A look at the vertical thermal structure of the atmosphere during a 63 mbar surface pressure fall

Introduction.

In the last third of November 2005, in the vicinity of the British Isles, there was a dramatic change in the surface pressure pattern, from strongly anticyclonic to strongly cyclonic. Over parts of the North Sea and coast of Holland the surface pressure fell by over 60 mbar in 60 hours.

The vertical thermal structure of the atmosphere over the region where this large change took place is examined, mainly in an attempt to identify the layer or layers that were responsible. An illustration is given showing the controlling relationship between vertical motion and layer thickness in the stratosphere.

Pressure and Thickness.

The pressure at any point in the atmosphere is determined by the weight of the atmosphere above that point. For any given layer, the pressure at the base can be considered to be a result of the mass of air above the top of the layer added to the mass between base and top. Thus the pressure at the top of the layer partly determines the pressure at the base, the remaining part being determined by the mean temperature of the intervening atmosphere. This is because the mass of air in a column is proportional to the mean temperature of that column, the higher the temperature, the lower the mass, the same being true for individual layers within that column. Considering the situation in terms of constant pressure surfaces instead of surfaces of constant height, the thickness, h0 (geopotential height difference between the base and top of a layer between constant pressure surfaces) is given by:

$$h0 = R*T/g*\ln(p1/p2)$$

where R is the universal gas constant, 287 J kg-1 K-1,
T is the mean temperature of the layer, degrees K
g is the standard gravitational acceleration, 9.80665 m s-2
and p1, p2 are the pressure at the base and top of the layer in mbar

For any two fixed pressures, p1, p2, g and R are constants, so h0 is directly proportional to T.

or

$$h0 = T * k$$

where $k = R/g*\ln(p1/p2)$

Thus any change in the layer thickness between any two pressure surfaces in the atmosphere is solely the result of a change in the mean temperature in that layer.

Synoptic situation

Fig 1 (page 3 below) shows the synoptic charts for 00z on the 23 November, and 12z on the 25th November in the vicinity of the British Isles. Three points are marked on the 23/00 chart, lettered A, on the coast of Holland, B, over Ekofisk, station 01400, and C, over Castor Bay, station 03918. These correspond to the points in table 1 below. From the charts it can be seen that the surface pressure pattern in the vicinity of the British Isles changed from strongly anticyclonic to strongly cyclonic. From a fairly flat high pressure system on 23rd 00z, pressure everywhere fell almost continuously for 60 hours, though the falls were greatest in the east, culminating in a low pressure centre over the North Sea by 25th 12z.

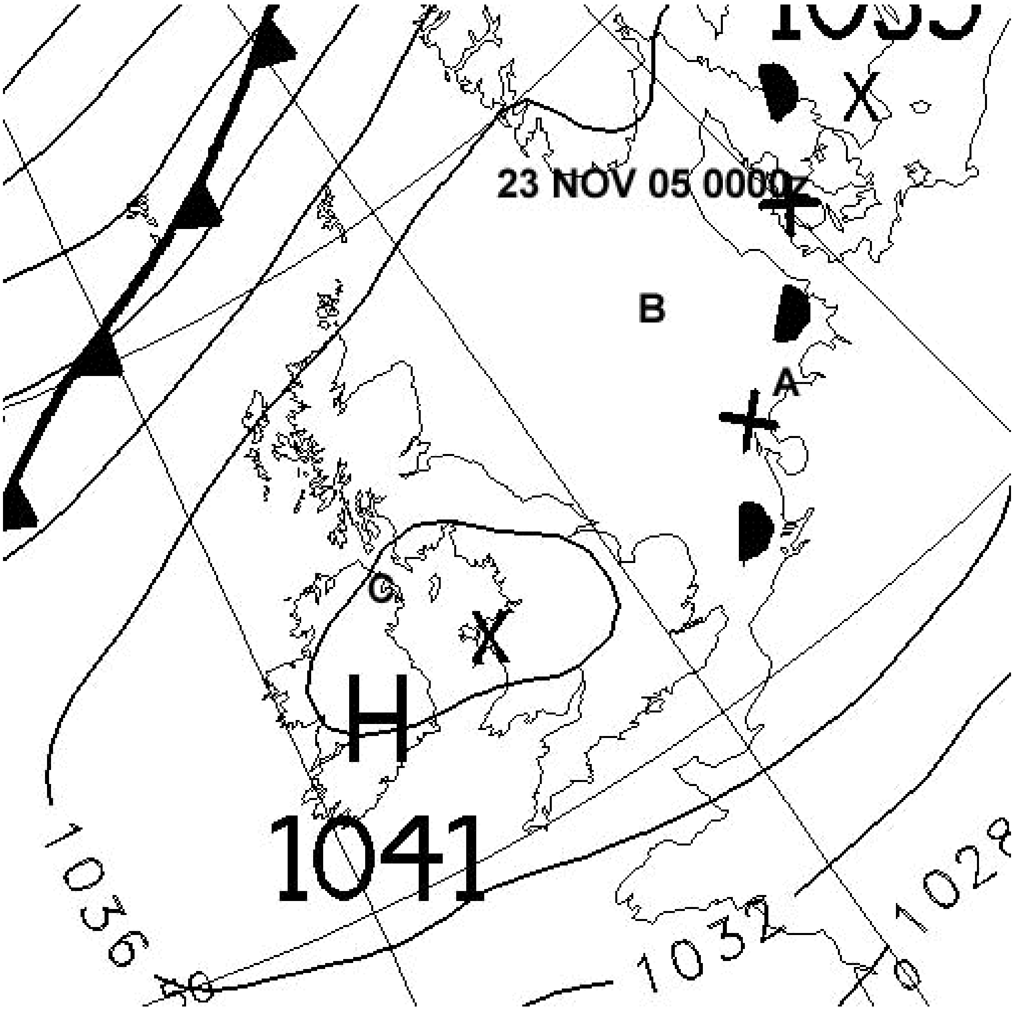
Thickness changes

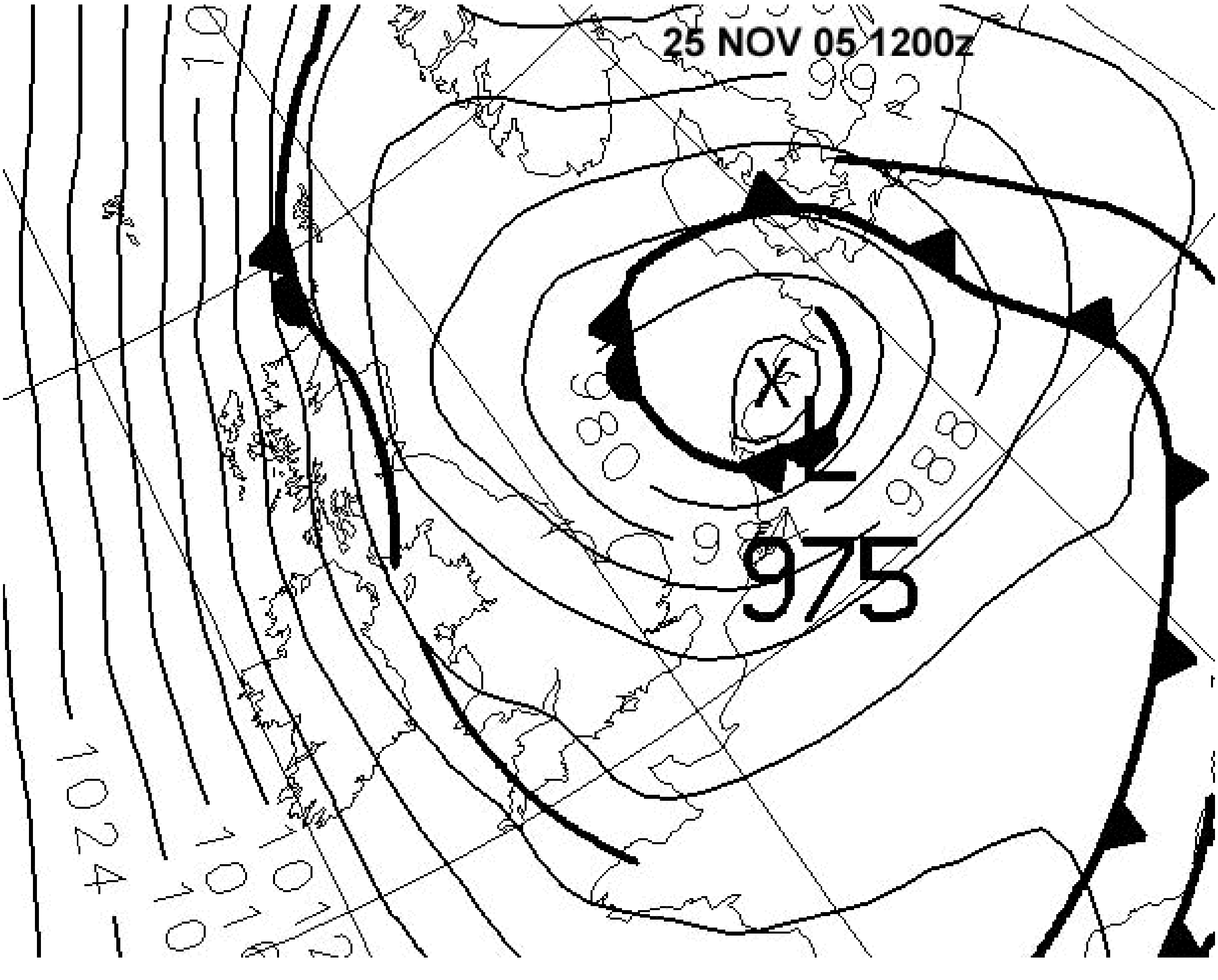
Table 1 shows the total 60 hour thickness change in dam for selected atmospheric levels, 23/00 to 25/12 over A, B and C. The appx. change, m per km, in the atmospheric column is shown in brackets. The layer above 50 mbar is assumed to reach to appx. 1 mbar, 50 km. P is the surface pressure in mbar.

Points	A	B	C
Above 50	+33 (+11)	+38 (+13)	+39 (+13)
50 to 100	+ 7 (+17)	+ 5 (+13)	+3 (+8)
100 to 300	+42 (+60)	+35 (+50)	+36 (+51)
300 to 1000	-31 (-34)	-33 (-37)	-45 (-50)
Total	+51	+45	+33
P start	1038	1038	1041
P end	975	983	1000
P change	-63	-55	-41

From Table 1 it can be seen that the change in surface pressure is proportional to the total change in thickness above, and that as the total thickness increases the surface pressure falls. At point A, where the total thickness change is greatest, we see from Table 1 that the thickness change in the stratosphere, above 300 mbar, is positive at all levels, and amounts to +820 m. If there were no other change in the atmospheric column above point A, the surface pressure would have fallen by 98 mbar there, from 1038 to 940 mbar. However, from the figures for thickness change in the troposphere, between 300 and 1000 mbar, it is evident that cooling took place there, amounting to a thickness change of –310 m, partly offsetting the stratospheric warming, and restricting the change in surface pressure to –63 mbar.

Fig1.


23 NOV 05 0000z
B
A
C
H
1041
1036
1032
1028


25 NOV 05 1200z
992
980
988
L
975
1024
1016
1012

The centre of the surface low was near point A, and by comparing the thickness changes there with those at points B and C, we can assess the relative contribution of the various atmospheric layers to the location of the surface low. The stratosphere provided an additional thickness increase of 40 m over point A compared with both points B and C, while the troposphere gives an addition of 20 m compared with point B, and 140 m compared with point C. Thus the 1000 mbar height at point A was 60 m (40 + 20) lower than point B, and 180 m (40 + 140) lower than point C.

Thickness changes and dynamic forcing

It can be seen that the cause of the dramatic pressure change that took place over 60 hours in the vicinity of the British Isles was a large-scale change that took place in the stratosphere, modulated by mainly advective changes in the troposphere. Very large thermal changes can and do take place in the stratosphere as a result of dynamic forcing. The stratosphere generally has a stable lapse rate, often nearly isothermal over considerable depth. Vertical motion associated with the dynamics of the strong stratospheric flows during the winter half-year easily lead to large thickness changes in the mid to upper stratosphere, and are strikingly evident during periods of sudden warming. Also, near the tropopause, associated with the upper tropospheric jet stream, strong vertical motions take place in both the lower stratosphere and upper troposphere.

For a given layer, the thickness change produced by a given physical vertical displacement of that layer depends on the temperature lapse, decreasing towards zero change as the lapse tends towards the dry adiabatic lapse rate from a stable one. Thus large dynamically induced vertical motions in the region of the tropopause have a much greater effect on the thermal structure of the lower stratosphere then the upper troposphere.

As an example, for the lower stratospheric layer 100 to 300 mbar, a 100 m vertical displacement in an isothermal atmosphere will result in a thickness change of 4.6 m per km. As this layer is about 7 km thick, every 100 m displacement will change the thickness in this layer by about 32 m. In the upper troposphere the thickness change associated with an identical displacement will be between zero for a dry adiabatic lapse rate to 1.8 m per km for a lapse rate of 7C per km, and will typically be confined to the upper 3 km or so of the troposphere, leading to a thickness change only one sixth of that in the stratosphere.

Over point A there was a change of 60 m per km in the 100 to 300 mbar layer (see Table 1) over a 60 hour period, indicating descent for the air in that layer of about 1300 m (layer mean), assuming that all the thickness change was due to vertical motion in an isothermal atmosphere, although in practice some of the change could have been due to advection.

The magnitude of the actual descent in this case can be judged from examination of the data over point B from radiosonde station 01400, and this is discussed below.

Adiabatic motion is vertical movement that causes changes in temperature in a sample of gas due only to accompanying expansion or compression in response to external changes in pressure, with no gain or loss of heat. Diabatic changes in temperature occur due to the addition or loss of heat to the sample, as the result of radiation, conduction or change of state. In the atmosphere, temperature changes caused by condensation or evaporation are typical diabatic processes, as are the changes associated with the vertical redistribution of heat during convection.

In adiabatic motion in a dry atmosphere, the potential temperature, (theta), of an air sample is conserved, and may thus be used as a tracer. Any changes in height of a theta surface will indicate real changes in the height of an air sample. In the stratosphere, and in this case in the lower stratosphere, there is very little water vapour so that diabatic changes are limited to turbulent mixing and radiation, which are both assumed to be small compared to the other dynamic adiabatic changes taking place in this instance.

Choosing a theta surface of 340 C from the data for station 01400, which is conveniently at 170 mbar at the start, at 23/11/05 00z, we find that over the 60 hour period of interest this surface descends to 240 mbar, and in approximate height terms, from 1282 to 1060 dam, a descent of 2.2 km. This is qualitatively in line with the deductions above argued from a thickness change perspective, where we deduced a descent of about 1.3 km. This latter figure is of course a layer mean over the entire layer 100 to 300 mbar, as opposed to the behaviour of a specific theta surface within that layer.

Fig 2 (page 6 below) is a combined plot of the cumulative thickness change in the 100 to 300 mbar layer over point B, and the change in height of the 340 theta surface. Note how the relationship is an inverse one, descending air warms and thickness increases, and note too how the relative slopes tally.

Fig 3 is a combined plot of the accumulated thickness change for the upper stratosphere above 100 mbar, and for the troposphere, again over point B. Note here that the upper stratospheric thickness increases throughout the entire period. In the troposphere, we can see decreasing thickness as cold air was advected southwards, with a slight recovery in the last 12 hours at that point.

Where pressure was lowest, point A, tropospheric cooling had reduced the thickness by 33 dam over 60 hours, but at point C, on the western periphery of the low at 25/12z, where the surface pressure was much higher than at the centre, the tropospheric thickness had decreased by a much larger 45 dam. At points B and C, the thickness change in the stratosphere was identical, the only difference in the entire atmospheric column was 12 dam more cooling in the troposphere over point C than point B, and it is this that determined that the surface pressure at C was 1000 mbar as opposed to 983 mbar at B. But the cause of the further decrease at point A, 975 mbar, compared with point B is 2 dam less cooling in the troposphere and 4 dam more warming in the stratosphere, of which the 7 dam more at A than B in the 100 to 300 mbar layer contributed.

Fig2.

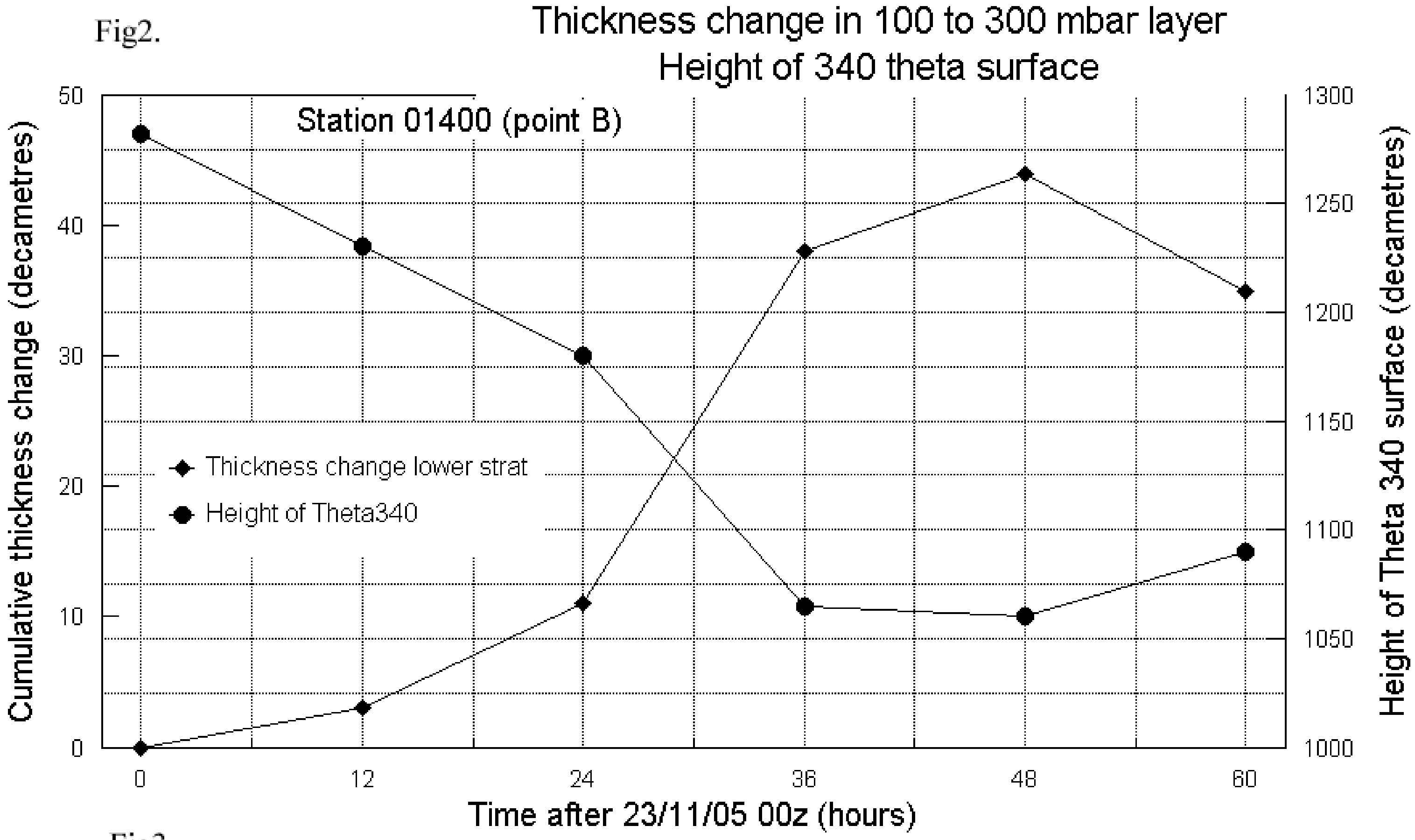
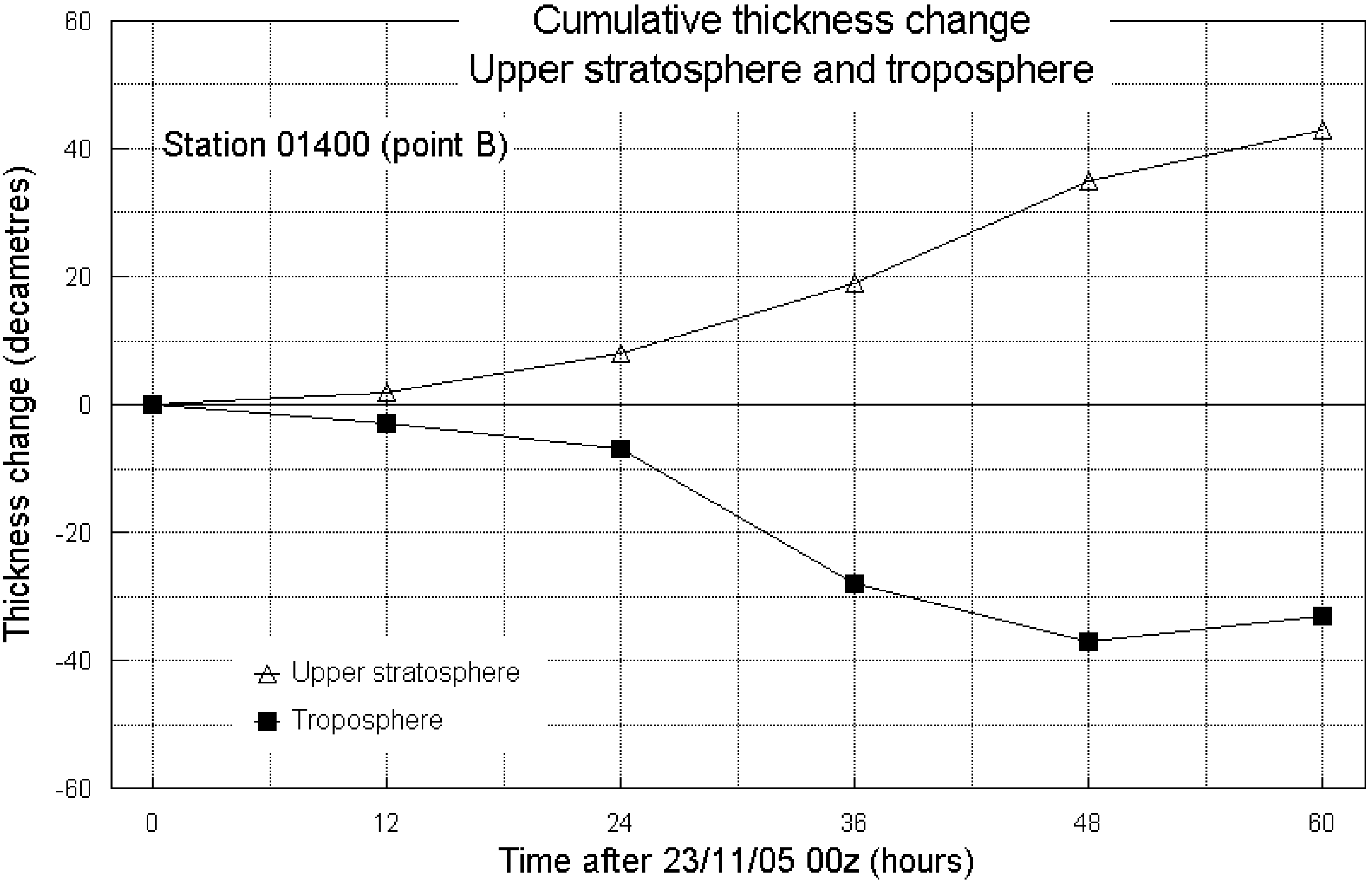

Thickness change in 100 to 300 mbar layer
Height of 340 theta surface
Station 01400 (point B)
◆ Thickness change lower strat
● Height of Theta340
Cumulative thickness change (decametres)
Height of Theta 340 surface (decametres)
Time after 23/11/05 00z (hours)
0
10
20
30
40
50
1000
1050
1100
1150
1200
1250
1300
0
12
24
36
48
60

Fig3.


Cumulative thickness change
Upper stratosphere and troposphere
Station 01400 (point B)
△ Upper stratosphere
■ Troposphere
Thickness change (decametres)
Time after 23/11/05 00z (hours)
60
40
20
0
-20
-40
-60
0
12
24
36
48
60

Conclusion.

The reason for the very impressive change from high pressure anticyclonic conditions to low cyclonic ones in the vicinity of the British Isles over the period 23rd to 25th December 2005 can be traced to a very large thickness increase in the stratosphere over the region. Additional dynamically induced effects in the vicinity of the tropopause served to enhance the effects of the mid-upper stratospheric changes. As the surface pressure pattern developed it led to cold advection in the troposphere whose effect was to partially offset the warming in the stratosphere, and modulated the pressure falls at the surface, rather more in the west than over the North Sea, which is why the surface low became centred at this latter location.

In the winter half year, the stratosphere in mid to high latitudes can be very dynamically active. As the season progresses, a circumpolar vortex intensifies and extremely strong gradients can be found on its periphery. With such a dynamically active region overlaying the troposphere, it is only to be expected that the dynamic effects will be felt in the atmosphere below. Another effect that can sometimes be seen arises due to the strong height gradients in the mid stratosphere. When the tropospheric pattern favours cyclonic development, the path taken by the surface low relative the orientation of the mid-stratospheric flow can be instrumental in defining whether the subsequent development will be small or dramatic.

In a recent example near the British Isles, an Atlantic low moving rapidly Northeast deepened from 1004 to 970 mbar in the 24 hours up to 00z on 8th November 2005, passing close to the Scottish Western Isles. In the 12 hour period from 12z on the 7th to 00z on 8th, the 1000 mbar height at the low centre fell from –92 m to –240 m, implying a total thickness change of +148 m in the atmosphere above. Analysis of the associated layer thickness changes over the centre showed that the tropspheric net change was +8 m, with cold advection between the surface and 500 mbar, and warm advection between 500 and 300 mbar. The total stratospheric change was +140 m, of which +90 m was due to the surface low moving across the stratospheric thermal gradient, and +50 m was due to dynamic development in the lower stratosphere. (Data from University of Wyoming, upper air charts, analysis.)

It is hoped that this very modest case study will serve to illustrate the importance of the stratosphere in influencing developments in the mid-latitude troposphere and in helping to shape surface pressure patterns on a day to day basis.

B J Burton. January 2006