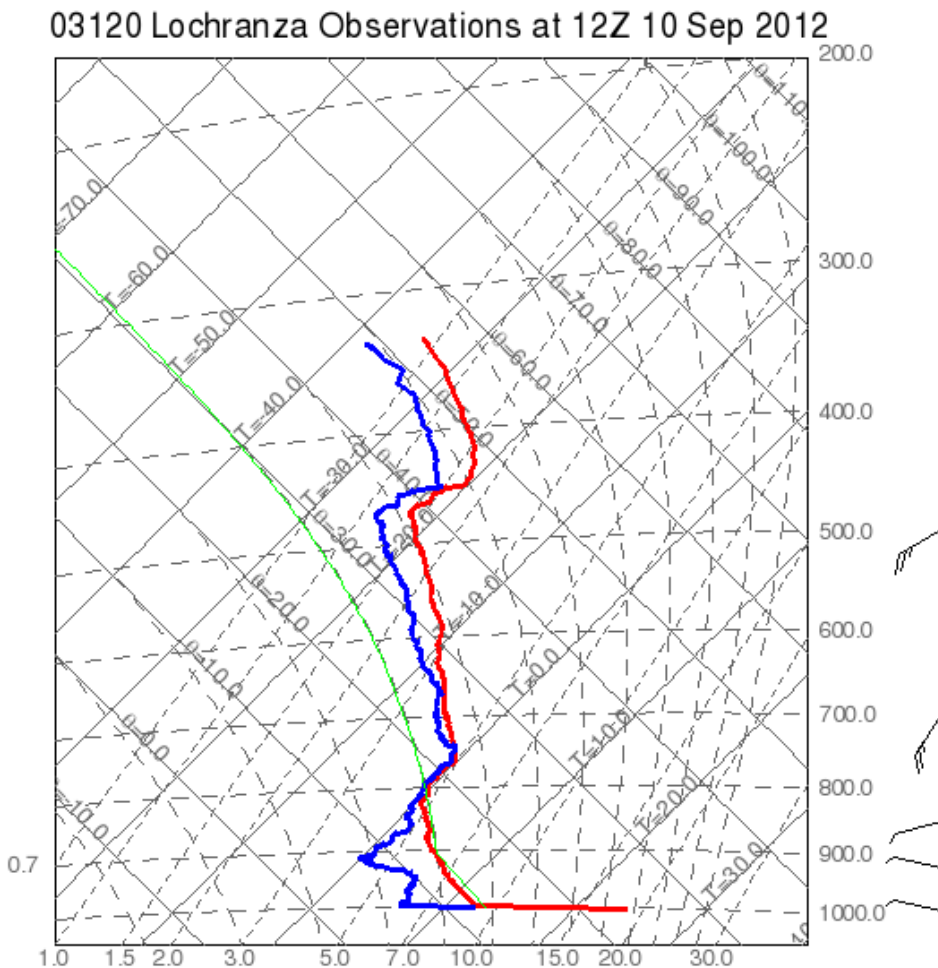


Figure 21. The radiosonde profile from Lochranza at 1200 UTC on the 10th of September 2012. The rapid decreases in temperature and humidity near the surface are simply a result of the sonde having been prepared indoors and then taken outside prior to launch, and so can be ignored.

There appear to be 3 distinctly different layers of air in this profile. Below 800 hPa the air is fairly moist but not saturated, the temperature lapse rate is dry adiabatic in the lowest 100 hPa and then follows an SALR. The value of θ_w in this lowest layer is about 8°C. Above 750 hPa the air is close to saturation (and may actually be saturated if we allow for the fact that the air is colder than 0°C but the sonde is recording humidity with respect to liquid water), the temperature lapse rate is less than the SALR and the θ_w values range from about 12 to 13°C. At

about 450 hPa there is a very strong temperature inversion and the air above this level is still rather moist. The θ_w of the air above this inversion increases to about 16°C.

Considering the lowest of these layers first, the boundary layer appears to be very well mixed up to about 950 hPa, probably by convective overturning driven by surface heating. Above 950 hPa a layer of rather drier air indicates that this convective mixing has been somewhat suppressed. This may be due to descending air associated with a frontal zone that caps the lowest layer (discussed below).

Between 850 and 700 hPa both temperature and dewpoint are pretty well isothermal with height, and the air is saturated. This layer is a classic indication of a frontal zone, a transition layer between the cooler Polar Maritime air near the surface and the warmer, moister returning Polar Maritime air above. The drier layer of air just below the frontal zone is also a typical signature of a front, as below the frontal surface air is often descending.

From 750hPa up to 470 hPa the air is returning Polar Maritime, with quite high θ_w . The air is pretty well saturated indicating a fairly active frontal system with deep layer cloud. The temperature lapse rate is less than the SALR indicating a stable airmass. In this layer the sonde is clearly ascending through the warmer air above the cold front. The rearward sloping nature of the front means although the cold front at the surface has already passed through Lochranza, above 750 hPa the warm air is still present over the station. Given that the surface front is about 150km away from Lochranza but the front is directly above Lochranza at 750 hPa (about 2500m) we can deduce that the slope of the front is about 1:60, a reasonable value for a cold front.

We know that this is a cold front because it is marked as such on the surface analysis in figure 20. However, a *warm front approaching* Lochranza would have a similar signature on a radiosonde profile to that of a cold front which has passed through the station (i.e. cold Polar Maritime air near the ground and warm moist Tropical Maritime or returning Polar Maritime air above the frontal surface). There is one clue from the radiosonde data alone that tells us that this *is* a cold front. Between 850 and 700 hPa (i.e. across the frontal surface) the wind *backs* with height. Winds backing with height indicate *cold advection* and cold advection happens behind cold fronts, whereas ahead of a warm front we would expect to see *warm* advection with the wind *veering* with height.

At about 450 hPa there is a sharp inversion in both temperature and dewpoint, with the air above this level being even warmer than the returning Polar Maritime air below. There are no frontal features on the synoptic chart that might explain this change, but it may be due to the air above this level originating from a more equatorwards source region than the rest of the warm sector. One way to investigate this further is to compute *back trajectories* for the air in

the profile using winds from NWP model analyses. Figure 22 shows such a set of back trajectories from the NOAA HYSPLIT model made available from the website of the NOAA Air Resources Laboratory (ARL). Trajectories for the previous 48 hours have been computed for air at 434 metres (the lowest layer), 4935 metres (in the warm sector) and 6935 metres (in the upper, very warm layer). As expected the air near the surface (red trajectory) has an origin at low levels near Iceland and so is clearly Polar Maritime. The air in the middle level (blue trajectory) has come from the mid-Atlantic over the previous 48 hours and has descended and then risen slightly during its journey. However, the air in the upper layer (green trajectory) has its origins not only further south but also much *nearer the surface* than the air which is now *below* it in the Lochranza profile. This explains the abrupt increase in θ_w in this airmass. This is evidence for the presence of a very distinct warm conveyor belt – a narrow ribbon of air originating near the surface in the sub-tropics and transporting warm moist air upwards and polewards through a weather system.

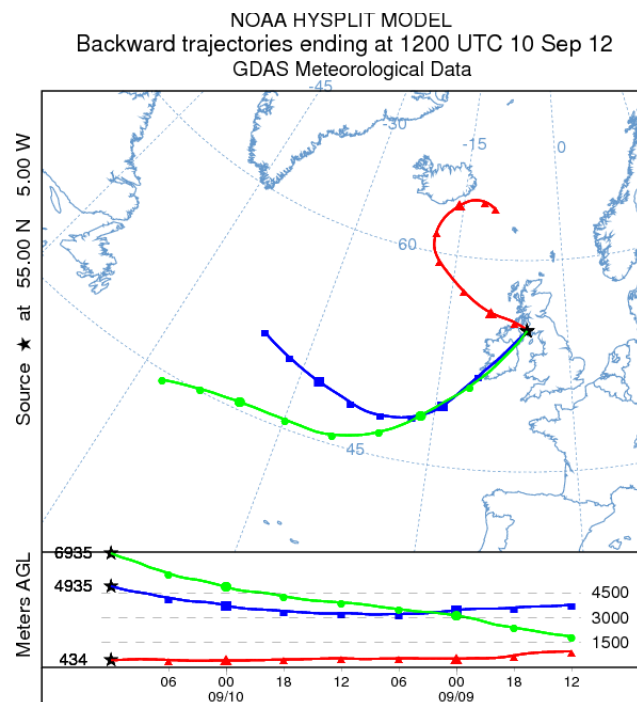


Figure 22. Back trajectories for 3 levels in the Lochranza radiosonde profile at 12 UTC on the 10th of September 2012. Red trajectory – air at 434m above Locahranza. Blue trajectory – air at 4935 metres above Lochranza. Green trajectory – air at 6935m above Locahranza. Trajectories from the NOAA HYSPLIT model provided by the Air Resources Laboratory.

In summary this is a complex profile showing a number of different features. The air near the surface is Polar Maritime in origin, moving in behind the surface cold front. The balloon has passed through a frontal zone between about 800 and 750 hPa and then passed through the warmer and moister returning Polar Maritime air in the warm sector. Above this layer is even

warmer moist air which has its origins near the surface south of 45°N, indicating the presence of a warm conveyor belt carrying air of sub-tropical origin through the system. Figure 23 is a schematic cross-section through the front near Lochranza, summarizing the ascent of the balloon through these different layers.

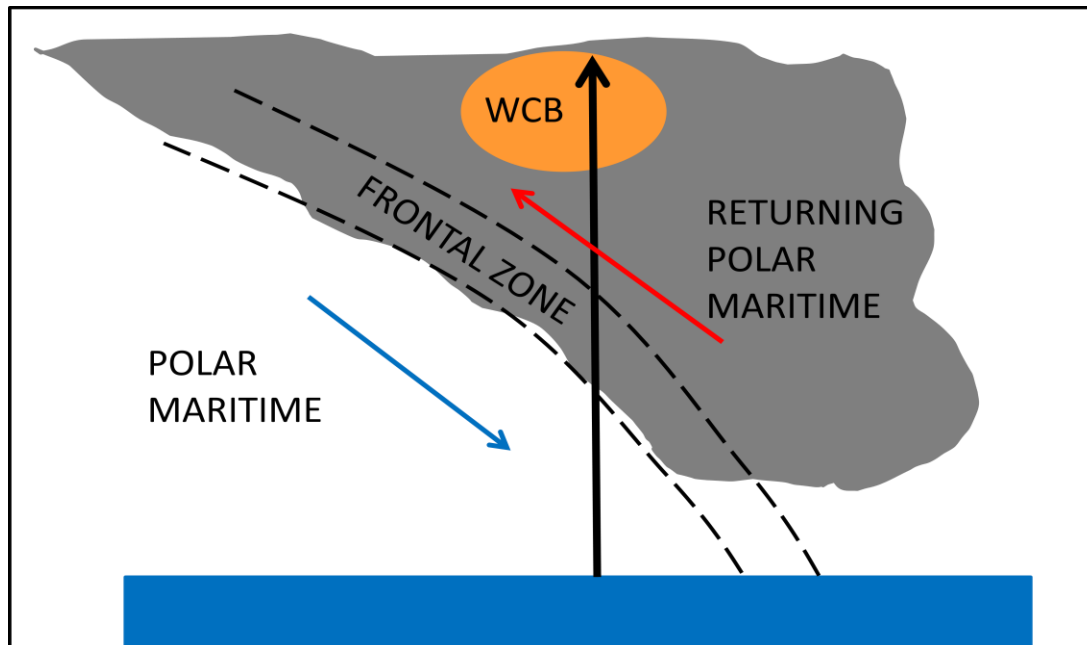


Figure 23. A schematic vertical cross-section through the cold front near Lochranza on the 10th of September 2012. The frontal transition zone is between the two dashed lines, with returning Polar Maritime air above this zone and Polar Maritime air below. The Warm Conveyor Belt is indicated by the orange oval labelled WCB. The vertical motion above and below the front is indicated by the red and blue arrows and the ascent of the balloon is indicated by the thick black arrow. Note that this schematic is not to scale in the vertical.

6.5 Example 5. An ascent in a Polar Maritime airmass with descending air

24 hours after the ascent shown in figure 21, the cold front that was south-east of Lochranza has moved further away and is now situated over northern France and the Low Countries (see the surface analysis in figure 24). This means that Lochranza is now in a Polar Maritime airmass with a north-westerly flow. Because there are no fronts in the vicinity of Lochranza at this time we would expect that the balloon would rise through Polar Maritime air all the way from the surface to the tropopause, and this is indeed the case. However, the profile is rather different from the Lerwick ascent on the 12th of September 2012 shown in figure 14.

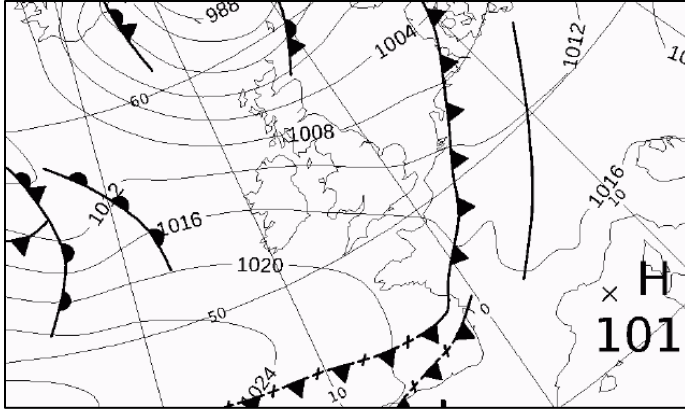


Figure 24. Surface analysis at 1200 UTC on the 11th of September 2012.

Figure 25 shows the Lochranza radiosonde profile for 1200 UTC on the 11th of September. Note that above 500 hPa there appear to be 2 slightly different temperature profiles plotted on the tephigram. This is because the radiosonde was still transmitting data after the balloon had burst and the sonde began to descend on its parachute.

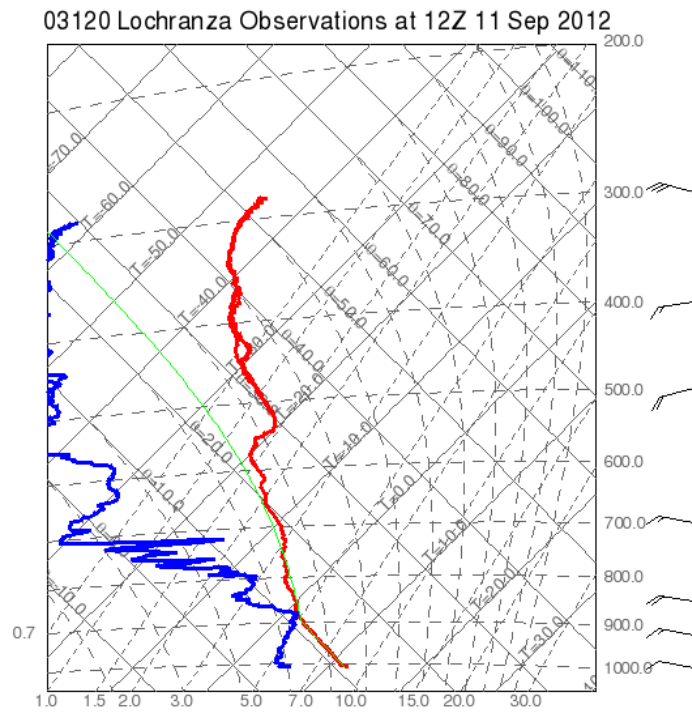


Figure 25. The radiosonde profile from Lochranza at 12 UTC on the 11th of September 2012. Note that the double temperature line above 500 hPa is due to the radiosonde continuing to transmit on its descent after the balloon had burst.

The boundary layer in this profile extends up to about 880 hPa and is very well mixed – both θ and HMR are constant with height. The boundary layer is capped with a very thin saturated layer suggesting either thin stratocumulus or shallow cumulus cloud.

Above this level the temperature lapse rate is close to the SALR but the humidity then generally decreases with height (with some small-scale fluctuations). Above 700 hPa the air becomes very dry indeed. At about 570 hPa the temperature lapse rate becomes isothermal for about 50 hPa. At this level the air also becomes even drier, with the dewpoint curve disappearing off the tephigram altogether. The isothermal temperature lapse rate together with the presence of very low humidity at this level suggests that the air here has been undergoing descent. Below this level the fact that the air is also quite dry suggests that there has been no convection extending above 850 hPa, which would act to increase the humidity in this layer if it were occurring. This also points to a suppression mechanism such as large scale descent. As the surface analysis shows (figure 24), there is a ridge of high pressure to the south-west of Ireland and this ridge is influencing the vertical temperature and humidity structure in south-west Scotland.

In summary then this profile, whilst being in a Polar Maritime airmass which might be expected to be convectively unstable or neutral (as indeed it is in the boundary layer), is being influenced by the large scale descent in a ridge of high pressure. Figure 26 below shows the IR satellite image for the same time as this ascent. The convective cloud tops around western Scotland and Northern Ireland appear grey, indicating that the tops are quite warm and the clouds are therefore rather shallow. The presence of mountain wave clouds over northern Scotland is an indicator of stable air in the mid-troposphere, another confirmation of the large scale descent associated with the ridge.

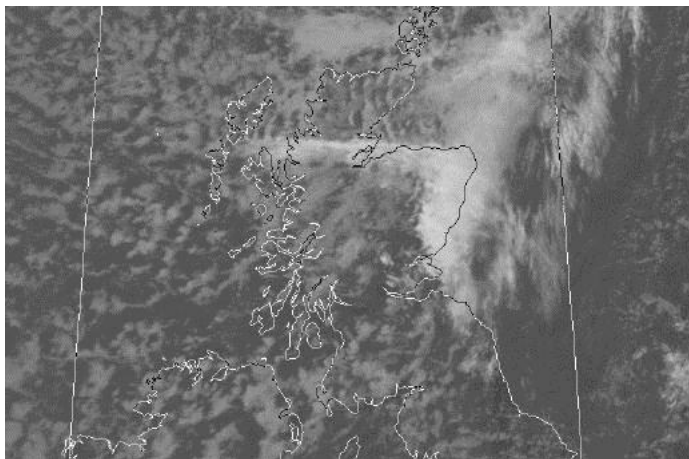


Figure 26. Infra-red satellite image for 1200 UTC on the 11th for September 2012 – the same time as the radiosonde profile in figure 25.

6.6. Example 6. 24 hours after example 5.

24 hours after the ascent discussed in section 6.5 above, the ridge of high pressure has built further north and now extends right up across Iceland – see the surface analysis in figure 27 below. A complex set of fronts is also now approaching the UK from the west. We would expect therefore that the influence of the ridge would be even more apparent on the radiosonde profile.

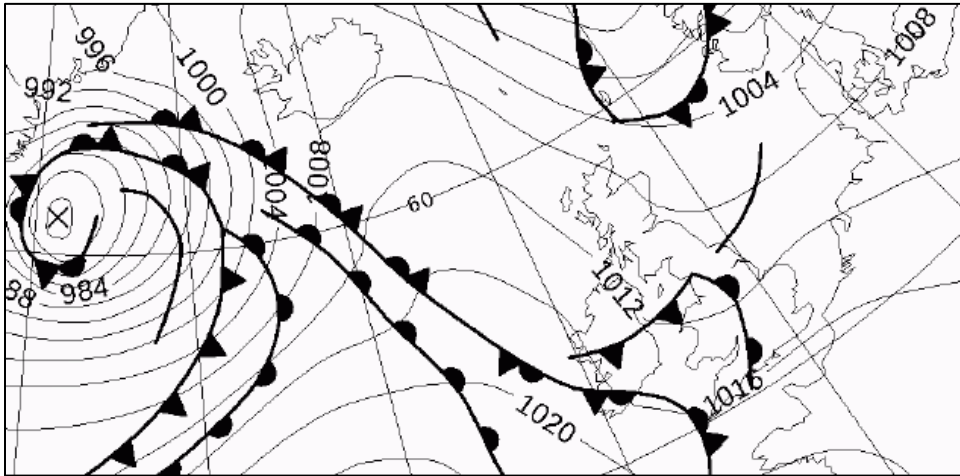


Figure 27. Surface analysis at 1200 UTC on the 12th of September 1012.

Inspecting the profile from Lochranza at this time (1200 UTC on the 12th of September 2012 – see figure 28) shows that, as expected, the ridge of high pressure is indeed exerting a strong influence on the profile. The descent that led to the isothermal layer at around 550 hPa on the 11th is now much clearer and lower down, with a strong subsidence inversion at around 750 hPa. Above this level the air is uniformly extremely dry indicating that descent has been the dominant influence on the profile over the previous 24 hours. Below the inversion there is a saturated or almost saturated layer from about 850 to 770 hPa indicating the presence of a layer of stratocumulus. Below this the boundary layer has a fairly well-mixed profile, at least in temperature, indicating the presence of shallow convective overturning which is feeding the moisture into the stratocumulus layer which caps the boundary layer.

Above 370 hPa the profile changes radically, with an isothermal layer from 270 hPa to about 320 hPa. The profile also becomes very much moister above this level. The θ_w values, which are about 6°C in the boundary layer, increasing gradually to about 10°C at 400 hPa, then increase to about 20°C by 300 hPa. This rapid increase in humidity and θ_w indicates the presence of a change of airmass. Below 370 hPa the air is Polar Maritime, but above this level the air becomes Tropical Maritime. The balloon burst at about 280 hPa but there is no sign of the tropopause at this level. A high tropopause is another indicator of a Tropical Maritime airmass.

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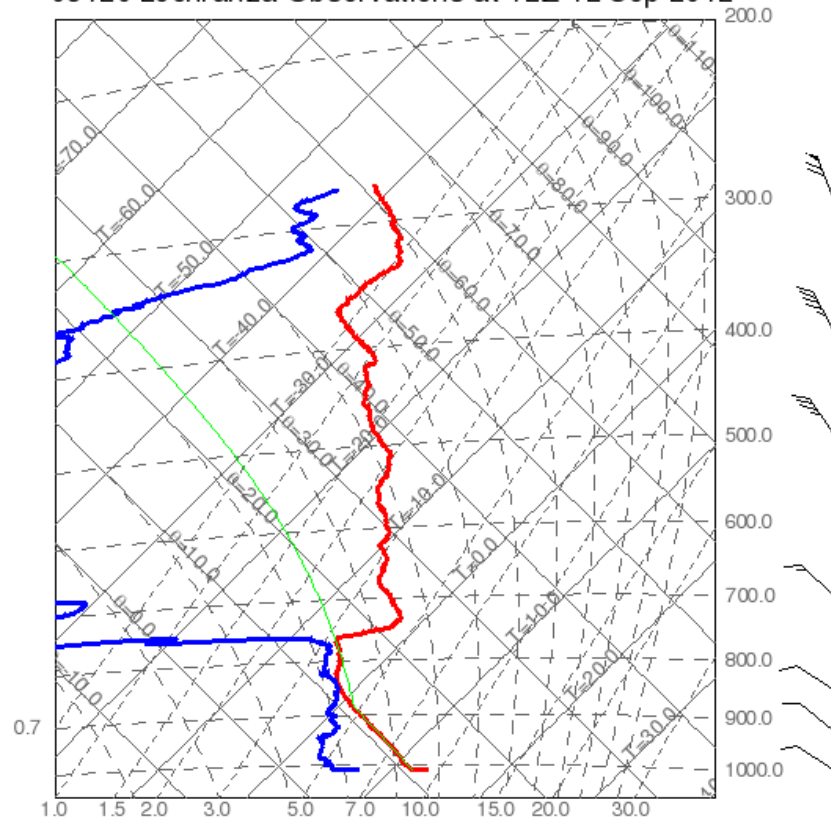


Figure 28. Radiosonde profile at Lochranza at 1200 UTC on the 12th of September 2012.

The humid, high θ_w air above 330 hPa is most likely to be associated with the complex system of fronts approximately 700km to the west of Lochranza at this time. The fact that the values of θ_w are so high suggests that this air has originated from near the surface in the subtropical Atlantic. This appears to be another example of a warm conveyor belt transporting very warm moist air through a weather system from near the surface in the sub-tropics. Note that from 700 hPa up to 300 hPa the wind vectors are veering with height, indicating the presence of warm advection ahead of the occluded and warm fronts to the west of Ireland. The occluded front is approximately 700km to the west of Lochranza, and appears in the radiosonde profile at about 8km above Lochranza. This gives a slope of about 1:90 for the frontal surface.

Back trajectories for the air in the Lochanza profile at 12 UTC have been calculated using the NOAA HYSPLIT model (figure 29). This confirms that the air at 500m (red trajectory) and 4000m (blue trajectory) have a Polar Maritime origin north of 70°N 48 hours previously. However, the air that is 10000m above the ground at Lochranza (green trajectory) originated *at the surface over the mid-Atlantic at about 37°N* 48 hours previously. This air underwent rapid ascent from near the surface to about 10km in altitude between 0600 and 1800 UTC on the previous day.

This rather rapid ascent from the surface to the upper troposphere is indicative of the presence of a warm conveyor belt.

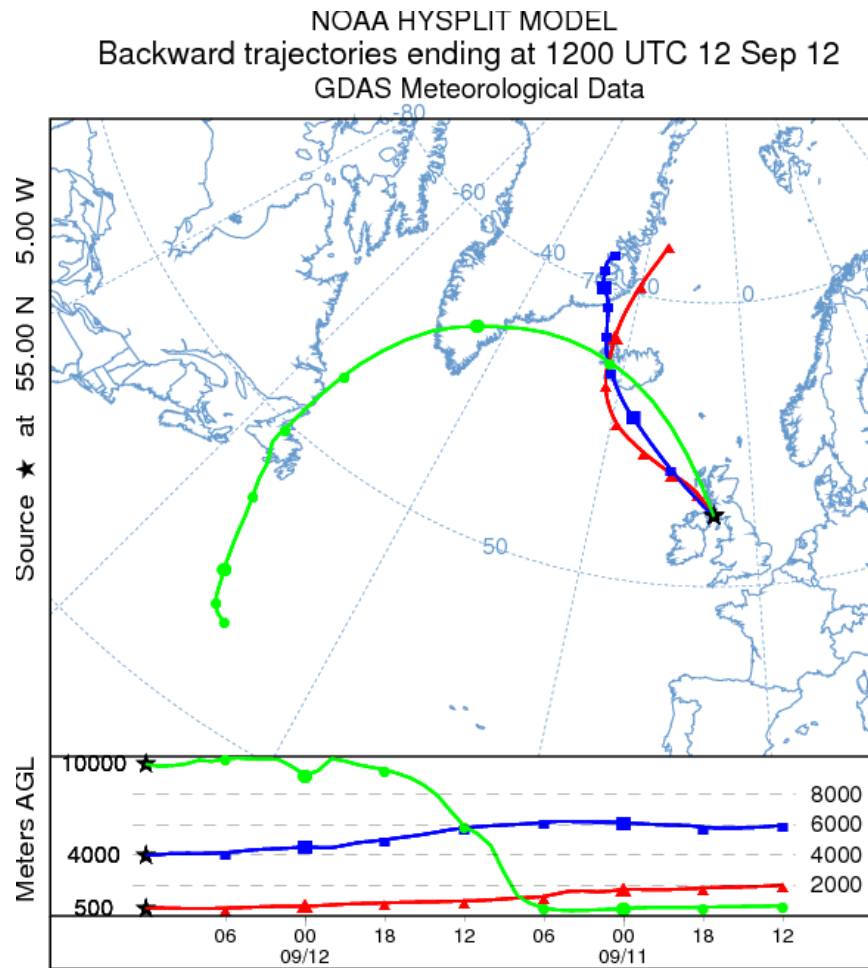


Figure 29. Back trajectories for 3 levels in the Lochranza radiosonde profile at 12 UTC on the 12th of September 2012. Red trajectory – air at 500m above Locahranza. Blue trajectory – air at 4000 metres above Lochranza. Green trajectory – air at 10000m above Locahranza. Trajectories from the NOAA HYSPLIT model provided by the Air Resources Laboratory.

In summary this ascent shows a well-mixed, Polar Maritime boundary layer, capped by a layer of stratocumulus. The mid-troposphere is dominated by descent in a ridge of high pressure leading to a strong inversion around 750 hPa and very dry air from this level up to about 350 hPa. At upper levels the radiosonde has detected the signature of the warm conveyor belt associated with the fronts to the west of Ireland. This air originated at the surface in the sub-tropics 48 hours earlier.

6.7 Example 7. 24 hours after example 6.

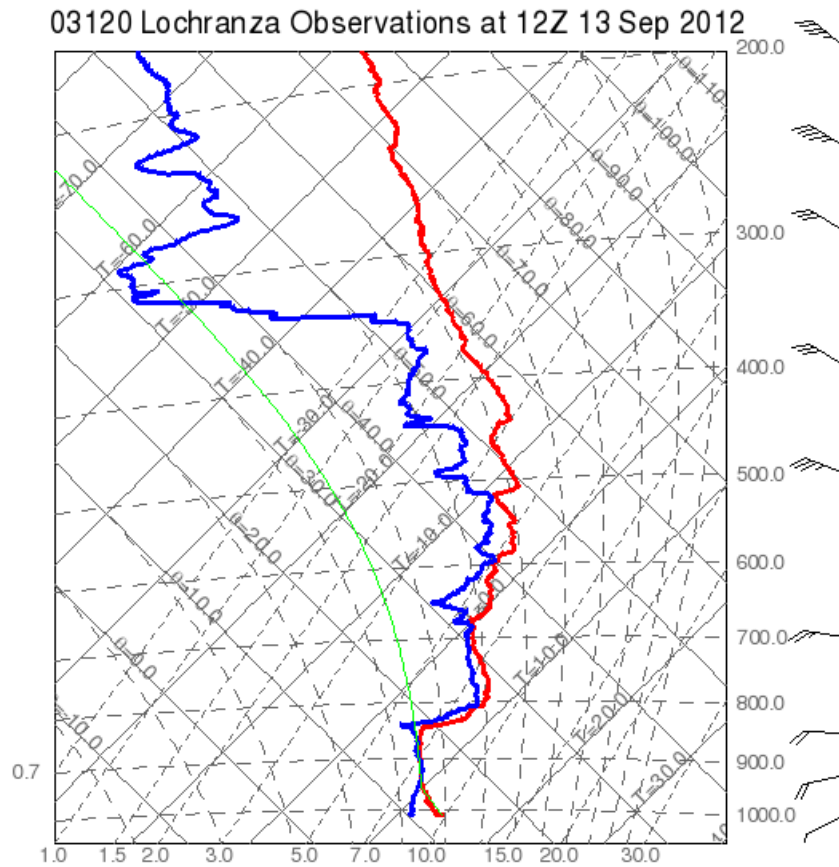


Figure 30. Radiosonde profile for Lochranza at 12 UTC on the 13th for September 2012.

By 1200 UTC on the 13th of September the Lochranza profile, shown in figure 30, is completely different to that 24 hours earlier (see figure 28). From the surface up to about 350 hPa the air is very moist, and through much of that depth it is either saturated or very close to saturation, especially below 500 hPa. This indicates the presence of layers of cloud extending from 950 hPa up to 500 hPa. There is a sharp temperature inversion at about 820 hPa but this inversion is certainly not due to subsidence as the dewpoint also increases rapidly at this level. Below the inversion the value of θ_w is about 11°C, which is already quite high and indicative of a Tropical Maritime airmass. Above the inversion θ_w increases to about 17°C at 800 hPa and continues to increase gradually with height, reaching about 19°C by 500 hPa. In this case the balloon ascended to almost 100 hPa and detected the tropopause near 150 hPa – above the top of the tephigram in this case. This is very high and again is indicative of air originating in the sub-tropics. The wind vectors veer gradually with height throughout the whole profile indicating the presence of warm advection.

The sharp temperature and dewpoint inversion at 820 hPa seems to indicate the transition from a Tropical Maritime airmass into an even warmer and moister tropical airmass. Examining the surface analysis for this time (figure 31) shows that Arran is within a very broad warm sector, with the cold front trailing back into the subtropics. The analyst has also marked a frontolysing (i.e. decaying) warm front embedded within the warm sector, which appears to be very close to, or even right over, Arran. This “extra” warm front appears to be associated with a plume of very warm moist air which has been shown on the analysis over the previous 24 hours as a warm sector within the warm sector. This plume was associated with an ex-tropical storm which has tracked north-eastwards and has now merged with the depression over Iceland. Despite the analyst indicating that this warm front is decaying, it still seems to have a very strong signature on the Lochranza profile at this time. The front appears at about 1.7km above the surface at Lochranza. If we assume a slope of about 1:100 for the frontal surface then the front is about 170km to the west of Lochranza at 1200 UTC.

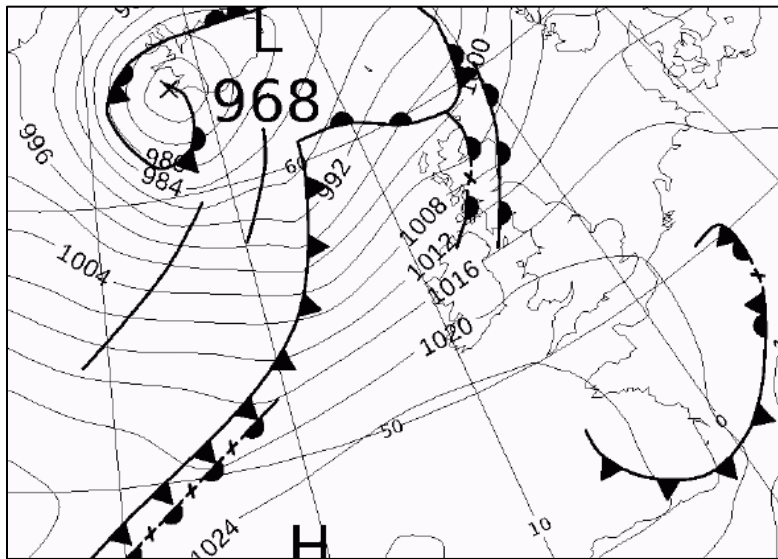


Figure 31. Surface analysis at 1200 UTC on the 13th of September 2012. The warm front symbol near Arran indicates a frontolysing (or decaying) warm front.

In summary, this ascent shows layers of moist, stable, sub-tropical air. There is a clear transition at about 820 hPa between warm, moist sub-tropical air and very warm moist sub-tropical air with very high θ_w . The tropopause in this case was above the top of the tephigram, indicating an origin for the airmass deep within the sub-tropics. In fact this air was associated with a tropical storm which had made a transition into the extra-tropics and had merged with the deep low near Iceland over the previous 24 hours. The frontolysing warm front indicated on the surface analysis shows the approximate limit of this very warm sub-tropical airmass at the surface.

6.8 Example 8. 20th July 2007 – Extensive flooding in England.

Figure 32 shows the 00 UTC ascent from Herstmonceux on the SE coast of England on the 20th of July 2007. In the following 24 hours there was extensive heavy rain over large parts of southern and central England, with several stations in Gloucestershire and Warwickshire recording well over 100mm of rain in the 24 hour period. The Met Office surface analysis for the same time is shown in figure 33. The analysis looks rather innocuous with slack pressure over the UK. However, the analyst has marked a trough over the south-west of the UK, and warm frontogenesis over the near continent.

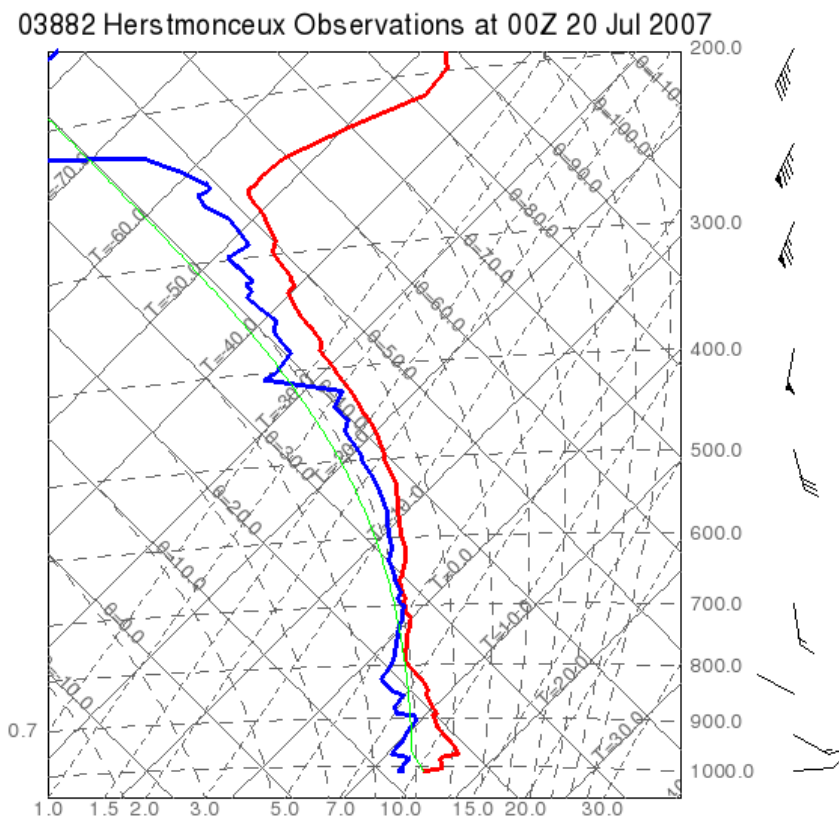


Figure 32. Radiosonde profile for Herstmonceux at 00 UTC on the 20th of July 2007.

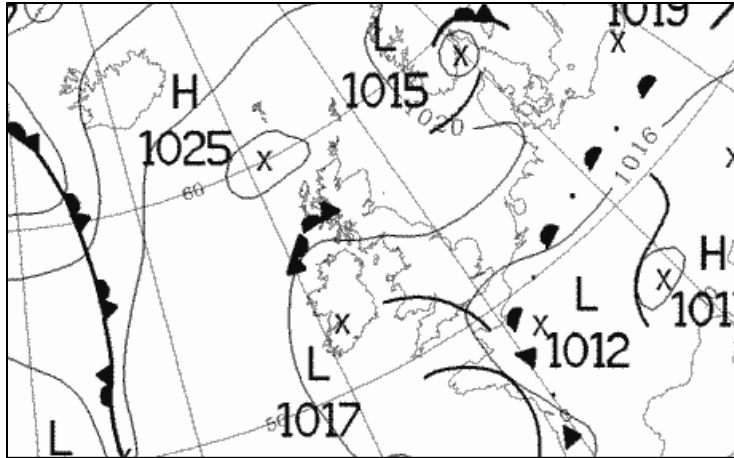


Figure 33. Surface analysis for 00 UTC on the 20th of July 2007, the same time as the radiosonde profile shown in figure 32.

The Herstmonceux profile shows a marked surface inversion due to overnight cooling and this is capped by a layer which is close to a dry adiabatic lapse rate. Above this there is a deep layer of saturated air with an approximately saturated adiabatic lapse rate. A Normand's point construction for the air at the surface confirms that the surface layer is stable. It is clear however that the profile is close to saturation or actually saturated through a considerable depth. A calculation of the amount of "precipitable water" in the column shows that if all the available water vapour in the column were to fall out as rain the resulting precipitation would amount to about 30mm. It wouldn't take much vertical motion to realise this amount of precipitation. How might this vertical motion be brought about?

One possibility is convection. If the daytime heating of the surface is taken into account, the profile becomes unstable. The maximum temperature across southern England on this day was about 23°C over a fairly wide area. If we perform a Normand's point construction for a surface temperature of 23°C and the same dewpoint as at 00 UTC, the Lifting Condensation Level is at about 860 hPa and is now several degrees warmer than the environmental air at this level. This means that the air would then continue to rise above this level, cooling at the SALR. Air rising along this curve would remain positively buoyant up to about 330 hPa, allowing for very deep convective clouds. Figure 34 shows this construction on the tephigram. The area between the parcel SALR and the environmental temperature curve measured by the radiosonde (shaded blue in figure 34) is equal to the Convective Available Potential Energy (CAPE) which in this case is about 650 J.kg⁻¹. Although this is not a huge CAPE value by global standards (CAPE in profiles over tropical or sub-tropical landmasses often exceeds 1500 J.kg⁻¹) it represents a fairly large amount for the UK. There is also considerable windshear in the lowest levels, from easterly winds near the surface to southerly winds at 700 hPa and above, and this would aid the development of organized convection, separating the updraughts and downdraughts. Large

values of CAPE together with large windshear give the potential for long-lived organized convection.

Another possibility for bringing about the vertical motion was that large-scale ascent was being forced by the presence of an upper level trough over the UK. This is not immediately apparent from the surface analysis or the tephigram, although the frontogenesis indicated over France and the Low Countries is a clue. This case emphasises the importance of studying all the potential forcing mechanisms for vertical motion. The deep convection diagnosed from the tephigram was embedded within a broader area of vertical motion in a saturated airmass, leading to the extreme rainfall totals experienced across southern and western England.

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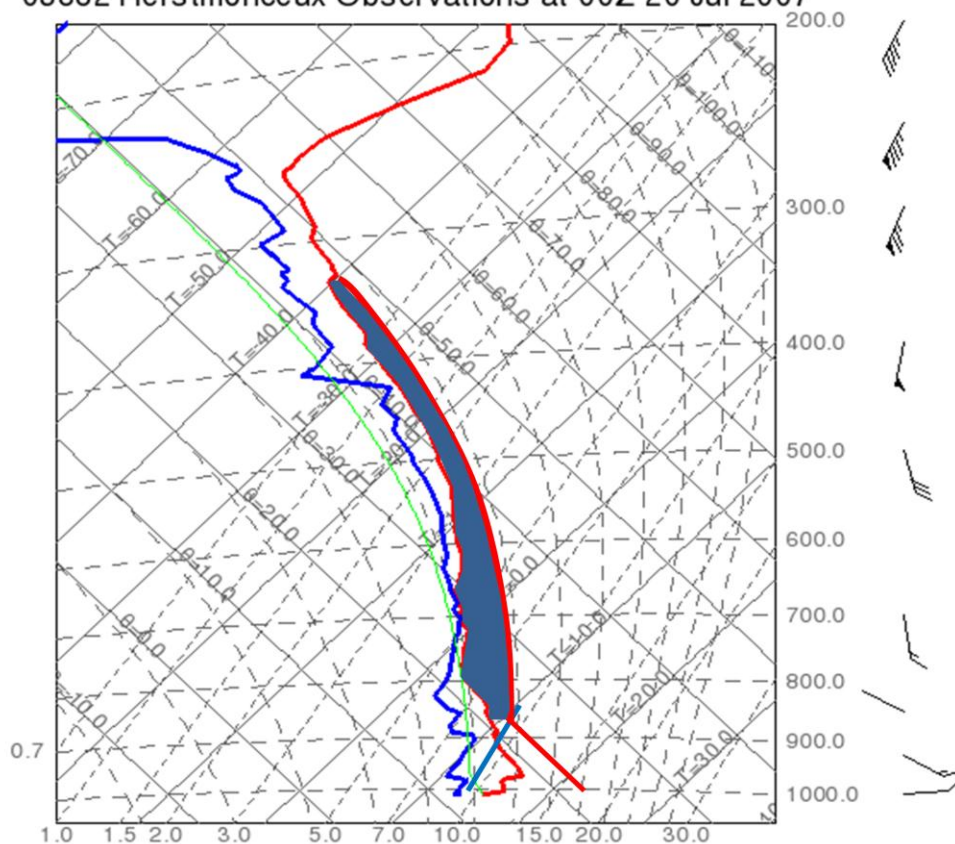


Figure 34. As figure 32, but with a Normand's point construction for a surface temperature of 23°C and subsequent parcel ascent shown in the red line. The blue shaded area shows the amount of CAPE in the profile for this parcel curve, equal to about 650 J.kg⁻¹.

On a profile of this nature, with a very deep layer of almost saturated air, any large-scale or convective vertical motion is likely to generate heavy precipitation. In this case there was considerable flooding due to rainfall accumulations of the order of 100mm in some places. These accumulations are 3 times larger than the amount of precipitable water in the column

above Herstmonceux. This indicates that there must have been a source of moisture feeding into the profile to maintain the precipitation once the initial water in the column had been rained out. This source was probably associated with low level advection of moist air as the developing warm front over northern France moved northwest into the UK.

6.9 Summary

Despite the fact that all the radiosonde profiles presented in this report are different, a number of common features have emerged. Inversion structures due to subsidence, frontal zones, well mixed or stable boundary layers, deep cloud layers and warm conveyor belts can all be recognised by their characteristic features. Using radiosonde profiles plotted onto tephigrams together with meteorological surface analysis charts and trajectory models can provide considerable insight into the nature of developing weather systems given a bit of practice in looking at the information.

The cases presented here are all for mid-latitude locations around the UK. For other parts of the world, particularly the Tropics, typical profiles may look quite different. However, the laws of thermodynamics are the same everywhere across the globe so the same methods of considering the effects of vertical motion or horizontal advection can still be applied when interpreting profiles.

7. Acknowledgements

The Lochranza radiosonde profiles presented in this document were made and provided by staff from the National centre for Atmospheric Science (NCAS) based at the University of Leeds.

Other radiosonde profiles were made by the UK Met Office and were accessed through the University of Wyoming Department of Atmospheric Science Atmospheric Sounding facility (<http://weather.uwyo.edu/upperair/sounding.html>)

The HYSPLIT trajectory model was run on-line using the NOAA Air Resources Laboratory (ARL) website (<http://ready.arl.noaa.gov/HYSPLIT.php>)

The satellite images in figure 15 and figure 26 were obtained from the University of Dundee Satellite Receiving Station website (<http://www.sat.dundee.ac.uk>).