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Storm Ciaran - A Broad Scale Thermal Analysis

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Between 1200z on the 1st November 2023 and 0000z on the 3rd, an intense storm, named Ciaran by the UK Met Office, travelled on a leftward curving path from about 450 nm west-southwest of Lands End to the central North Sea, the centre passing eastwards along the English Channel before crossing over the southeast of England. The gradient on its south side reached extreme values at about 00z on the 2nd, and moderated slowly thereafter. Damaging winds were experienced over northwest France and the Channel Islands. Model output charts from the University of Wyoming were used to determine the thermal structure of the storm.

The centre of storm Ciaran experienced explosive deepening between 12z on the 1st and 00z on the 2nd, the analysed central pressure falling from 972 hpa to 954 hpa in that 12 hour period. The following analysis was carried out by listing the geopotential at 1000, 500, 300 and 100 hpa at two points, A and B, moving with the low, point A being located over the surface centre of the low and point B located 220 km to the south of A.

Throughout this article, the 1000 hpa geopotential is used as a proxy for the MSL pressure. Comparison of the Wyoming MSLP charts with those of the Met Office ASXX show slight differences at point A. The ASXX MSLP values when converted to equivalent 1000 hpa geopotential and expressed to the nearest decametre were -24, -39, -37 and -35 in 12 hour steps from 12z on 1st to 00z on 3rd. The Wyoming values at the same times were -25, -41, -40, and -35. As the Wyoming charts are being used for data at other levels, the Wyoming 1000 hpa values are used without modification.

The geopotential at any level in the atmosphere (up to at least 80km) can be found from a knowledge of the geopotential at some higher level immediately above, plus the intervening thickness, which is directly proportional to the mean temperature of the layer. A thickness budget with its change with time and/or place can provide useful information about the processes occurring in the atmosphere, and in particular, can show the level or levels that have had the gratest contribution to the surface developments.

Date/time	100 hpa	300 hpa	500 hpa	1000 hpa
1/12	1612	888	526	-25
2/00	1603	873	509	-41
2/12	1593	866	512	-40
3/00	1584	866	514	-35

Table 1A. Values of geopotential (gpdam) over the centre of storm Ciaran, 1200z on 1st November 2023 to 00z on 3rd November 2023

Date/time	100 hpa	300 hpa	500 hpa	1000 hpa
1/12	1622	908	541	-14
2/00	1611	883	522	-20
2/12	1597	874	518	-25
3/00	1587	868	518	-27

Table 1B . Values of geopotential (gpdam) over point B, 220km south of point A, 1200z on 1st November 2023 to 00z on 3rd November 2023

Date/time	100 to 300 hpa	300 to 1000 hpa	500/1000 hpa
1/12	724	913	551
2/00	730	914	550
2/12	723	906	552
3/00	716	901	549

Table 2A, Values of geopotential thickness at point A over the centre of storm Ciaran, 1200z on 1st November to 0000z on 3rd November.

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Date/time	100 to 300 hpa	300 to 1000 hpa	500/1000
1/12	714	922	555
2/00	728	903	542
2/12	723	899	543
3/00	719	895	545

Table 2B. Values of geopotential thickness at point B 220km south of point A, 1200z on 1st November to 0000z on 3rd November

12 hour period	Above 100 hpa	100/300 hpa	300/1000 hpa	Net
1/12 to 2/00	+9	+6	+1	+16
2/00 to 2/12	+10	-3	-8	-1
2/12 to 3/00	+9	-9	-5	-5

Table 3A. Values of thickness change in 12 hour steps at point A, 1200z on 1st to 0000z on 3rd.

12 hour period	Above 100 hpa	100/300 hpa	300/1000 hpa	Net
1/12 to 2/00	+11	+14	-19	+6
2/00 to 2/12	+14	-5	-4	+5
2/12 to 3/00	+10	-4	-4	+2

Table 3B. Values of thickness change in 12 hour steps at point B, 1200z on 1st to 0000z on 3rd

Date/time	100 hpa	300 hpa	500 hpa	1000 hpa
1/12	+10	+20	+15	+11
2/00	+8	+10	+13	+21
2/12	+4	+8	+8	+15
3/00	+3	+2	+4	+8

Table 4A. Geopotential gradient in gpdam between points A and B, +ve = westerly component, -ve = easterly component

Date/time	100/300 hpa	300/1000 hpa
1/12	-10	+9
2/00	-2	-11
2/12	-4	-7
3/00	+1	-6

Table 4B Thermal gradient in gpdam between points A and B, +ve = westerly component, -ve = easterly component

12 hr. period	Above 100 hpa	100 to 300 hpa	300 to 1000	Net	Gradient
1/12 to 2/00	-2	-8	+20	+10	increasing
2/00 to 2/12	-4	+2	-4	-6	decreasing
2/12 to 3/00	-1	-5	-1	-7	decreasing

Table 5. 12 hour thickness change at point A relative to point B

Date/time	100 hpa	300 hpa	1000 hpa
1/12	78	155	85
2/00	62	78	163
2/12	31	62	116
3/00	23	16	62

Table 6. Geostrophic wind, knots, between point A and B. W to E component.

Date/time	100 hpa wind knots	100/300 thermal wind, knots	300/1000 thermal wind, knots	1000 hpa wind knots
1/12	+78	-77	+70	+85
2/00	+62	-16	-85	+163
2/12	+31	-31	-54	+116
3/00	+23	+8	-47	+62

Table 7. 1000 hpa geostrophic wind between points A and B, knots, resulting from the geostrophic wind at 100 hpa plus the intervening thermal wind, W to E components, +ve = westerly

Layer	T-24	T-12	T0	T+12	T+24
Above 300 hpa	+5	+13	+23	0	0
300 to 1000	+1	-2	-14	-2	-3
Net	+6	+11	+9	-2	-3

Table 8. Mean 12 hour thickness changes over the centre of 200 North Atlantic rapidly deepening cyclones, 1989 to 2009. Note, increasing thickness in a layer signifies falling pressure below that layer.

Tables 1A and 1B show the values of geopotential for points A and B in 12 hour steps from 1200z on the 1st November 2023 to 0000z on 3rd November 2023. Looking at the values for 100 hpa geopotential, it can be seen that at both points the system was experiencing decreasing geopotential at that level, indicating that the atmospheric thickness above 100 hpa was increasing, either due to the orientation of the thermal gradient there relative to the movement of the surface low, and/or developments occurring above 100 hpa, and/or thermal advection . In the 36 hour period, at point A the change in total thickness was +10 gpdam, composed of +28 gpdam above 100 hpa and -18 gpdam below, while at point B it was +13 gpdam, composed of +35 gpdam above 100 hpa and -22 gpdam below (Tables 3A and 3B).

Tables 2A and 2B show the thickness values over points A and B respectively, in 12 hour steps in the 36 hours period of interest. At both locations we see the thickness in the lower stratospheric layer 100 to 300 hpa initially increases then decreases as an eastward moving warm anomaly in that layer catches up with then overtakes the surface feature. In the 300 to 1000 hpa tropospheric layer, at point A we see an initial slight increase in thickness, then a strong decrease. while at point B we see an initial large decrease in thickness followed by a slowing in the rate of cooling.

Table 3A and 3B show these thickness changes, including for the region above 100 hpa, allowing a complete thickness budget for the changes above points A and B. Here we see pointers to the cause of the extreme gradient that developed on the south side of Ciaran. In the 12 hour period to maximum depth, while the surface pressure in the centre of the low was falling fast, we see a net warming over the centre of +16 gpdam, while just 220 km to the south at point B, the net warming is only +6 gpdam. Looking at the tropospheric layer 300 to 1000 hpa, in the same period over point A the thickness increased by +1 gpdam, while simultaneously at point B it fell by a massive -19 gpdam.

Table 4A shows the geopotential west to east gradient between points A and B, west is +ve. In the first 12 hours the gradient at 1000 hpa increases from +11 to +21 gpdam then decreases steadily over the next 24 hours. Meanwhile, the thermal gradient between points A and B, table 4B, changes in the first 12 hours from a +9 gpdam (westerly) component to a -11 easterly one. Table 5 shows the relative change in thickness between points A and B, highlighting the change in the first 12 hours that accompanied the massive increase in low level winds.

Table 6 shows the resulting geostrophic westerly wind component in knots . (See page 8 below for explanation of how the wind speeds were calculated). At 100 hpa we see the component decreasing over the 36 hours, while at 300 hpa the initial 155 knot jet decreases steadily to 16 knots, partly as the surface low moves northwards away from the jet axis. At 1000 hpa we see a massive increase in geostrophic component from +85 knots to +163 knots. However, the correction to obtain the gradient wind, after allowing for curvature (50N, radius 220 km), would be in the order of 90 knots, but still leaving a gradient speed of over 70 knots. It should be emphasised here that this is a coarse scale analysis, and as such is only applicable to the mean conditions between points A and B at specific 12 hour intervals. Stronger geostrophic gradients on a smaller scale are a possibility, and the existance of a sting-jet cannot be ruled out.

Table 7 shows how the geostrophic flow at 100 hpa is modified by the thermal winds in the lower stratosphere and entire troposphere to produce the flow at 1000 hpa. It is evident that a westerly thermal wind detracts from the 100 hpa flow, while and easterly one adds to it. Initially, at 12z on 1st, a strong easterly thermal wind in the 100 to 300 hpa layer is associated with the warm pulse in that layer as it overtakes the surface low. 12 hours later, by the time of maximum depth of the 1000 hpa cyclone (maximum in terms of the 12 hour steps in this study), the easterly thermal component in the lower stratosphere had decreased substantially, and the 100 hpa flow had also decreased a little. However, the massive change in the tropospheric thermal from 70 kt. westerly to 85 knot easterly is very likely the primary cause of the development of the very strong geostrophic flow at 1000 hpa. In terms of the 100 to 1000 hpa thermal W to E gradient, this changes from -7 kt at 12z on 1st to -101 kt at 00z on 2nd, and is still -85 kt at 12z on 2nd.

Table 8 shows the mean 12 hour thickness change for 200 North Atlantic rapidly deepening cyclones between 1989 and 2009, where T0 is the time of minimum msl pressure. In the present study of storm Ciaran, the analysis starts at T-12. From T-12 to T0, the thickness change above 300 hpa over the centre was +15 gpdam, somewhat less than the 200 example mean of +23 gpdam. The Ciran thermal change in the troposphere was +1 gpdam, but the 200 case mean was -14 gpdam. Here, then, is possibly another factor contributing to the development of a very strong flow on the south side of Ciaran, namely it had an atypical warm core. At the same time a fairly normal cold flow advected quickly around the south of the low, as seen by the change in 300 to 1000 hpa thickness at point B, where it fell by 19 gpdam (Tables 2B and 3B) between 12z on 1st and 00z on 2nd. It appears from table 2A that, while the 300 to 1000 hpa thickness started to decrease after 00z on the 2nd, the 500 to 1000 hpa thickness actually did not commence falling until after 12z on the 2nd. This would suggest that the warm core of Ciaran was located mainly in the lower troposphere, probably indicating that relatively warm air in that layer was circulating near the centre, its movement coupled to the movement of the surface low. The contrast with the colder air to the south generated a strong easterly thermal in the troposphere (table 4B), which when combined with a weaker easterly thermal in the lower stratosphere (table 7), augmented the 62 knot westerly flow at 100 hpa to produce the 163 knot westerly component at 1000 hpa.

Camborne	(03808)				
Date/time	100 hpa	300 hpa	500 hpa	1000 hpa	mslp
1/00	1604	904	546	-7	992
1/12	1601	885	532	-7	992
2/00	**1602**	**872**	**512**	**-36**	**958**
2/12	1591	870	520	-18	978
3/00	1592	876	526	-14	983
3/12	1602	887	532	-11	987

Table 9a .Sequence of 12 hourly geopotential (gpdam) for Camborne, 90km NE of the centre of storm Ciaran at 00z on 2nd November 2023

Camborne	(03808)	Thickness	
Date/time	100 to 300 hpa	300 to 1000 hpa	500 to 1000 hpa
1/00	700	911	553
1/12	716	892	539
2/00	**730**	**908**	**548**
2/12	721	888	538
3/00	716	890	540
3/12	715	898	543

Table 9b Sequence of 12 hour geopotential thickness data for Camborne

Brest	(07110)				
Date/time	100 hpa	300 hpa	500 hpa	1000 hpa	mslp
1/00	1605	905	547	-3	997
1/12	1605	893	539	-3	997
2/00	**1602**	**877**	**517**	**-30**	**964**
2/12	1594	867	521	-14	983
3/00	1593	872	524	-12	986
3/12	1601	888	532	-8	990

Table 10a. Sequence of 12 hourly geopotential (gpdam) for Brest. 150 km SSE of the centre of storm Ciaran at 00z on 2nd November 2023

Brest	(07110)	Thickness	
Date/time	100 to 300 hpa	300 to 1000 hpa	500 to 1000 hpa
1/00	700	908	550
1/12	712	896	542
2/00	**725**	**907**	**547**
2/12	727	881	535
3/00	721	884	536
3/12	713	896	540

Table 10b. 12 hourly sequence of geopotential thickness (gpdam) for Brest.

Larkhill	(03743)			
Date/time	100 hpa	300 hpa	500 hpa	1000 hpa
2/06	1594	866	511	-38

Table 11a Values of geopotential (gpdam) for Larkhill, 60 km NNW of the centre of storm Ciaran at 06z on 2nd November 2023

Larkhill	(03743)	Thickness	
Date.time	100 to 300 hpa	300 to 1000 hpa	500 to 1000 hpa
2/06	728	904	549

Table 11b Values of geopotential thickness (gpdam) over Larkhill at 06z on 2nd November 2023

In table 9a is the sequence of 12 hour geopotential measured at Camborne (03808) between 00z on 1st and 12z on 3rd at 100, 300, 500 and 1000 hpa, and in table 9b. the corresponding thickness in gpdam over Camborne for the layers 100 to 300, 300 to 1000 and 500 to 1000 hpa. Storm Ciaran passed to the south of Camborne early on the 2nd, and lay about 90 km to the SE of that station at 00z on 2nd. From table 9b, the passage of a warm anomaly in the lower stratosphere is much in evidence, but at the same time there was also a peak in tropospheric thickness as the tip of the thermal wave crossed.

Table 10a shows the sequence of geopotential measured at Brest (07110) at the same levels as at Camborne, and table 10b is the corresponding thickness. Again we see the lower stratosphere thermal anomaly approaching between 12z on 1st and 00z on 2nd, but here the peak was not felt until after 00z on 2nd, the 100 to 300 hpa thickness being slightly higher at 12z on 2nd than at 00z.

Storm Ciaran lay about 150 km NNW of Brest at 00z on 2nd and its closest approach would have been a little after that. From table 10b we see that the tropospheric warm pulse was near Brest at 00z on the 2nd, but by 12z on the 2nd the colder airmass in the lower troposphere was well established there, with the 500 to 1000 hpa thickness falling by 12 gpdam in the 12 hours to 12z on 2nd.

Table 11a and 11b show the data for an ascent at 06z on 2nd from Larkhill, (03743), when storm Ciaran was located about 60 km SSE of that station. Here we see similar values of lower stratospheric thickness as at Camborne 6 hours earlier, although the fact that in this layer the thickness was slightly lower at Larkhill than at Camborne suggests that the centre of the tongue of warmest air in the 100 to 300 hpa layer was tending to move on a track slightly south of east. The thickness in the lower troposphere at Larkhill was similar to both the Camborne and Brest values 6 hours earlier. It does indicate that the lower troposphere was not particularly cold on the north side of the surface low, at least within about 100 km of the centre.

Figure 1 (p9) is a map of the lower stratospheric and lower tropospheric thickness relative to the surface low centre of Ciaran at 12z on the 1st and 00z on the 2nd, during which time the 1000 hpa geopotential at the centre fell by 16 gpdam (analysed surface pressure fell from 972 to 954 hpa). What is immediately evident is that a tongue of warm air in the 100 to 300 hpa layer advected east-southeastwards and developed dynamically such that it provided increasing thickness values in this layer over the surface storm centre. At the same time, the thermal structure in the lower troposphere developed from an open wave to a breaking wave, with indications already that a nodule of warmer air was being isolated over the surface low centre. As mentioned before, reference to Table 8 shows that the isolation of a warm nodule over the centre of rapidly deepening North Atlantic lows is not the typical behaviour. Conversely, the advection and/or development of a warm anomaly in the lower stratosphere to be located over the centre of this type of low at the time of maximum depth is typical, and has been present in all of this type of rapidly deepening North Atlantic depression that I have studied in the last 30 plus years.

Discussion

This broad scale study of the thermal evolution of the atmosphere over a rapidly deepening mid-latitude low, storm Ciaran, which produced damaging surface winds on its southern flank, enables some understanding to be gained as to the contribution that different levels in the atmosphere make in determining the intensity and path of a surface low of this type, and also to illustrate the probable source of the extreme winds associated with storm Ciaran. Table 3A shows that for the 12 hour period of maximum deepening, 12z on 1st November to 00z on 2nd, the 1000 hpa geopotential at the centre of the storm fell by 16 gpdam. This indicates that the thickness of the total atmospheric column over Ciaran increased by 16 gpdam, and that the proportion of this increase ascribed to various levels in the atmosphere was 6% for the troposphere below 300 hpa, 38 % for the lower stratosphere, 100 to 300 hpa, and 56 % for the rest of the atmosphere above 100 hpa. In other words, 94% of the deepening was associated with what was happening thermally above 300 hpa. A point worth mentioning here is that, if there is an easterly thermal gradient in the lower stratosphere, the trajectory of a surface low relative to that pattern will be a factor as to whether the low deepens or not, and by how much. Any surface feature that tracks with a northerly component will very often experience increasing thickness values in the stratosphere. Another factor will be associated with any development that is occurring in the lower stratosphere due to the dynamics of the flow there. For instance, if we consider the level of the maximum wind, changes in vorticity along the flow and also vertically above and below that level will determine the magnitude and sign of vertical motion occurring, which is especially important around the tropopause when the flow in strong there. There may also be wave action at any level in the stratosphere that can quite rapidly alter the thermal pattern, as in the case of sudden stratospheric warming events, though there is no evidence that this was a factor in this case.

To get a feel for how important any of these factors may have been in this case, we can look at the changes that appear at 100 hpa over the surface centre of Ciaran. From table 3A, we see that there was an almost constant increase in thickness above 100 hpa, amounting to +28 gpdam between 12z on the 1st and 00z on the 3rd over point A, while over point B, there was an even larger increase amounting to +35 gpdam. Taken on its own, this will have tended to reduce the geostrophic gradient to the south of Ciaran at 100 hpa. During the surface deepening phase of Ciaran, up to 00z on the 2nd, the reason for the exceptional increase in 1000 hpa geopotential gradient between A and B was undoubtedly the large tropospheric cooling over B which amounted to -19 gpdam (table 3B), as opposed to a +1 gpdam warming in that layer at A. After 00z on 2nd, the deepening of Ciaran ceased. and the 1000 hpa geostrophic gradient between A and B weakened due to greater tropospheric cooling at A than at B (-13 and -8 gpdam respectively), augmented by less warming over A than B in the atmosphere above 300 hpa (+7 and +15 gpdam respectively) So as the centre of Ciaran cooled, net -6 gpdam, the region to its south that experienced the exceptional winds warmed, net +7 gpdam, easing the geostrophic gradient.

The sequence of ascents at Camborne show that between 00z on the 1st and 00z on the 2nd, the lower stratosphere warmed by +20 gpdam as the warm anomaly approached, while the troposphere cooled overall by -3 gpdam, though in the first 12 hours to 12z on the 1st it cooled a lot, the 300 to 1000 hpa thickness down by 19 gpdam, only to increase by 16 gpdam in the next 12 hours as the tropospheric thermal wave approached. Post 00z on the 2nd, we see the lower stratosphere over Camborne cooling, down by 14 gpdam by 00z on 3rd, while in the troposphere there is an initial cooling of -18 gpdam in the 12 hours to 12z on 2nd followed by warming of +9 gpdam in the next 24 hours. In the lower troposphere, in the 500 to 1000 hpa layer, the thickness peaked at 548 gpdam at 00z on the 2nd, then fell to 538 gpdam by 12z on 2nd, recovering to 543 gpdam over the next 24 hours. Interestingly, 5 out of the 6 ascents at Camborne terminated above 10 hpa, only the one when Ciaran was closest terminated earlier, but did manage to provide data up to 100 hpa. In the period 00z on 1st to 12z on 1st, the total thickness above 100 hpa increased by +3 gpdam, while above 10 hpa the change was +4 gpdam. In 24 hours between 12z on the 1st and 12z on the 2nd, the total thickness above 100 hpa increased by +10 gpdam in the face of cooling of -15 gpdam above 10 hpa, there being a warming of +25 gpdam in the 10 to 100 hpa layer. In the next 24 hours, from 12z on the 2nd to 12z on the 3rd, the total thickness above 100 hpa decreased by -11 gpdam, and above 10 hpa, by -10 hpa. The warming in the period 12z on 1st to 12z on 2nd in the 10 to 100 hpa layer during the 24 hours that spans the period of the passage of the lower stratospheric warm anomaly suggests a coupling with the mid to upper stratosphere. As a warm anomaly in the lower stratosphere is associated with descent in that layer, and a cool anomaly with ascent, a fact that also holds for other layers higher in the stratosphere, the fact that the passage of the warm anomaly in the 100 to 300 hpa layer occurred around 00z on the 2nd, and the passage of a warm anomaly above 100 hpa was between 00z and 12z on the 2nd, could suggest the passage of a wave sloping upwind with height above 300 hpa. Also, the fact that there is no appreciable warm anomaly seen in the sequence above 10 hpa for the period 12z on the 1st to 12z on the 3rd may be an indication that the wave damped in the mid stratosphere, though the 26 gpdam cooling in the atmosphere above 10 hpa between 12z on the 1st and 00z on the 3rd could also be part of the same atmospheric structure, but with the wave at that level having an opposite phase to the one below.

Finally, the evolution of the lower stratospheric and tropospheric thermal patterns as storm Ciaran deepened rapidly, shown in Figs 1 and 2, clearly illustrate that the movement and juxtaposition of the two thermal patterns was key in determining how Ciaran evolved in that 12 hour period. This type of thermal evolution during the development of mid-latitude depressions would seem to be commonplace, but the way that the tropospheric warm wave evolved such that the troposphere over Ciaran remained relatively warm would appear to be atypical when compared with the mean of 200 North Atlantic examples, table 8, and Burton (1), and would have been a contributary factor in the production of the extreme surface winds associated with this storm. A more typical evolution would be a substantial cooling in the troposphere at the time of maximum depth.

It is worth restating that the net thickness of the whole atmosphere above the centre of a surface low is at a local maximum, conversely, above the centre of a surface high, there is a net thermal low. It is also worth noting that the same holds true for any level in the atmosphere (up to at least 80km), and that lows and highs, troughs and ridges at any level can be thought of as being at the base of a thermal anomaly in the atmosphere above. It is instructive to use temporal changes in thickness at various layers in the atmosphere, producing a thickness budget, in order to pin down the level or levels that are principally involved in the evolution of geopotential features. It may surprise some, when seeing the results from using the thickness budget method, just how large a part is played by the atmosphere above the tropopause in shaping surface features.

Links to 3 hourly IR satellite images are available below.
Geostrophic winds were calculated from the formula below:

$$Vg = g/f * \Delta Z/\Delta n * 1.9425 \quad \text{knots}$$

Where Vg is the geostrophic speed in knots
g = 9.80665 acceleration due to gravity
f = 1.12 * 10 ^ -4 Coriolis parameter at 50 deg N
ΔZ = contour or thickness gradient, meters
Δn = distance over which ΔZ is measured, meters

or in this case ; k * ΔZ knots, where Δn is 220,000m and ΔZ is in decametres.
where k = 7.75 (approximately), thus 1 dam = nearly 8 knots.

(1) B.J.Burton, 2019, Atmospheric pressure and thickness:
http://www.woksat.info/wwp/atmthk01.pd

3 hour sequence of Eumetsat MSG satellite IR images showing development of storm Ciaran

http://www.woksat.info/etcafk01m/indexafk01m.html
http://www.woksat.info/etcafk02m/indexafk02m.html

Fig1. Thickness pattern in the vicinity of storm Ciaran, red = 100 to 300 hpa, lower stratosphere, purple = 500 to 1000 hpa, lower troposphere, 1st November 2023 1200z to 2nd November 2023 0000z. Units gpdam. The location of the surface centre of storm Ciaran is marked with a black cross.