Explosively deepening surface low over the UK on 1st November 2009 .

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Introduction.

During the 24 hours commencing the 1st November 2009 at 00z, a surface low deepened explosively over the UK, with the central pressure falling at a rate exceeding the classification of a 'bomb', namely 24 mbar in 24 hours, by a considerable margin. In fact, in the 18 hours to 18z on the 1st , the central pressure fell from 1004 to 969 mbar, an average rate of 1.9 mbar/hr.

At 00z on the 1st, a wave depression was located near 48N 12W, with a central pressure of 1004 mbar. At 12z on the 1st, the same low had deepened to 980 mbar and was now near 54N 03W. 12 hours later, at 00z on the 2nd, the central pressure was down to 965 mbar near 58N 01W. The majority of the deepening was accomplished by 18z on the 1st, and pressure changes in the centre were small after this time. The movement of the low also slowed markedly at the same time. A sequence of surface analysis charts at 6 hourly intervals is shown in Fig1.

The average rate of fall in the low centre over the 24 hours was 1.6 mbar/hr. The equivalent 1000 mbar height at the centre fell from +3 dam to –30 dam in the same time.

In this article, the thermal structure of the atmosphere above the low is examined, and the levels where the changes in thermal structure had most influence on the resulting fall in surface pressure are indicated by the thickness budget method. The thickness budget gives a measure of the thermal changes taking place over an interval of time in consecutive layers in a column extending over entire atmosphere, summed and applied to a starting pressure at the surface to derive the pressure at the end of the interval of time.

The Upper Troposphere.

At 00z on the 1st, the surface low centre lay well to the right of a westerly jet stream at 300 mbar, and was located near the right exit of the jet. The driving upper trough lay well to the west over the Atlantic, and was amplifying. By 12z on the 1st, the trough had moved eastward to a position just west of Ireland, and was continuing to amplify and sharpen, with the flow ahead backing markedly. The downwind jet was now orientated SW to NE, and had sunk southwards somewhat, leaving the deepening surface low now on its northern side, under its left exit. By 00z on the 2nd, the trough had sharpened further and moved eastwards to lay from central Scotland to NW France, the flow on its eastern flank now backed to SSW'ly, with the downwind jet axis located over the North Sea, and the deepened surface low well to its NW.

Thermal analysis.

In order to help understand the reasons for a surface pressure change of this magnitude, it is first necessary to appreciate that the pressure at any level in the atmosphere arises due to the action of gravity on the entire atmosphere above that level, but it is independent of the atmosphere below that level. So it is the mass of air above a level that determines the pressure at that level, and the mass of air in a column is directly proportional to its mean temperature. The result of this is that for a given thickness of air, measured by the height difference between the top and the base, the pressure at the base of the column will fall if the column is warmed, and rise if it is cooled. Another way of looking at this is to consider how the thickness of a layer can change when the pressure at the top and base of a column are fixed. If the column is warmed, the distance between the two pressure levels will increase, and if it is cooled, will decrease. This distance is known as the thickness, and it provides a useful tool for atmospheric investigations and analysis.

A formula for calculating the thickness, Z, of a layer is:

$$RT/g \ln p2/p1 = Z \qquad \text{Eq1.}$$

where Z is the geopotential thickness between fixed pressure levels p1 and p2,
R is the gas constant for dry air, = 287 J kg^{-1} K^{-1}
g is the standard of gravitational acceleration = 9.8 m sec^{-2}
T is the mean temperature of the layer, in deg K.

For any given layer bounded by fixed pressure surfaces, and given that R and g are constants, Z can only change in response to a change in mean T, so that

$$(R/g \ln p2/p1)\, \Delta T = \Delta Z \qquad \text{Eq 2}$$

Where Δ indicates a change in space or time.

Fig 1. Sequence of 6 hourly surface charts
1 Nov 09 00z to 2 Nov 09 00z. (C) Met Office

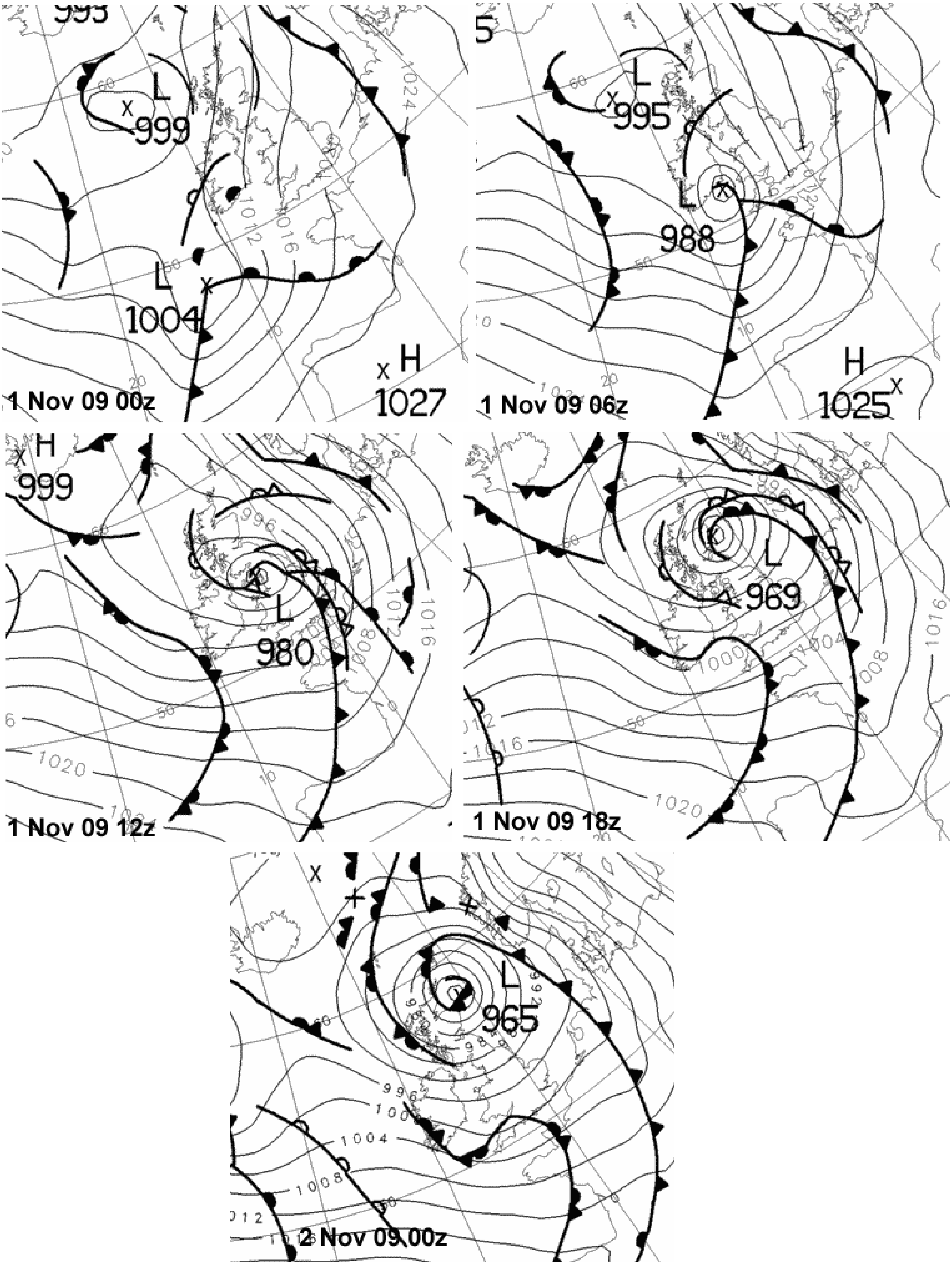

Table 1. Geopotential height data (dam) for positions over the low centre (M) and at 200 km to the N, E, S and W

1 Nov 2009 00z					
P mbar	M	N	E	S	W
1000	+3	+7	+8	+10	+8
500	569	561	570	576	568
300	938	927	940	948	937
100	1630	1623	1630	1635	1630

1 Nov 2009 12z					
P mabr					
1000	-17	-9	-8	-6	-7
500	540	538	549	549	538
300	903	897	916	916	894
100	1612	1607	1614	1617	1611

2 Nov 2009 00z					
P mbar					
1000	-30	-21	-17	-17	-17
500	520	524	527	527	526
300	876	880	886	881	878
100	1598	1596	1600	1601	1597

Table 2. Geopotential thickness, dam, between fixed pressure levels

1 Nov 2009 00z					
P mbar	M	N	E	S	W
500 to 1000	566	554	562	566	560
300 to 500	369	366	370	372	369
100 to 300	692	696	690	687	693

1 Nov 2009 12z					
P mbar					
500 to 1000	557	547	557	555	545
300 to 500	363	359	367	367	356
100 to 300	709	710	698	701	717

2 Nov 2009 00z					
P mbar					
500 to 1000	550	545	544	544	543
300 to 500	356	356	359	354	352
100 to 300	722	716	714	720	719

Table 3. 12 hour thickness change, dam

1 Nov 00z to 1 Nov 12z					
P mbar	M	N	E	S	W
300 to 1000	-15	-14	-8	-16	-28
100 to 300	+17	+14	+8	+14	+24
Above 100	+18	+16	+16	+18	+19
Total	+20	+16	+16	+16	+15

1 Nov 12z to 2 Nov 00z					
P mbar					
300 to 1000	-14	-5	-21	-24	-6
100 to 300	+13	+6	+16	+19	+2
Above 100	+14	+11	+14	+16	+14
Total	+13	+12	+9	+11	+10

The data is shown in Tables 1, 2 and 3. In Table 3, there is a row labled 'Above 100' . Although the thickness above 100 at any specific time is not known, the change can be inferred from the change in 100 mbar height, as this reflects the change in thickness of the entire atmosphere above 100 mbar. When considering the row marked total, this is the true total change in thickness of the entire atmospheric column above the 1000 mbar level at each of the points above the low. Remember that a positive thickness change will equate to a fall in height, and of pressure, at the base of the column, which in this case is at the earth's surface.

Upper analysis charts from the University of Wyoming, http://weather.uwyo.edu/upperair/ , for the 1000, 500, 300 and 100 mbar fixed pressure levels are available at 12 hour intervals for the day in question, and were used to investigate the changes in the thermal structure over the deepening low, and to produce the values given in tables 1, 2 and 3. The geopotential height to the nearest dam was read off the charts at each level for a position directly over the surface low centre, (M), and at 4 positions 200 km from the centre to its North, East, South and West, labled N, E, S and W respectively. The tabulated values are shown in Table 1.

Results.

1) The Troposphere, up to 300 mbar.

At point M, at 00z on the 1st, the actual value for geopotential height at 1000 mbar was +3 dam. To see how the thermal changes affect this value after 24 hours, the thickness total changes at M in Table 3 need to be subtracted, because increasing thickness causes lowering pressure at its base, from the initial 1000 mbar height. The combined total change of +33 dam for the 24 hours period gives a 1000 mbar height of –30 dam at 00z on the 2nd Nov. The equivalent change in surface pressure can be found from Eq1, in the form:

$$1000(\exp(\Delta hg/RT))-1000 = \Delta P \qquad \text{Eq3}$$

where ΔP is the change in surface pressure,
Δh is the change in 1000 mbar height
and R, g and T have the same meaning as in Eq1.

As a rough guide, for a mean temperature of 10C, a change of 10 dam in 1000 mbar height equates approximately to a change of 12 mbar in surface pressure. So a fall of 33 dam in 1000 mbar height at the low centre equates to a pressure fall of 39 mbar, e.g. 1004 – 39 = 965 mbar.

The total thickness change at the other points 200 km from the centre are : N, +28 E, +25 S, +27 and W, +25. Subtracting these values from the thickness change at M gives an indication of how the gradient around the low increased above that at 00z on the 1st, in the 24 hours. The change is most in the E and W points, and least at N. The initial height gradient between M and N was 4 dam, the lowest, and at this point to the north of the centre it remained weakest, ending up at 7 dam. The point at S had the strongest gradient initially, 7 dam, and the modest increase brought it up to 13 dam by 00z on the 2nd. E and W both started with 5 dam and ended up with 13 dam after 24 hours.

An estimate of the geostrophic low level wind can be obtained from the difference in 1000 mbar height between M and each of the other points, which are at a known distance from the centre.

The formula $V = g \, \Delta h / f \, \Delta n$ Eq4

where g is the acceleration due to gravity, V is the geostrophic wind speed in m sec^{-1} .
f is the Coriolis parameter, $2\Omega\sin\text{Ø}$, where Ω is the Earth's angular momentum, 7.29×10^{-5} rad s^{-1} and Ø is the latitude. For 55N an approximate figure for f is 1.2×10^{-4} making g/f = 81667
Δh is the difference in height on a constant pressure surface over distance Δn
In this case, for Δn = 200 km, each 1 m height difference equates to a geostrophic speed of 0.41 m sec^{-1} .

At 00z on the 1st, the geostrophic speed between M and the cardinal points was N,16 E,21 S,29 and W,21 m sec^{-1}. It should be noted that geostrophic wind speed needs to be corrected for curvature of the flow and for friction before an estimate of the surface, or 10 m wind, can be made. The flow at S was fairly straight, in the warm-sector of the developing wave depression, and the 29 m sec^{-1} (56 kn) there was probably a reasonable estimate of the flow above the friction layer. However, at the other points the values would need to be reduced due to cyclonic curvature.

At 00z on the 2nd, the low had reached maturity, and the isobars around it were fairly circular. The calculated values for geostrophic wind based on the 1000 mbar height difference between M and the cardinal points 200 km away was; N,37 E,53 S,53 and W,53 m sec^{-1}. Assuming circular contours of radius 200 km, these speeds would need to be reduced by a little over half to obtain a gradient speed. The resulting speeds would be 18 m sec^{-1} at N and 26 at the rest, or approximately 50 kn. Note that these figures can only be an estimate, as they assume that the distribution of pressure/height was fairly uniform around the low, and that the spacing of height contours at the points used was identical to the average value over the 200 km between the centre and the points, which may not have been the case. Nevertheless, the values obtained are not unreasonable in light of the reported surface winds at the time.

In the first 12 hour period, Table 3 shows that cooling had taken place throughout the troposphere, and was greatest at W and least at E. This is consistent with cold air being drawn into the low from the west, while the original warm air in the developing wave at 00z on the 1st is thrown eastwards as it occludes. In the second 12 hour period, the greatest tropospheric cooling is seen at E and S, as the cold air drawn into the low circulates to its south, while the cooling at N and W are now modest, as some of the system's warm air is circulated from the eastern side of the low to its western side. Over the centre itself, the cooling is much the same in both periods.

Overall, the cooling over the centre up to 300 mbar amounts to 29 dam, while at points S and W it is greater by 11 and 5 dam respectively, and less by 10 dam at N. At E the cooling was the same as at M. The greatest overall change was at S, -40 dam, which is not surprising as this was located on the warm side of the baroclinic wave, in its warm sector, at 00z on the 1st. The small change at N, -19 dam, compared with –29 at the centre, is due to N already being partially in the cold airmass at 00z on the 1st.

2) The lower stratosphere, 100 to 300 mbar.

Here we see large increases in thickness associated with advection and dynamics. Over point M, the 24 hour change in this layer amounts to +30 dam, almost entirely offsetting the cooling in the troposphere below. If there had been no other thermal changes in the atmosphere above 100 mbar, the 24 hour change in 1000 mbar height at point M would have been +1 dam. In other words, the low would not have deepened at all, but would have filled slightly. It is similar over point N, a net change of +1 dam, while at E the cooling was 5 dam more than the warming. At S the net change was –7 dam and at W –8 dam. Had these thermal changes told the whole story, and there was no net change in the atmosphere above 100 mbar, the pattern at 1000 mbar after 24 hours would have shown a low of +4 dam, with a very strong gradient on its south and west flanks.

Fig2 shows a sequence of 100 to 300 mbar thickness charts at 12 hour intervals from 00z on the 1st to 00z on the 2nd Nov 2009. Also on each chart the position of the surface low centre is marked by a cross. A number of things are evident in the charts, firstly the location of a warm anomaly to the northwest of the low at 00z on the 1st. The central thickness was appx 724 dam at this time. The surface low has relatively low thickness values over it and is well away from, and on the south side of the maximum thickness gradient, associated with the jet stream in the upper troposphere below.

12 hours later, the warm anomaly has moved to a position close to western Ireland, with a central thickness of 723 dam. As the warm anomaly develops, the thickness gradient on its eastern flank tightens and the thermal wind rotates in response to dynamic cooling to the north in this layer. The surface low is now located much closer to the warm anomaly, and is under rising thickness values.

By 00z on the 2nd, the dynamic development has resulted in a marked elongation of the thermal anomaly, with possibly the original central thickness near north Wales with a value of 722 dam, and also a new 722 dam value almost over the position of the surface low. From the shape of the anomaly, which has become much narrower, it is possible to see the effect on the upper tropospheric flow, which has a sharpening upper trough associated with these thermal changes. The narrowing of the anomaly is caused in part by the next upwind system, with its jet extending south-eastwards on the western flank of the warm anomaly, leading to a faster eastward advection of lower thickness values to the west of the anomaly than of higher values on its eastern side. It should be noted too, that there is unlikely to be any further contribution to the lowering of surface pressure in the low centre from the thermal structure in this layer, unless a second anomaly were to engage with this system. While it is conceivable that changes in the upwind jet might induce increased descent and warming on the southern flank of the anomaly, the gradual slow loss of thickness near the centre of the anomaly over the 24 hours is probably an indication of radiational cooling in the absence of dynamic descent there, and as such may be expected to continue.

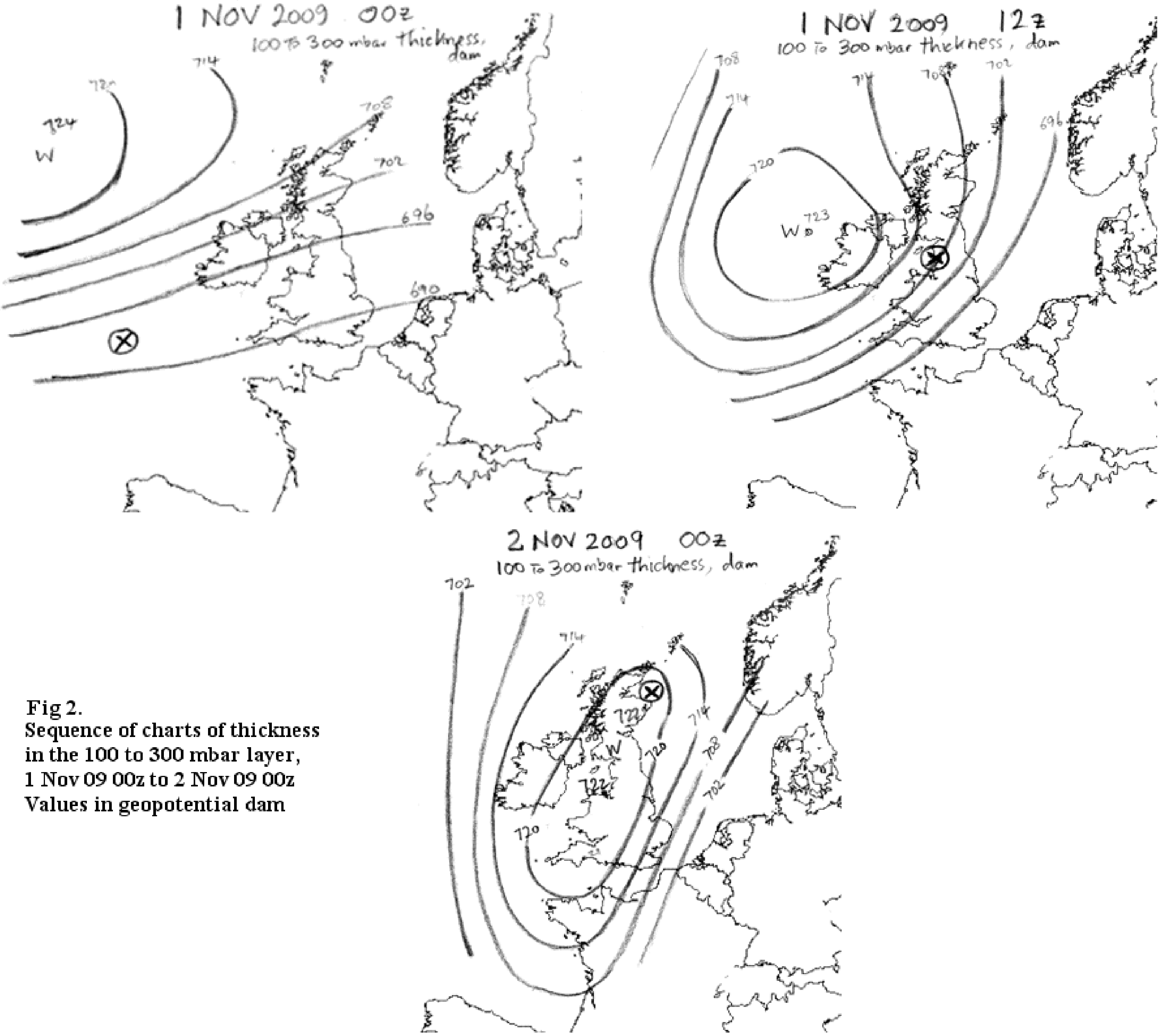

Fig 2.
Sequence of charts of thickness in the 100 to 300 mbar layer, 1 Nov 09 00z to 2 Nov 09 00z
Values in geopotential dam

3) The mid/high stratosphere and mesosphere, above 100 mbar.

During the rapid deepening phase of this low, as noted previously the warming in the 100 to 300 mbar layer over the low centre was almost exactly matched by the cooling in the troposphere. However, since the 1000 mbar height in the low centre fell by 33 dam, the thermal changes accompanying this fall must have been present above 100 mbar. In fact, in the 24 hours between 00z on the 1st and 00z on the 2nd, the thickness in the atmosphere above 100 mbar increased by 32 dam over the low centre, enough to account for nearly all of the fall in pressure there. Some of that change was a result of the track taken by the surface low, across the upper atmospheric thermal gradient towards higher thickness values. The rest of the change was due to developments taking place in the upper stratosphere or mesosphere.

In order to gauge the geographic extent of this warming in the upper atmosphere, relative to the low, data from radio-sonde ascents was used to calculate the change in thickness in layers above 100 mbar over the domain of interest. Where the ascent did not reach 10 mbar, data from the University of Wyoming upper air analysis at 10 mbar was used. Table 4 shows the results for the layers 10 to 100 mbar, and above 10 mbar.

Table 4. Thickness change (dam) in the 10 to 100 mbar layer, and above 10 mbar, for upper air stations covering the UK, in the 24 hours ending 00z on 2nd Nov 2009.

Layer mbar	Camborne	Valentia	Castor Bay	Lerwick
10 to 100	+10	-1	+2	-3
Above 10	+10	+13	+14	+14

Table 4 shows that warming was taking place widely in the vicinity of the UK over the 24 hours ending 00z on the 2nd in the atmosphere above 10 mbar. At all stations except Camborne, the layer 10 to 100 mbar was experiencing little change, only at Camborne did this layer experience significant warming. This data for the thickness changes above 10 mbar is extremely interesting, as it shows that dynamic effects taking place in the upper reaches of the atmosphere had a decisive effect in the rapidity of development of a surface low. If the changes in thickness above 10 mbar are subtracted from the total observed thickness change for the whole atmospheric column, and all other changes were left in place, the low would only have deepened by 17 dam, just over half the observed deepening, and the resulting central pressure would have been appx. 984 mbar at 00z on the 2nd. Of course, it would not be realistic to remove the changes above 10 mbar without making due allowance for the effect this may have had on the developments in the lower stratosphere and troposphere, and it is only offered as an illustration of the magnitude of the effects due to the higher atmospheric layers.

With an average change of between +13 and +14 dam in the layers above 10 mbar over the low centre, and a change of +32 dam in all layers above 100 mbar over the low, we see that appx. 45 % of the deepening could be ascribed to the upper atmosphere above 10 mbar, and 55 % to the stratosphere between 10 and 100 mbar. As noted previously, the lower stratospheric layer between 100 and 300 mbar experienced +30 dam of warming in the 24 hours over the low centre, so that this value added to the +32 dam tells us that the stratosphere and above over the low centre warmed by +62 dam. It is again interesting, if unrealistic, as an illustration to consider that, in the absence of the observed tropospheric cooling over the low, the central pressure would have fallen by 74 mbar, and from a starting pressure of 1004, this would have produced a low of 930 mbar.

Another consideration that stems from the data in Table 4, is that the widespread and fairly uniform nature of the warming in the upper stratosphere would have tended to lower the pressure over a wide area, not just at the surface, but also in the troposphere generally. Although a detailed look at the thermal changes above 10 mbar over the whole of Europe was not intended to be included in this study, when overlaying the 10 mbar charts for 00z on the 1st and the 2nd, it can be seen that warming was taking place over the whole of Europe west of a line eastern Poland to the southern Adriatic. 24 hour thickness changes were greatest to the northwest of the UK, with a reported change of +31 dam at Thorshavn. The +15 isopleth runs from Bodo to just west of Ireland and the +10 from Stockholm to Humberside to mid Iberia. For the UK, the min was +9 dam over the southeast and the max +15 dam over the Hebrides.

Discussion.

It is a fairly normal course of events to find thermal anomalies in the lower stratosphere moving and developing in association with the development of some feature in the upper troposphere and/or at the surface, both cyclonic and anticyclonic. As in this case, when a surface low has ended its deepening phase, it is often found that a warm anomaly in the 100 to 300 mbar layer has become nearly coincident with the low. It is also observed that warm anomalies in the lower stratosphere are implicated in most mid-latitude cyclogenetic situations, and it is often the case that a warm anomaly can be traced back to a time before the appearance of a feature at the surface to which it becomes subsequently linked.

Warm anomalies in the lower stratosphere are intricately linked to cyclonic vorticity maxima in the upper troposphere, which in turn help shape weather patterns in the lower troposphere. As air flows through regions containing vorticity maxima or minima, it will experience vertical stretching or shrinkage. In effect, the greater the vorticity change that a column experiences, the greater the vertical stretching and horizontal shrinkage. Conversely, as air exits a vorticity maximum, the associated vertical column will shrink vertically and expand horizontally. For air to ascend from lower reaches of the troposphere, conditions above must be conducive to the removal of this air efficiently, otherwise the process will stall or may not even be initiated. This applies both to convection and to more general mass ascent. Also, the very action of removing air at an upper level will induce ascent from below, creating favourable conditions for convergence at lower levels.

The reason for the link between thermal anomalies and vorticity maxima may be found in the fact that the contour pattern and its associated vorticity changes at any level in the atmosphere depends on the contour pattern at some higher level, modified by the intervening thermal field. This aspect also highlights the link between the thermal field in the lower stratosphere and the upper tropospheric jet stream. As the jet stream flow is driven by the pressure gradient at its level, and this gradient arises due to the gradient at some higher level plus the intervening thermal gradient, the thermal field in the layers immediately above the jet stream level must have an important role in shaping and maintaining a jet stream in the layer below.

The fact that the lower stratosphere is normally stably stratified is also important, as dynamically induced vertical motions under these conditions will produce relatively large changes in mean temperature and layer thickness, whereas in the upper troposphere where the lapse rate is generally close to adiabatic, vertical motions will have only minimal effect on layer mean temperature and thickness. With the dynamic feedback mechanism that exists between the jet stream flow, with its vorticity changes, and the lower stratospheric thermal field, it can easily be seen how thermal anomalies can develop in the lower stratosphere, as it is one of the most dynamically active regions of the atmosphere.

Throughout this study, the layer 100 to 300 mbar has been taken to represent the lower stratosphere. While this assumption is valid for the airmass present in this case of explosive deepening, where the 300 mbar level was mostly in the stratosphere, it need not always be the case. Indeed , it is normal to find that the tropopause level rises between the poleward and equatorward side of a mid-latitude jet stream. Thus, the use of the 100 to 300 mbar layer, which is appropriate in this case to describe the lower stratosphere, is by no means fixed, and other appropriate layers could be used in different circumstances, for instance the 100 to 200 mbar layer, or 70 mbar to 200 mbar. Nearer the tropics, on the equator side of the sub-tropical jet, the troposphere can extend to the 100 mbar level or a little above, leaving the 100 to 300 mbar layer wholly in the troposphere.

Conclusions.

In this paper, a detailed look has been taken at the thermal structure of the atmosphere above a fixed area moving with the surface low. This low underwent a period of explosive deepening as the central pressure at the surface fell from 1004 mbar to 969 mbar in 18 hours. By concentrating on the changes in thickness in different layers of the atmosphere during the development, it is possible to learn a great deal about how changes in the thermal structure of the atmosphere above the troposphere effects events at the surface. Tracing the thermal changes in the entire atmosphere using a thermal budget provides a useful way to understand the essential processes associated with surface developments.

From this study, it was found that the troposphere above the surface low cooled continuously, chiefly due to the advection of ever colder air into the low's circulation. The track taken by the low as it curved towards the north would have assisted this. As a counter to the 'filling' tendency imposed by this cooling, it was found that there was an increase in thickness in the lower stratosphere associated with the movement and development of a pre-existing warm thermal anomaly, which almost exactly countered the decrease below. These together would not have caused the surface pressure to fall, and the thermal budget in the layer from 100 mbar to the surface was neutral. It was in the atmosphere above 100 mbar, that is the mid and upper stratosphere and the mesosphere, where the thickness changes that matched the fall in surface pressure were located. It was also found that at levels above 10 mbar, thickness changes that accounted for nearly half of the fall in surface pressure were occurring over a very wide area, encompassing nearly the whole of Europe.

Many meteorologists have a tendency to attempt to understand the troposphere without taking into account the atmosphere above. There is bound to be a temptation to look at changes in the atmosphere from the bottom up, as we are immersed in the atmosphere at its lowest level. However, what happens at any level in the atmosphere is largely determined by what happens above that level, and the changes that the atmosphere experiences have their origins in the layers above. It would thus be more logical, when considering changes at the surface, to look at the atmosphere from the top downwards, and not the bottom up.

Finally, it is hoped that by drawing attention to some simple basic analysis tools, such as the thickness budget, a better understanding of the processes at work in the atmosphere will be gained.

B J Burton   22 November 2009