Thickness and its uses

Thickness -- a short explanation!

'Thickness' is a measure of how warm or cold a layer of the atmosphere is, usually a layer in the lowest 5 km of the troposphere; high values mean warm air, and low values mean cold air.

It would be perfectly feasible to define the average temperature of a layer in the atmosphere by calculating its mean value in degrees C (or Kelvin) between two vertical points, but an easier, practical way to measure this same mean temperature between two levels can be gained by subtracting the lower height value of the appropriate isobaric surface from the upper.
Thus one measure of thickness commonly quoted is
= height (500 hPa surface) - height (1000 hPa surface) *[for those of you, like me, too old to catch up with all the changes the world brings, millibars = hPa!, so 500 hPa is exactly the same as 500 mb.]*

In practical meteorology, the most common layers wherein thickness values are analysed and forecast are: 500-1000 hPa [abbreviated to TT or TTHK] ; 850-1000 hPa; 700-1000 hPa; 700-850 hPa and 500-700 hPa. By subtracting the lower (height) value from the upper value, a positive number is always gained. The 500-1000 hPa value is used to define 'bulk' airmass mean temperature, and can be seen on several products available on the Web. The other 'partial' thicknesses are used for special purposes, for example, the 850-1000 hPa thickness is used for snow probability and maximum day temperature forecasting, as it more accurately defines the mean temperature of the lowest 1500 m (5000 ft) or so of the atmosphere.

Advection is simply the meteorologists word for movement of air in bulk. When we talk about warm advection, we mean that warm air replaces colder air, and vice-versa. These 'bulk' movements of air of differing temperatures can be seen very well on thickness charts, and differential advection, important in studies of stabilisation / de-stabilisation, can also be inferred by considering advection of partial thicknesses.

If you pull up thickness charts from the web, it it useful to highlight the isopleths of thickness, and work out, from either the mslp pattern, or the 500 hPa pattern, whether cold or warm advection is taking place. It should be possible with practice to find warm and cold fronts (tight thickness pattern), and areas where the thermal gradient (spacing of thickness lines) is changing - note particularly areas where developments tend to decrease spacing of thickness lines -->> increased potential for atmospheric development.

Total Thickness (500-1000 hPa) isopleths (when shown in combination with other fields) are conventionally drawn as long-dash lines, with the values either thus [540] or white numerals on a black/solid rectangle. (Where there is no conflict, i.e. the thickness isopleths are the only ones shown, then usually sold/continuous lines are used.) Certain isopleths are considered 'standard', mainly for historical reasons: They are listed hereunder, with the colour code convention used by the UK Met.Office on internal charts.
474 - red 492 - purple 510 - brown 528 - blue 546 - green 564 - red 582 - purple

Operational charts usually show isopleths at 6 dam intervals but some international forecast output will only have the standard isopleths as above: for example the UKMO 2-5 day charts. *(If you want to compare forecast values over and near the British Isles with extremes, see here).*

Can the 500-1000 hPa patterns be used to infer the snow risk? Well, yes they can, but because the layer is so deep -- some 5 km, or 18000 ft of the lower atmosphere, its not a good indicator. As a VERY rough guide the following may be used:

Rain and snow are equally likely when the 500-1000 hPa thickness is about 5225 gpm (or 522 dam). Rain is rare when the 500-1000 hPa thickness is less than 5190 gpm. Snow is extremely rare when the 500-1000 hPa thickness is greater than 5395 gpm.

Thickness --- a much longer explanation!

[Q] Thickness? ....thickness of what?

[A] From time to time in meteorology newsgroups, the word 'thickness' is used, particularly when talking about snow probability, or the prospect of warmer, or colder weather generally. If you simply want to remember that 'Thickness' is a measure of how warm or cold a layer of the atmosphere is, usually a layer in the lowest 5 km of the troposphere, and that high values mean warm air, and low values mean cold air, then you can ignore the rest of this FAQ. If you wish to know a little more, read on!

[Q] What is 'Thickness' and how is it measured?

[A] Although it would be perfectly feasible to define the average temperature of a layer in the atmosphere by quoting/calculating its mean value in degrees C (or Kelvin) between two vertical points, from the early days of upper air meteorology, it was realised that from the hydrostatic equation, an easy to calculate measure of this same mean temperature between two levels could be gained by subtracting the lower height value of the appropriate isobaric surface from the upper. (** see alternative name below)

The hydrostatic equation, in its simplified form, is $-dp/dz = pg/RT$ ...... Eq(a)

here:
dp being the pressure difference across two defined levels
dz the height difference between those two levels
g the gravitational constant
R specific gas constant for dry air
T average temperature in layer (strictly average virtual temp.)

Eq (a) states that the *change of pressure with height* (above a point where the total pressure of the column is p), is governed by the *mean temperature* over the vertical distance involved.
Thus in cold air/low T values, -dp/dz is larger than in warm air/high T. ... or putting it another way, lets start out at 1000 hPa and ascend vertically; in cold air, you would reach the level of 500 hPa sooner (greater rate of change of p) than in warm air. Thus the vertical distance from the level of 1000 hPa to the level of 500 hPa is less in cold air than in warm air
....cold air => low thickness values;

....warm air => high thickness values.
(for a more rigorous treatment/discussion of the hydrostatic equation, see any good textbook on meteorology - there is a list below).

Thickness can be calculated from the heights reported on a radio-sonde ascent, or a thermodynamic diagram can be used to add up the partial thicknesses over successive layers to achieve the net (total) thickness.

An example of the former would be
500 hPa height = 5407 m
1000 hPa height = 23 m
Thickness = 5407-23 = 5384 m (or 538 dam)

Careful note must be made when the height of the 1000 hPa surface is below msl thus: 500 hPa height = 5524 m
1000 hPa height = - 13 m
Thickness = 5524 -(-13) = 5537 m (or 554 dam)

[NOTE: you will also see 'thickness' charts referred to as 'Relative Topography' charts for this reason - this is especially so on web output from centres in mainland Europe.]**

[Q] What are the most common layers through which the thickness is analysed / forecast and what are they used for?

[A] In practical meteorology, the most common layers wherein thickness values are analysed and forecast are: 500-1000 hPa [abbreviated to TT or TTHK] ; 850-1000 hPa; 700-1000 hPa; 700-850 hPa and 500-700 hPa.
By subtracting the lower (height) value from the upper value, a positive number is always gained. Some values are quoted in metres, and others dekametres (tens of metres), dependent upon the use to which the value is put. In general, when dealing with the lower atmosphere, metres are used to better refine the output to the inferred surface parameter (e.g. maximum temperature), whilst for the deeper layers, dekametres (10's of metres) are sufficiently accurate.)

500-1000 hPa: (also known by some meteorologists as the 'total' thickness, for historical reasons). This is used to define the broad average temperature for the lower half of the troposphere. From the hydrostatic equation (see Eq(a) and reference (1) below),

$Z_2 - Z_1$ = RT/g * ln(p1/p2) ..... Eq(b)

replace p1 and p2 by 1000 hPa and 500 hPa respectively
therefore ln(2) = 0.69
R = universal gas constant for dry air = 2.87 * 10^2 kg^1 K^1
g = 9.81 ms^2
T = mean temperature through layer (K)
Z1, Z2 = heights of isobaric surfaces p1,p2 (in metres)
by substitution, and allowing for the fact that T in the original equation is Kelvin, we have, for the 500/1000 hPa layer....
mean temperature (degC) = (Thickness/20.3) - 273 ..... Eq(c)

thus for 5640 m thickness --- this represents a mean T = +5 degC
5460 m -4
5280 m -13 and so on.
and further, it can be seen that for 10 m (1 dam) change of thickness in this layer, this represents a change in mean temperature through the layer of 0.5 degC. It is useful to remember this when, for example, looking at the Royal Met.Soc 'Weather Log' which shows the deviation from normal of thickness values over a large part of the northern hemisphere ... an anomaly of + 4 dam doesn't mean quite as much as one of + 2 degC!

[Using this relationship, it is also possible to come up with a crude approximation to the expected ***surface*** maximum temperature - for more on this, see here.]

850-1000 hPa: This is useful for defining the temperature structure in the lowest 1500 m or so of the atmosphere, and can therefore be used in such things as rain/snow prediction, maximum temperature forecasting etc.

700-1000 hPa: Similar to 500-1000 hPa but focussed rather more on the lowest 3 km of the atmosphere and therefore an attempt to combine the broader measure of the 500-1000 hPa and the finer details obtained by layers nearer the earth's surface.

500-700 hPa/700-850 hPa: Used in studies of differential thermal advection, particularly when considering possible convection, degrees of instability etc.

[Q] What is the historical relevance of 'gridding'?

[A] Before the advent of super-fast main-frame computers, and the better understanding of the character and physics of the upper air, upper wind forecasts up to 24 hours ahead depended upon a process known as 'gridding' - the arithmetical manipulation of layer thicknesses. A surface/msl pressure chart would be analysed, then the isobaric pattern would be converted to equivalent 1000 hPa height contours, taking into account the temperature if this deviated significantly from the 'standard'; the thickness pattern would be drawn, using thermal wind relationships and known patterns associated with frontal systems, then the 1000 hPa and thickness patterns overlaid, and at the intersection of the 'grid' of such contours, the resultant 500 hPa (or other height, depending upon the thickness used) could be achieved, using the relationship that h(500) = h(1000)+h'(thickness).
This gave better results than just using the poor network of actual 500 hPa heights/winds, and by using thicknesses (i.e. differences), the systematic errors of differing radio-sondes could be effectively ignored .

More importantly, to produce a forecast upper air chart, first the forecast surface pattern was produced using known empirical relationships/rules of thumb etc., then the thickness pattern adjusted to fit around this forecast pattern, keeping the correct relationship found both in analysis and conceptual models in mind, then again by gridding, or graphical addition of the 1000 hPa contours and the thickness pattern, the upper contour pattern could be produced. It was essentially this process that was used to forecast all upper winds until the work could be put on a more rigorous/mathematical basis by the solving of complex equations using the big number- crunching machines from the late 1960's. (Incidentally, you can tell the vintage of someone working in meteorology by whether they refer to the parameter 500-1000 hPa thickness as the Total thickness ... a hangover from these days of gridding charts.)

Further reading: For a useful summary of this method of upper wind forecasting, see Ref:(2) and for a historical perspective, see Ref:(4) "Bomber Command upper air unit" - RAS Ratcliffe.

[Q] Does gridding have any relevance today?

[A] The reverse of gridding (graphical addition of thickness values to a lower surface height), is de-gridding, and can be a useful technique to master, both to achieve a surface pattern from a 500 hPa/Total Thickness chart, and to attain a simplified conceptual idea of development due to upper air processes.

From the definition of Total Thickness (h') where: h' = h(500) - h(1000) ..... Eq(d)

where h' = total thickness
h(500) = height of the 500 hPa barometric surface
h(1000) = height of the 1000 hPa barometric surface

re-arranging Eq(d), we have h(1000) = h(500) - h' ... Eq(e)

At levels near msl, the *approximate* relationship [**see cautionary note below #**] holds that a difference of 6 dam = a difference of 8 hPa. ... Eq(f)

Thus, from Eq(e), if at a certain point on a chart, a 500 hPa contour of 540 dam, is crossed by a thickness isopleth of 528 dam, the value of h(1000) = 540-528 = +12 dam. From Eq(f), this relates to an isobaric value of (12/6)*8 = +16 hPa (or 1000+16 = 1016 hPa) All other intersections of the 540 hPa/500 contour, and the 528 thickness isopleth yield the same value. Consideration of other intersections will build up a pattern of 1000 mb (and hence msl) values, and the surface pattern can then be inferred from these two fields.
We can go further, and see that it is clear from Eq(e) that by either *decreasing* the 500 hPa contour value (trough approaching), or *increasing* the thickness values (warm advection), the height of the 1000 hPa surface will lower, and because 1000 hPa and mslp are linked, mslp will lower===> development. Where *both* terms are strong (omega development, whereby an upper short- wave trough engages an area of strong warm advection), then explosive cyclogenesis is possible, all other factors being suitable. This is of course a very simplistic explanation of development, but it is a useful conceptual idea to keep in mind when trying to interpret upper air charts.

[# The relationship 6 dam=8 mbar is a *very* approximate one, and was accepted at the time because upper air charts were drawn to 6 dam intervals, surface charts to 8 mbar intervals (or multiples thereof), and accepting the inferred 0.75 dam per millibar (i.e. 6/8) relationship kept things simple. In reality, using the hydrostatic equation (Eq(b) above), for average mean sea level pressure of 1013mbar, average surface temperature of 15degC and taking a narrow 'slice' of the air around mslp, then the true value is **0.83** dam/mbar: other values are 0.80 dam/mbar for mean temperature 0degC and 1000mbar, and at 20degC and 1000mbar, it would be 0.86]

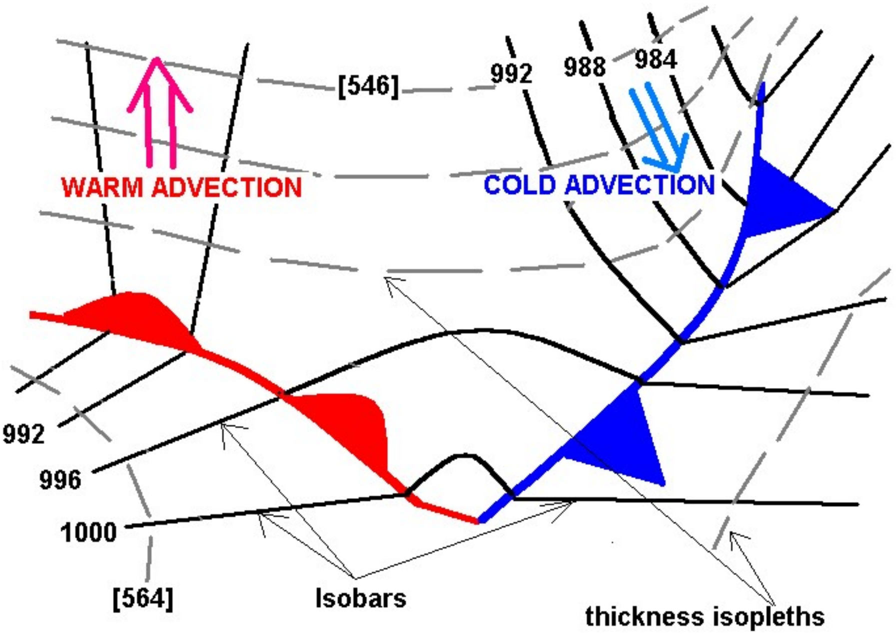
[Q] How are thickness isopleths shown on synoptic charts?

[A] Total Thickness (500-1000 hPa) isopleths are conventionally drawn as long-dash lines, with the values either thus [540] or white numerals on a black/solid rectangle. Certain isopleths are considered 'standard', mainly for historical reasons, and are coloured (in UK Met.O use) according to the following convention:
474 - red
492 - purple
510 - brown
528 - blue
546 - green
564 - red
582 - purple
Operational charts usually show isopleths at 6 dam intervals but some international forecast output will only have the standard isopleths as above: for example the Bracknell 2-5 day charts.

[Q] What about advection? How can I use it?

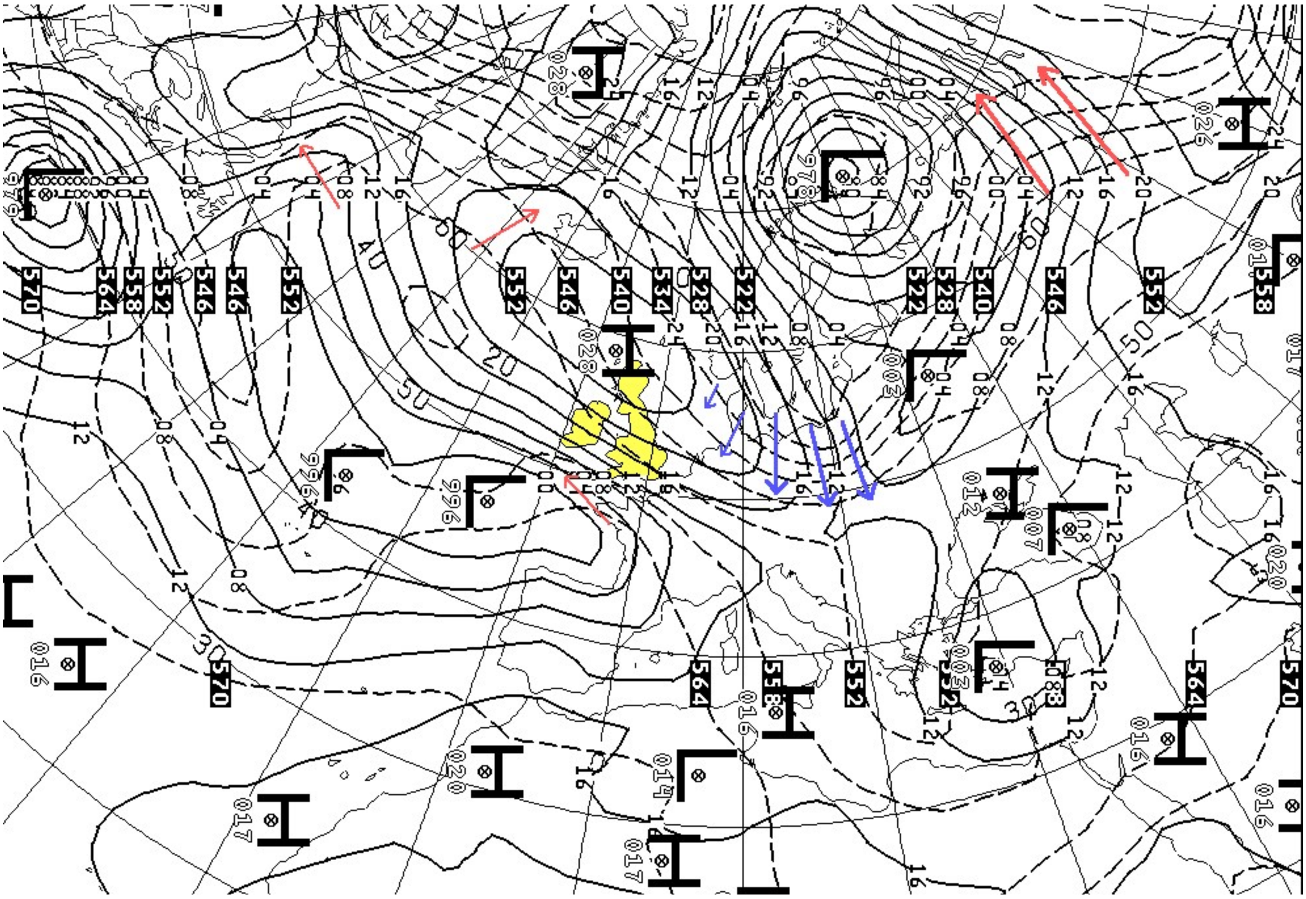
[A] Advection is simply the meteorologists word for movement of air in bulk. When we talk about warm advection, we mean that warm air replaces colder air, and vice-versa. These bulk movements of air of differing temperatures can be seen very well on thickness charts, and differential advection, important in studies of stabilisation/de-stabilisation, can also be inferred by considering advection of partial thicknesses.

Example:



If you pull up thickness charts from the web, it it useful to highlight the isopleths of thickness, and work out, from either the mslp pattern, or the 500 hPa pattern, (or indeed any wind in the layer) whether cold or warm advection is taking place. It should be possible with practice to find warm and cold fronts (tight thickness pattern), and areas where the thermal gradient (spacing of thickness lines) is changing - note particularly areas where developments tend to decrease spacing of thickness lines -->> increased potential for atmospheric development. See also the section relating to thermal winds

Below, is an example of a mslp and thickness chart drawn from the NWS site. Red (warm) and blue (cold) arrows show some areas of significant advection.

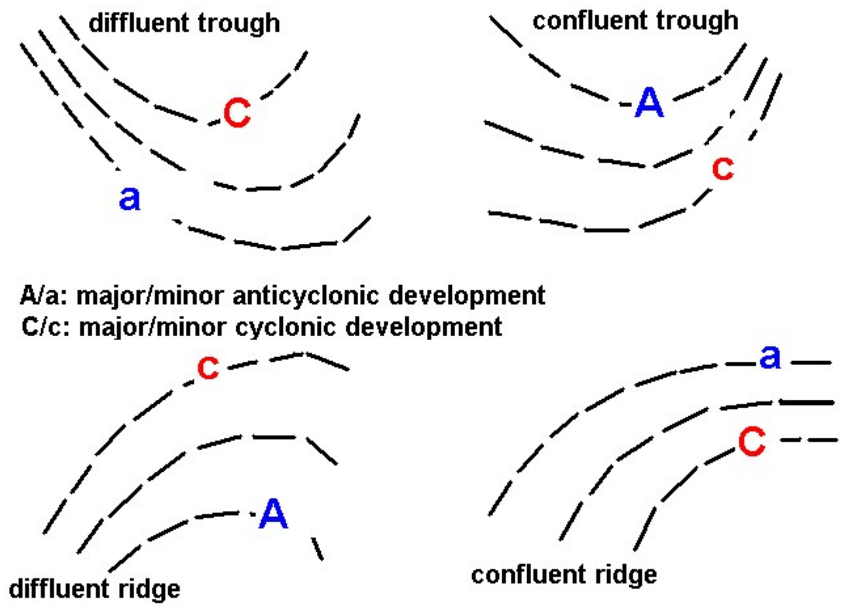


[Q] What about the various patterns of thickness isopleths?

[A] The most obvious patterns that the thickness isopleths can take up look very like those you would see on a surface/isobaric chart: highs, lows, troughs and ridges. A closed high-value contour, usually labelled 'W' is referred to as a warm dome; a closed low-value contour (or series of same), labelled 'K' is a cold pool. The 'W' and 'K' denote WARM and KALT respectively - possibly from the Norwegian/German roots of much of the research into upper air patterns. Cold pools are especially important, being often the first indications that the potential for small/mesoscale deep and vigorous convective activity exists, given a suitable trigger action and sufficient moisture. (They are sometimes not resolved by NWP suites adequately either, particular those with long grid lengths.) The horizontal spacing of thickness isopleths is also a useful indicator of the potential for development. Close spacing shows that cold air lies adjacent to warm air -- no doubt with an attendant frontal surface. More importantly, the fact that such a baroclinic zone (surfaces of temperature and pressure intersecting at an angle)

exists, means that the *potential* for development is strong -- a slight displacement, i.e. forcing by a high level jet streak, will lead to substantial falls of pressure and consequent 'weather'.
*(**Examples of all these features**, with further notes, can be found by clicking* **here**.)

Meteorologists will always play close attention to zones of 'tight' thickness contouring for this reason. Troughs and ridges denote tongues of cold and warm air respectively, and, from work by RC Sutcliffe (& others) during and after the Second World War, they can also be used to infer the magnitude and sign of development on the surface. The details of the mathematics are beyond this FAQ, but it is only necessary to recognize the patterns as below:



[Q] Can the 500-1000 hPa patterns be used to infer the snow risk?

[A] Until the advent of NWP suites capable of using model variables to routinely predict the 850-1000 hPa partial thickness (the one now commonly used in the UK to assess likelihood of snow - see below), the 500-1000 hPa total thickness was used much more extensively than now. In the 1950's and 1960's, some studies were published which attempted to refine the TTHK association with snow/rain prediction ... the results are presented below BUT REMEMBER, better predictors are available and should be used where possible.

(1) Lamb: Q Jnl R.Met.Soc. 1955 Critical value for equal probability of rain and snow(NW Europe)

Average: 527 dam (extremes: 521 to 546)
Established snowfields: 536 dam
Windward edge of snowfields: 528 dam
Seas with SST around 10degC and over windward coasts: 523 dam

Lamb's analysis was undertaken for the whole of NW Europe, including places like Riga and Stockholm, which may explain the difference in the average figure from that in the following section. However, Lamb did make a more detailed analysis for inland stations in the British Isles, where he found that when there **was** snow lying, the critical values were 5305-5335 gpm, and with *no* snow lying 5225 gpm, which accords more with Murray below)

(2) Murray: 1959 Using an analysis for the **UK only**, found the following:

Rain and snow are equally likely when the 500-1000 hPa thickness is about 5225 gpm (or 522 dam)

Rain is rare when the 500-1000 hPa thickness is less than 5190 gpm

Snow is extremely rare when the 500-1000 hPa thickness is greater than 5395 gpm; it is rather uncommon when the value is greater than 5305 gpm.

A personal view here, but I have always regarded the 522 dam isopleth as a better 'first guess' at snow vs rain than the 528 value for frontal precipitation. Indeed, I joined the Met.Office at a time when TTHK were still being extensively used for this purpose, and 522 was regarded as the 'snow-line'

(3) Murray: 1959 Also carried out a more detailed investigation using a combination of predictors, the 500-1000 hPa TTHK, the surface (screen) temperature and the height of the freezing level. (I have only shown the TTHK/screen temp relationship as this is the most useful one for those with access to WWW met.products.) He presented the results in graphical form, but for ease of use, I have converted them to tabular format, using the 'standard' TTHK values. The use of a graph implies greater precision than is usual anyway.

(a) percentage probability (P) of type of precipitation in relation to surface temperature and 500-1000 hPa thickness.

SCREEN TEMPERATURE (degC) >>	-1	0	1	2	3	4
TTHK (dam)						
516	A	A	A	A	A	A

522	A	A	B	C	C	C
528	A	B	C	C	D	D
534	A	B	C	D	D	D

A is P >90%
B is 90% >P> 50%
C is 50% >P> 10%
D is P< 10%

In critical rain/snow situations, one of the variables that is difficult to forecast is the screen temperature. Therefore this method is not the answer it may at first sight seem.

(4) Boyden .

In the course of work to compare various predictors, Boyden gave the following figures. 500-1000 hPa TTHK

5180 gpm: 90%
5238 gpm: 70%
5258 gpm: 50%
5292 gpm: 30%
5334 gpm: 10%

In the course of this work, Boyden confirmed what others have already pointed out, that the 500-1000 hPa thickness parameter is the poorest discriminator for rain/snow. The best was height of freezing level and surface temperature, both difficult to forecast in 'critical' situations, and the next best/least worst was the 850-1000 hPa value, though Boyden devised the correction 'factor' that we all now use to take account of mean sea level pressure and local height.

[Q] So, how are the 850-1000 hPa values used.

[A] This parameter can be used in several ways, the two of most use to the 'bench' forecaster are: (1) calculation of the risk of rain vs. snow, and (2) forecasting the daytime maximum temperature.

(1). Because the layer from 1000 hPa to 850 hPa covers the lowest 1500 metres or so of the atmosphere, it is better suited to deciding on which phase precipitation will reach the ground (i.e. whether snow will melt to sleet or rain), than the 'total' thickness layer 500-1000 hPa. Statistical relationships have been produced:

The following are un-adjusted critical values and adjusted values for the 850-1000 hPa partial thickness found by statistical analysis: snow probability:
Probability:...........................90%.....70%.....50%.....30%.....10%
850-1000 hPa(gpm).............1279.....1287....1293....1297....1302 (un-adjusted)
850-1000 hPa(gpm).............1281.....1290....1293....1298....1303 (adjusted-see below)

It is important to remember that when mslp values differ markedly from 1000 hPa, or the height of a station/area differs greatly from msl, a correction has to be made to the partial thickness before assessing the snow risk. Also, the partial thickness only takes into account the mean *temperature* of the lowest 250 hPa or so of the atmosphere and not the humidity, which is of vital importance for accurate snow prediction. Downward penetration of snow is greatly aided when precipitation falls into dry air.

Boyden found that the following correction should be made to the partial thickness (850-1000 hPa): (Z - h)/30

where Z: height in metres of the 1000 hPa surface above msl
h: height in metres of the ground asl.
... and then the second line of critical values used in the table above.

(2). The 850-1000 hPa is a very good layer within which to determine the air mass likely to affect your station and therefore its use to work out the potential daytime maximum temperature has long been recognised. One such, after Callen and Prescott, relates the partial thickness values.... to the cloud classification for the day ahead.

The relationship between 850-1000 hPa thickness (h*) and the unadjusted maximum temperature (Tu) is given by: Tu = -192.65 + 0.156h* ... Eq(g)

An adjustment is then added to this figure, depending upon forecast 'cloud class' and the time of the year.

The four cloud classes are:(simplified)
Class 0: Low and medium cloud generally less than half cover. High cloud not overcast. Fog only around dawn, if at all.
Class 1: Roughly 50% cloudiness. If fog occurs, it clears slowly during the morning.
Class 2: Mainly cloudy. If fog occurs, clears by midday, but slowly.
Class 3: Overcast with rain/snow etc. Persistent Fog.

Then the following matrix can be used to find the adjustment to be added to Tu. (Whole values degrees C only)

MONTH CLASS

	0	1	2	3
JAN	-4	-4	-5	-5
FEB	-3	-3	-4	-5
MAR	-1	-2	-3	-4

APR	+1	0	-1	-2
MAY	+2	+1	0	-1
JUN	+4	+3	+1	0
JUL	+4	+3	+1	0
AUG	+3	+2	+1	0
SEP	+1	0	-1	-1
OCT	-1	-1	-2	-3
NOV	-2	-3	-4	-4
DEC	-4	-4	-5	-5

The original work was based on maxima recorded at Gatwick airport, using upper air ascents (12Z) from nearby Crawley radio-sonde .. both sites now no longer providing the appropriate data. They should NOT be used for latitudes well away from the south of England, particularly in the 'winter half-year', when insolation values (due to differing sun angle and daylength parameters) will differ markedly with latitude.
Also, where marine influence is strong then the values will be highly modulated by local sea surface temperatures.
There are a series of graphs, from which it is technically possible to read off the correction to decimals of a degree, and to refine the correction dependent upon the position in the month, but for practical meteorology, these will do!

Some reading/references:

(1): Essentials of Meteorology auth: D.H. McIntosh and A.S. Thom Taylor and Francis Ltd
(2): The practice of weather forecasting auth: P.G. Wickham HMSO
(3): Introduction to Meteorology auth: S. Petterssen McGraw-Hill Book Company, Inc.
(4): Meteorology and World War II ed: B.D. Giles Royal Meteorological Society
(5): Handbook of Aviation Meteorology: The Met.Office/HMSO
(6): Source book to the Forecasters' Reference Book: The Met.Office/College

Sutcliffe Development Theory

Notes relating to atmospheric development diagnosed using total thickness (TTHK) charts.

[1. This note was put together to give a 'flavour' of the ideas surrounding diagnosis of development from thickness charts. If you have come to this page as a first-year student of meteorology, then this is NOT for you!]
[2. Inevitably, given the history of the times (1940's), the efforts of meteorologists on the 'winning' side has assumed dominance. However, it is clear that much work was done in Germany both before and during the Second World War, and this contribution should be remembered. If I find more in this, I will add it.]

The science of forecasting has come a long way since the days of ancient weather lore and a belief in the whims of the gods! During the mid-19th century, the birth of a scientific basis to weather forecasting was witnessed, with the use of the developing electric telegraph networks to exchange data, the discovery of 'laws' relating the wind field to the pressure distribution (Buys Ballot, 1857), and later in the century, the analysis of weather types associated with depressions and anticyclones (Abercromby, 1883).

During the 'Great War' of 1914-1918, as is well-known, the 'Norwegian' frontal & air-mass theories were thoroughly researched and once hostilities ceased, they were enthusiastically adopted & developed by the leading meteorological services around the world - indeed, perhaps a bit too enthusiastically, as they didn't necessarily apply to sub-tropical / tropical regions or indeed to all occasions in the mid-latitudes. Not only that, work on the dynamic basis for atmospheric development tended to be somewhat overshadowed.

Nevertheless, the work of Bjerknes (father & son), Bergeron & Solberg formed the basis of 'front-line' forecasting work up to and including the Second World War. To produce a 'PROG' of the weather 18 to 24 hours ahead involved use of empirical techniques which moved the fronts based on gradients across them, moved the lows (or highs) following continuity and rules based on flow patterns around these features, and in large part, experience of situations past: the upper air (even if it was available), didn't get much of a look-in in the process.

The foregoing might imply that somehow the 'upper air' was ignored! Not a bit; much work was undertaken using primitive kite and balloon ascents during the early part of the 20th century, and increasing air-flights produced more information. Meteorologists realised that to understand & predict the 'weather', they would need more information on & understanding of, air flow well above the surface. The problem was - lack of data!

The Second World War provided the impetus (and the data) for research into upper air patterns and their influence on the surface weather. As part of the procedure for analysis and forecasting of upper air patterns, thickness charts (partial and total) became the stock-in-trade of weather services (particularly for RAF Bomber Command, the USAAF & the Luftwaffe), and out of these charts came the ideas of development theory tied to forcing aloft - R.C. Sutcliffe in the United Kingdom had already researched this immediately prior to the outbreak of war (alongside the work of others, particularly Brunt & Petterssen), and by the latter half of the 1940's he had enough data to publish his seminal work in 1947 (see references below).

Sutcliffe showed that development (expressed in terms of relative divergence between 1000 and 500 hPa levels) can be diagnosed from total thickness charts: in crude terms, the equation can be expressed as . . . .

[div(500-1000)] = [LAT] + [STEER] + [DEV]

where:-
div(500-1000) represents the relative divergence through that column.
[LAT] .. the 'latitude' term
[STEER] .. the 'steering' term
[DEV] .. the 'developmental' term

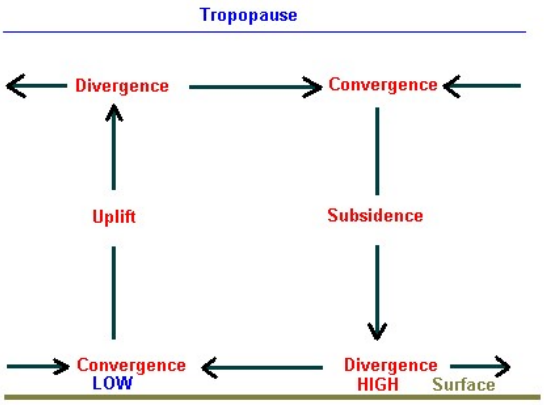
the thermal wind (500-1000hPa) appears in each term, so the stronger the thermal wind (i.e. the tighter the thickness gradient), then the more effective is the vorticity-driven development that takes place.

The [LAT] term, which diagnoses the variation of the Coriolis parameter with latitude in the direction of the thermal wind - is generally small, but is important for example in the creation of the notorious 'Scandinavian High' in winter, and the significant areas of low pressure following cold outbreaks from the north over the west & central Mediterranean in late autumn / early winter.

The [STEER] term is proportional to the strength of the thermal wind and to the variation of surface vorticity in the direction of the thermal wind. This term is dominant when the pattern of surface vorticity is well marked & the thermal wind almost 'zonal' (or running west-to-east), i.e. immediately before distortion of the Polar Front undergoing wave-development. This confirms the subjective assessment that small-scale mid-latitude lows are 'driven' along coupled to the thickness gradient aloft - tighter gradient, swifter movement.

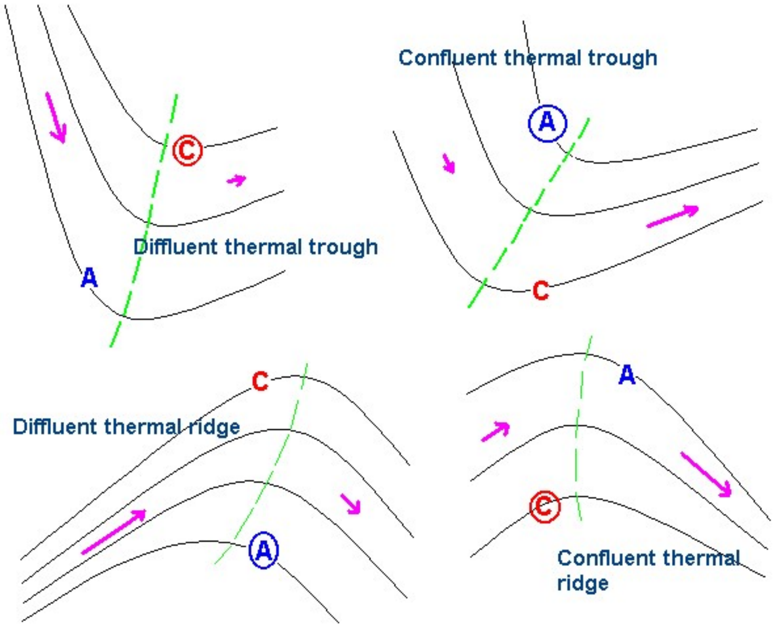
The remaining term [DEV] is proportional to the strength of the thermal wind and to its variation of vorticity along the flow. Curvature and shear of the thickness pattern contribute to the latter, and give rise to the 'standard' developmental patterns indicated below.

With developing low pressure at the surface, horizontal convergence at low-levels implies upward motion through the troposphere, and divergence aloft (in the region of the tropopause). The converse applies for developing high cells. The circulations are indicated on this classic diagram:-



The work by Sutcliffe (and others) can be summed up neatly in a graphical format; there are four basic patterns of thickness isopleths (indicated below). With each pattern, there is associated a major and minor (vorticity-driven) surface development area.

Chart showing developmental regions associated with thickness (500-1000 hPa) patterns.



C: cyclonic development (circled = major / most effective forcing)
A: anticyclonic development (circled = major / most effective forcing)
Green-dashed lines: approximate thermal ridge / trough axes
Magenta arrows: direction / proportionate strength of thermal wind

For more on all these matters, see the references below.

References:
'A Contribution to the Problem of Development', R C Sutcliffe; QJRMetS/RMetS, 73, 1947

'The Theory & Use of Upper Air Thickness Patterns in Forecasting', R C Sutcliffe & D Forsdyke; QJRMetS/RMetS, 76, 1950
'Weather Map', Meteorological Office/HMSO, 1956
'The Meteorological Glossary', Meteorological Office/HMSO, 1972
'Dynamical meteorology: some milestones', B W Atkinson; RMetS (in "Dynamical Meteorology, An introductory selection"), 1981

Selected glossary of terms:

Buys Ballot's Law: as originally formulated: " if you stand with your back to the wind (in the northern hemisphere), then low pressure lies on your left-hand side ". This gives rise to the standard patterns (in the Northern Hemisphere) of anticlockwise winds circulating around a low pressure area, and clockwise motion around an area of high pressure (reverse for the Southern Hemisphere).

Convergence: When air flows in such a way that the area occupied by a particular 'group' of air particles lessens ('drawing together'), the pattern is said to be convergent. Convergence in the atmosphere is associated with vertical motion, and hence development (or weakening) of weather systems. For example, convergent flow near the surface is coupled to, and may be the primary cause of, upward motion, leading to cloud formation/shower initiation etc.

Coriolis parameter: as a consequence of Earth's rotation, air moving across its surface appears to be deflected relative to an observer standing on the surface. The 'deflection' is to the right of movement in the northern hemisphere, to the left in the southern hemisphere. (also known as the Coriolis acceleration, or deflection)

Divergence: When air flows in such a way that the area occupied by a particular 'group' of air particles grows ('spreads apart'), the pattern is said to be divergent. Divergence in the atmosphere is also (along with convergence/q.v.) associated with vertical motion, and hence development (or weakening) of weather systems, depending upon the level where the divergence is dominant in a particular atmospheric column. For example, divergent flow aloft is coupled to, and may be the primary cause of, upward motion, leading to widespread cloud formation/cyclogenesis etc.

Norwegian model: The classical idea of a travelling wave depression on the polar front running forward (usually west-to-east) and deepening, with the cold front moving faster than the warm front, thus 'occluding' the warm sector, with the parent low slowing / turning to the left (in northern hemisphere), and filling up.

Thermal wind: a theoretical (vector difference) wind that relates the magnitude of the horizontal temperature gradient in a defined layer to the real winds that blow at the top and base of that layer. The speed of the thermal wind is proportional to the temperature gradient.

Thickness (or **Relative Topography**): The difference in height between two layers in the upper air. The most commonly used being the thickness between 500 mbar (or hPa) and 1000 mbar (or hPa), and normally expressed in dekametres. The larger the value of thickness, the warmer the column of air.

Tropopause: the (usually) abrupt change from falling temperatures with height in the tropopause, to near-uniform, or rising temperatures in the stratosphere.

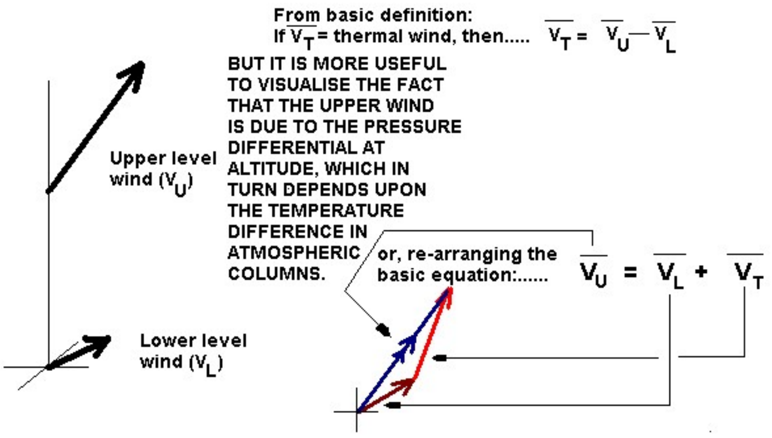
Troposphere: lowest layer of the atmosphere, with an average depth of 16 to 18 km around the equator, 9 to 12 km temperate latitudes and well below 9 km much of the time in arctic regions. There is a general fall of temperature with height (i.e. a positive lapse rate), with an average value of some 6.5 degC / km (or 2 degC / 1000ft).

Vorticity: a measure of the 'spin' of a portion of a fluid - in our case, of atmospheric particles. Vorticity in a cyclonic sense is designated 'positive', and in an anticyclonic sense is designated 'negative'. In synoptic meteorology, we often only consider vorticity in a horizontal plane - i.e. the 'spin' behaviour of air particles as they move along in the atmospheric flow as depicted on classical 'weather maps'.

Zonal: A predominantly west-to-east airflow is termed zonal (and an east-to-west airflow is negative zonal). The strength of the flow in any sector may be expressed in terms of a zonal index given by the difference in average contour height between two latitude circles through the sector.

Thermal Winds

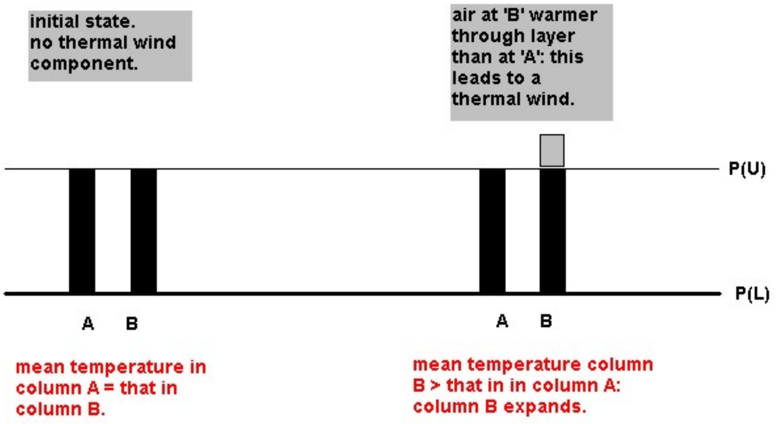
A *thermal wind* is defined as the vector difference between two *actual* winds at different levels in the atmosphere, conventionally calculated (as in the case of thickness q.v.), by subtracting the **lower-level wind** from the **upper-level wind**. Put differently, and more practically, it is that velocity component (remember: velocity has both speed and direction), that must be added to a lower level wind to produce the upper level wind. Graphically, these statements can be demonstrated thus:....



Although the principal thermal wind used in operational meteorology is that through the layer between 1000 hPa and 500 hPa, in fact thermal wind calculations can be applied between *any* two levels in the atmosphere.

In the atmosphere, air moves (the wind 'blows'), because of pressure differential between two points. This is usually demonstrated at mean sea level, using as examples the sea breeze, or the Asia monsoon. Why this should be so can be demonstrated when it is remembered that heat gain or loss by a column of the atmosphere produces expansion/contraction of that column:

consider



1. Initially, with both columns having the same mean temperature, there is *no pressure differential* between them at any level.

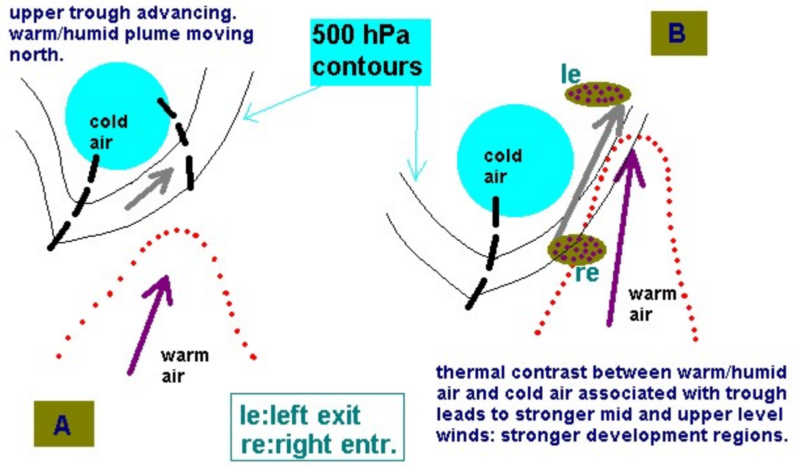
2. Column B is now warmed, *and expands*.

3. Whilst the total amount of atmosphere above P(L)A=P(L)B, i.e. there is no pressure difference at the lower level (usually taken to be msl), there is now a pressure difference at P(U), whereby P(U)B>P(U)A, due to the expansion of the column: there is a bit more of the atmosphere above P(U) than there was before.

4. So, a thermal difference exists between the two columns, this giving rise to the notional "thermal wind", which is a convenient way of visualising the way real pressure differences are set up, leading to real winds at upper levels.

thus strong thermal winds imply marked difference in actual wind with heights, and strong thermal winds (and therefore strong 'real' winds), are associated with frontal boundaries and strongly-sheared convective situations. An example is shown below:

- Upper trough advances eastwards - positive vorticity advection 'spins up' the atmosphere in a region within which warm air is being advected northwards - increased convergence - destabilisation due to colder air overlaying warm/humid air.
- As cold air (associated with upper/short-wave trough) butts up to warm air (associated with northward-moving plume), the enhanced thermal gradient (i.e. thermal wind component) leads to stronger upper level winds.
- The associated development areas, (which are a result of un-balanced forces due to accelerations/decelerations aloft), are made more active, and rather than 'pure' convective activity, bulk lifting of the troposphere occurs, releasing potential instability, and leading to organisation of convective storms, rather than isolated cells/clusters.
- The resultant thermal forcing often manifests itself in a pseudo -frontal boundary at the surface, and aloft, taking over from the pre-existing, and often weak boundary between the cool/maritime air (rPm), and the very warm/humid (modified Tc) air.
- The enhanced pressure gradient at the surface leads to a quickening of the northwards advection of the warm/humid air, with the upper trough overrunning, releasing further deep/vigorous convection.
- The main air mass cold front, driven by the main upper trough sweeps through and displaces the humid air/thunderstorms, thus cutting off the activity.



Thermal winds 'blow' so as to obey Buys Ballot's Law with cold thicknesses to the left in the NH.

The 'standard' layer through which the thickness (and associated thermal wind component) are calculated in synoptic meteorology is the 500-1000 hPa layer. However, whereas it is possible to calculate the notional 1000 hPa height, even if it is below the msl, things are a little more difficult with thermal wind calculations.

1. 1000 hPa often in the friction-affected BL (within about 1500 m above local ground level), and the measured wind is backed/reduced as a result, and therefore does not reflect the true gradient at 1000 hPa.
2. 1000 hPa may be at/below msl, and no meaningful 1000 hPa wind can be measured.

The lower level wind is often replaced by the 925 hPa or 900 hPa wind, or even the 850 hPa wind if these are not available. However, in these cases, care needs to be exercised when using such thermals alongside the accompanying thickness plots.

Because low level winds in a developmental (mid-latitude) situation are much less than those at jet levels, from the definition of the TWC, the polar front jet is really a large-scale hemispheric thermal wind -- blowing in response to large scale changes in distribution of air of differing temperature -- i.e. air mass discontinuities. Change the arrangement of the blocks of warm and cold air, and you change the direction, and strength, of the upper level jet. This is why, for example, study of sea surface temperature anomalies are important for long-term climate change.

Thickness and maximum surface temperatures

Approximate relationship between Thickness (or Relative Topography): 500 - 1000 hPa & the maximum screen temperature (^{o}C) [NW maritime Europe; also see cautionary notes below]

Thickness 500-1000 hPa (in metres)	Nil / Poor insolation (a)	Moderate / High insolation (b)	High summer: strong sun
5100	-6	-1	
5150	-3	2	

5200	-1	4	
5250	2	7	
5280	3	8	
5300	4	9	
5350	7	12	
5400	9	14	15
5450	11	16	17
5460	12	17	18
5500	14	19	20
5550	16	21	22
5600	19	24	25
5640	21	26	27
5650	21	26	27
5700	24	29	30
5750	26	31	32
5800	29	34	35
5820	30	35	36

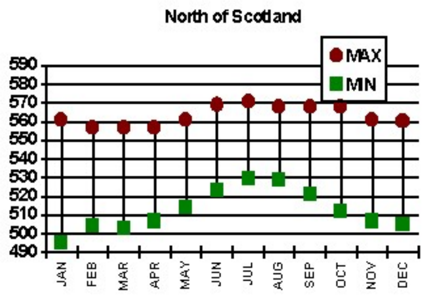
Notes:
(a): Generally overcast, thick cloud cover - minimum effective insolation; also generally applicable to the mid-winter period of low solar angle. Precipitation would imply the figure might be a degree or two lower still.
(b): Fine, sunny much of the time up to day-maximum occurrence. If the sunshine is particularly strong in spring & summer, then this figure may be a couple of degrees (at least) higher. These figures though would NOT apply to mid-winter, low solar-angle events.
(c): In mid-winter, with low thickness values in particular, temperatures will be lower still - perhaps by as much 5degC due to limited insolation.

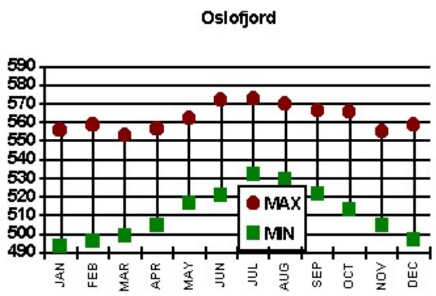
These figures are based on the *theoretical* relationship between the average lapse rate within the lower troposphere (2 degC/1000ft) and the implied mean temperature (within the layer 500 - 1000 hPa) given by the total thickness values. They take no account of the type of surface (sea, dry land, snow-cover etc.) and also there is no allowance for seasonal variation of solar energy available.
Sunny figures further imply that a dry adiabatic lapse rate (3 degC/1000ft) exists at time of maximum temperature from the surface to 850 hPa.

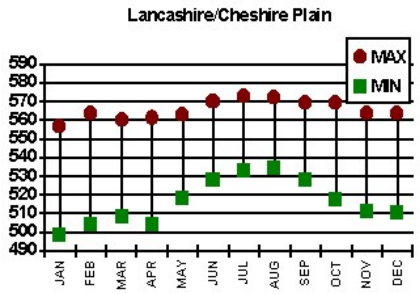
However, this is a very crude relationship, and the figures given above should be regarded as the rough 'limits' of expected maxima. In practice, they will vary by several degrees. This is why forecasting day maxima based on total thickness has fallen out of fashion.

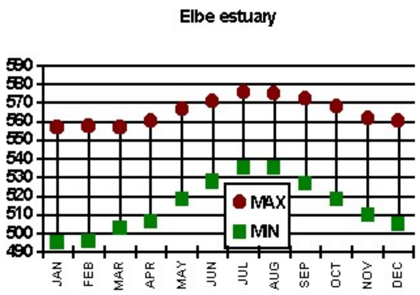
Thickness Extremes

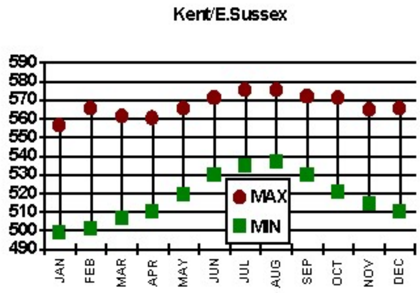
The 6 figures presented below show maximum and minimum values of total thickness (h[500] - h[1000]) in dekametres. PLEASE READ THE CAUTIONARY NOTES BELOW:

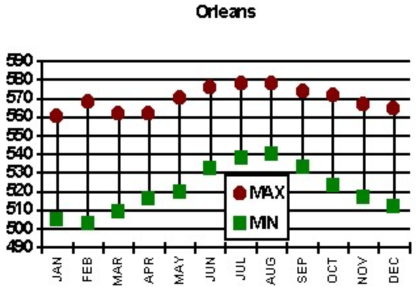

North of Scotland


Oslofjord


Lancashire/Cheshire Plain


Elbe estuary


Kent/E.Sussex


Orleans

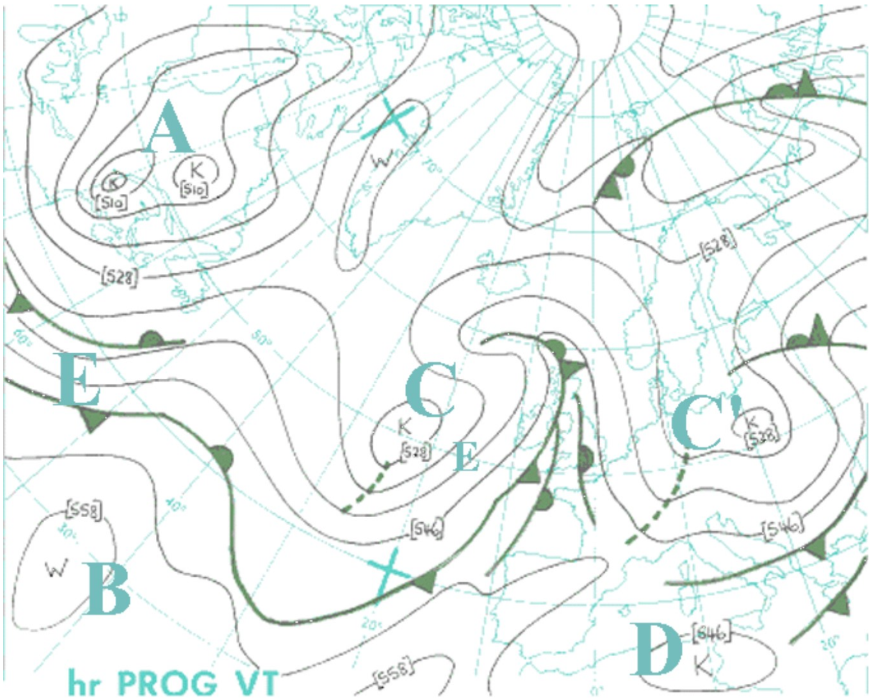
HIGHEST BRITISH ISLES:.... 576 dam in July & August around the Channel Islands.
LOWEST BRITISH ISLES:..... 491 dam in January around the Shetland Islands.

- Locations/values are deliberately displayed in general terms as these data are extracted from small-scale charts. They are here given to roughly define the 'reasonable' limits of total thickness values.
- The series covers the period 1945 - 1993, so extremes may not be up to date. Also the early years analysis would not be as accurate as middle/latter parts of the series.
- Data are extracted from records held at the National Meteorological Library. They are displayed here purely for amateur/educational use. If you wish to use these values in any way - i.e. to support an article, you must contact the NML (see the uk.sci.weather FAQ for details), and obtain detail and permission.

Thickness Pattern Definitions

The chart shown here is intended to show some common features to be found on the 500-1000 hPa thickness chart over the North Atlantic & Europe. It does not represent any one particular situation, and is rather artificial as a result. Refer to the text below for an explanation of the features.

(last updated 29 JAN 2000)



A: ***COLD POOL (QUASI-STATIONARY, LONG-LASTING TYPE).***
B: ***WARM DOME.***
C: ***COLD POOL (TRANSITORY/MOBILE TYPE).***
C': ***COLD POOL (TRANSITORY/SLOW-MOVING TYPE).***
D: ***COLD POOL (LOW-LATITUDE TYPE).***
E: ***BAROCLINIC ZONES.***

COLD POOLS:

There are at least three distinct types of cold pool:

1. Large (in areal extent), slow-moving vortices at latitudes poleward of roughly 50deg N & S (**Example A**). They are often over, or immediately downwind of the source regions of polar or arctic air masses, in such areas as the Canadian Arctic or Siberian Russia. They take up the characteristics of quasi-permanent features, often appearing on monthly, or even seasonal average maps. The column of very cold (dense) air associated with this version of the cold pool, is reinforced by net outgoing radiation which produces a highly stable, bitterly cold near-surface environment, with a surface ridge or anticyclone on MSLP charts.

2. Once cold air from the source region as detailed in (1.) above is caught up in the circulation of mid-latitude depressions, the characteristics of the air mass are altered. Warming from below (over relatively warmer sea surfaces for example), leads to instability developing, and with an accompanying injection of moisture (after a reasonable length of passage over the sea), cloudy convection (showers, thunderstorms) is triggered. Cold pools (**Examples C, C'**) in these situations are often maxima of such activity, with surface charts showing west or northwesterly airflow, often with cyclonically curved isobars. The cold pool will move in the general synoptic flow, and will eventually warm out (disappear) due to sensible & latent heat exchanges within the environment of the cold pool. However, as at **example C'**, sometimes the cold pool will transform into a slow-moving, longer-lasting entity, particularly if the feed of ex-polar air on its western flank is maintained - this occurs in highly meridional situations.

3. A pool of cold air can also become 'detached' at lower latitudes (**Example D**), i.e. away from the mid-latitude westerly zone, and drift slowly over relatively warmer seas, (e.g. the Mediterranean), and lead to intense convective development, often taking on marked cyclonic characteristics through the troposphere, and giving rise to locally severe condtions due to heavy rainfall, severe thunderstorms and squally winds. Remnants of these types of cold pool will sometimes drift polewards in summer and bring outbreaks of severe convective activity to mid-latitude regions, as these features will destabilise hot/humid airmasses.

WARM DOMES:

This is a term that is not often heard nowadays, but is applied to the opposite case of the cold pool (**Examples B**) , where relatively warm (high thickness value) air is enclosed within a closed contour value. The associated low-level weather will be quiet, settled with little vertical development of cloud, if any at all.

BAROCLINIC ZONES:

Areas where there are marked contrasts between cold and warm air masses (**Examples E**). These can be determined on a thickness chart by a packing together of contours. Usually associated on a msl chart with classical fronts, and therefore an area for potential cyclonic development.