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**HANDBOOK
OF
WEATHER FORECASTING**

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PREFACE

The Handbook of Weather Forecasting was written mainly for distribution within the Meteorological Office to provide forecasters with a comprehensive and up-to-date reference book on techniques of forecasting and closely related aspects of meteorology. The work, which appeared originally as twenty separate chapters, is now re-issued in three volumes in loose-leaf form to facilitate revision.

Certain amendments of an essential nature have been incorporated in this edition but, in some chapters, temperature values still appear in degrees Fahrenheit. These will be changed to degrees Celsius when the chapters concerned are completely revised.

CHAPTER 2
ANALYSIS OF UPPER AIR CHARTS

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CHAPTER 2

ANALYSIS OF UPPER AIR CHARTS

2.1. INTRODUCTION

Since weather occupies three dimensions in space, no study of it is complete without a study of the vertical structure of the atmosphere. Observations of temperature, humidity, pressure and wind in the free atmosphere are recorded regularly at a number of land and ocean stations but the number of these stations is small compared with the number of stations for 'surface' observations. This is largely due to the cost of maintaining upper air stations, particularly over the oceans. Fortunately, irregularities in the spatial distribution of the values of the temperature, humidity and wind are not so great in the upper air as at the surface. This is not to be construed as meaning that the present distribution of upper air stations is satisfactory. All forecasters would wish to have a closer network of stations and more frequent soundings, particularly so over the oceans where the present network of ocean weather ships is much too sparse even to approach a satisfactory state. In consequence of this it is of the utmost importance in the analysis of upper air charts to ensure that no observation is neglected unless there are good grounds for considering it to be grossly inaccurate. This is not meant to imply that all observations should be accepted as exact; critical weighting of the various items of information is essential for sound analysis. The importance of continuity from one level to another and from one time to another in upper air analysis cannot be overstressed. Over the oceans it is quite easy for an important feature on one chart to be lost 12 hours later in the space between simultaneous soundings made many hundreds of miles apart. It is absolutely essential that any feature clearly portrayed on one chart should not be neglected at higher or lower levels or dropped from subsequent charts without very good reason.

The observations used on upper air charts are in the main instrumental and with the exception of the wind are measured by an instrument (radio-sonde) remote from the station. The patterns of instruments are various and unfortunately the accuracy of all patterns or even of all instruments of one pattern is not uniform. The inaccuracies fall broadly into two groups – systematic errors characteristic of the design of the radio-sonde and the techniques employed in its operation, and non-systematic errors affecting any particular ascent. Irregularities due to the former are frequently noticed (at the time of writing) at national boundaries at the higher levels (mainly 200 mb. and above) and largely arise from radiation effects on the radio-sondes. This effect is most marked at high levels in the day-time, and it is noteworthy that such instrumental errors are generally a function of height so that if an error is found or suspected at one level, it must be allowed for at other levels in the same ascent. A non-systematic error on any ascent may or may not affect the accuracy of the information for levels other than that at which it occurs, depending on the nature of the error and on the technique used for calculation of the results of the sounding.

The observations in the upper air enumerated above can obviously be plotted in a variety of ways. One way is to plot observations on charts of the earth's surface, each chart having observations for a particular height or level plotted on it. These charts fall into two groups, charts portraying the variation of pressure over surfaces of constant height above mean sea level and charts showing the variation of height over levels of constant pressure. Surface charts are examples of the former type, but for the upper air it is more convenient in practice to use charts of constant-

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pressure levels. This system has the following advantages. One geostrophic wind scale can be used for all levels (see Section 2.2.) and this scale can also be applied to the thickness isopleths giving a simple determination of the thermal wind (see Section 2.3.). Further, isotherms on isobaric surfaces are lines of constant potential temperature. In addition upper air observations as received are, for the most part, basically in terms of pressure.

Another way of making use of upper air data is to plot the data on vertical cross-sections of the atmosphere. Such analysis is carried out for special occasions in the Meteorological Office and the methods are dealt with in Chapter 4. Two methods of analysis not in regular use in the Meteorological Office, isentropic analysis and frontal contour analysis, are also described in Chapter 4.

The upper air charts in daily use in the Meteorological Office are constant-pressure charts. Such charts are drawn for all or some of a series of standard-pressure levels: 1000, 700, 500, 300, 200 and 100 mb. Occasionally a chart for 850 mb. is drawn and charts for higher levels (for example 70, 50, 30, 20 or 10 mb.) may be drawn in future. On each chart is plotted for each sounding, the temperature ($^{\circ}\text{C}.$), the height of the pressure level (geopotential metres) and the wind (degrees true and knots). Contours of height are drawn on these charts at intervals of 60 geopotential metres. (Though the unit of height is the geopotential metre, this is so nearly equal to the metre that the difference is immaterial and where no confusion is likely to exist heights will be given in metres for the remainder of this chapter.) Additional data for certain levels can also be plotted on these charts (see Section 2.6.1.).

A further set of charts of considerable use to forecasters and upper air analysts are the thickness charts. On these charts are plotted the thicknesses of the air column between two chosen pressure levels and in addition the vector differences between the winds at the two pressure levels. The isopleths of equal thickness are drawn at intervals of 60 metres. In addition to the charts for the thickness between consecutive standard levels, the 1000–500 mb. thickness chart is also drawn. This chart is much used for forecasting (see Chapters 5 and 6).

2.2. GEOSTROPHIC WINDS AND CONTOUR CHARTS

Geostrophic winds can be obtained from an upper air chart by a method similar to that used on mean-sea-level surface charts. As mentioned above, the relationship between the contours on a constant-pressure chart and the geostrophic wind is particularly simple.

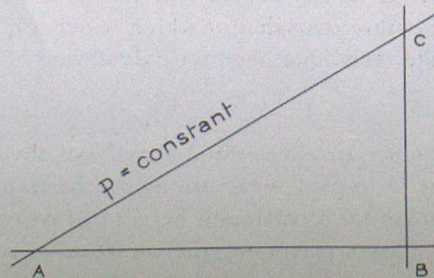


FIGURE 2.1 *Constant-pressure surface*

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In Figure 2.1 let ABC be a vertical section in which AC is the intersection with a constant-pressure surface, CB vertical and AB horizontal. Thus if the x -axis is in the direction AB and the z -axis is vertical, the pressure p at any point C (x, z) is a function of the height z and the horizontal distance x , so that

$$\delta p = \frac{\partial p}{\partial x} \delta x + \frac{\partial p}{\partial z} \delta z.$$

But since AC is in the constant-pressure surface, $\delta p = 0$ so that

$$\frac{\partial p}{\partial x} \delta x + \frac{\partial p}{\partial z} \delta z = 0.$$

By the hydrostatic equation

$$\frac{\partial p}{\partial z} = -g\rho, \text{ where } g \text{ is the acceleration due to gravity and } \rho \text{ the air density,}$$

so that

$$\frac{\partial p}{\partial x} \delta x = g\rho \cdot \delta z$$

or

$$\frac{\partial p}{\partial x} = g\rho \frac{\partial z}{\partial x}.$$

From the equation for the geostrophic wind components, the component along the y -axis,

$$v_g = \frac{1}{f\rho} \cdot \frac{\partial p}{\partial x} \quad (\text{see Chapter 13}) \quad \dots \quad (1)$$

so that for a constant-pressure surface, by substitution,

$$v_g = \frac{g}{f} \cdot \frac{\partial z}{\partial x}.$$

Similarly it may be shown that the component of geostrophic wind along the x -axis is

$$u_g = -\frac{g}{f} \cdot \frac{\partial z}{\partial y}, \quad \dots \quad (2)$$

so that if V_g is the geostrophic wind and n the distance measured along the normal to the contours

$$V_g = \frac{g}{f} \cdot \frac{\partial z}{\partial n}, \quad \dots \quad (3)$$

and the direction of V_g is parallel to the contours with low contour values on the left in the northern hemisphere when one's back is towards the wind. It will be

noticed that the air density does not appear in the equation for the geostrophic wind so that one geostrophic wind scale can be used for all constant-pressure-level charts.

Reference has been made above to the relationship between the geostrophic wind and the contours of a constant-pressure chart. In practice this relationship is embodied in a geostrophic wind scale, designs for which are given in Chapter 13, Figures 2(a) and (b). The real wind is of course not equal to the geostrophic wind and a better approximation is the gradient wind. The derivation of the gradient wind is discussed in Chapter 13, Section 13.3.2.

2.3. THICKNESS CHARTS AND THE THERMAL WIND

If u_1, v_1 and u_2, v_2 are the components of the geostrophic winds at two pressure levels p_1 and p_2 , and if we write u', v' for the components of the differences between the winds at the two levels, then from Section 2.2., writing $z' = z_2 - z_1$, where z_1 and z_2 are the heights of the surfaces,

$$\left. \begin{aligned} u' = u_2 - u_1 &= -\frac{g}{f} \left(\frac{\partial z_2}{\partial y} - \frac{\partial z_1}{\partial y} \right) = -\frac{g}{f} \frac{\partial}{\partial y} (z_2 - z_1) = -\frac{g}{f} \frac{\partial z'}{\partial y} \\ \text{and } v' = v_2 - v_1 &= \frac{g}{f} \left(\frac{\partial z_2}{\partial x} - \frac{\partial z_1}{\partial x} \right) = \frac{g}{f} \frac{\partial}{\partial x} (z_2 - z_1) = \frac{g}{f} \frac{\partial z'}{\partial x} \end{aligned} \right\} \dots (4)$$

These equations are similar in form in every way to equations (1) and (2) so that the difference in geostrophic winds can be obtained from the contours of a thickness chart for the two selected-pressure levels using the geostrophic scale prepared for a constant-pressure-level chart. The direction of this wind vector also has low thickness values to the left. This wind vector is called the thermal wind between the two pressure levels. It is of interest to note that in the case of constant-height charts the thermal wind is not simply related to the pressure-difference isopleths.

From the hydrostatic equation $\frac{\partial p}{\partial z} = -\rho g$ and the gas equation $p = \rho RT$, we have

$$\frac{\partial p}{\partial z} = -\frac{gp}{RT}$$

or integrating $\int_{z_1}^{z_2} dz = -\frac{R}{g} \int_{p_1}^{p_2} T \frac{dp}{p}$

i.e. $z' = -\frac{R}{g} \int_{p_1}^{p_2} T d(\log p) \dots (5)$

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By averaging T over equal intervals of $\log p$ an average value T_m can be obtained. We then have

$$z' = -\frac{R}{g} T_m \int_{p_1}^{p_2} d(\log p) = -\frac{R}{g} T_m \log \left(\frac{p_1}{p_2} \right) \quad \dots (6)$$

The variation of g is insignificant, so for any two selected-pressure levels the thickness z' is directly proportional to the mean temperature T_m of the air column between p_1 and p_2 . It therefore follows that thickness charts also show the distribution of mean temperature between the two selected-pressure levels. Thus areas of warm and cold air, corresponding to larger and smaller values of T_m respectively, will be identified on the charts by areas of relatively high and low values of the thickness respectively. Further, since for any selected layer the thickness is proportional to the mean temperature, it follows that the thermal wind is parallel to the mean temperature isotherms for the layer. In any homogeneous air mass the variation in the value of T_m and hence z' will be zero, but in practice the air mass is not homogeneous, especially when the area considered is large, and then the mean temperature varies slowly horizontally so that there will be a small horizontal gradient of thickness. Across a frontal surface the horizontal gradient of temperature is large and so in the region between the positions where a frontal surface cuts the lower and upper selected-pressure levels there will be an increased gradient of mean temperature. If the frontal surface were nearly vertical this gradient of mean temperature would be very large depending on the gradient of temperature of the front and would show on the thickness chart as a belt of closely packed isopleths along the position of the vertical frontal surface. However, as most frontal surfaces slope at a small angle to the horizontal, the belt of isopleths is not closely packed but only shows a concentration of thickness gradient along the frontal region. The thickness lines cross the front at an angle which depends on the temperature contrast across the front and the degree of heterogeneity in either of the air masses parallel to the frontal surface.

At an occlusion there is a tongue of occluded warm air the base of which lifts progressively away from the point of occlusion and the mean temperature of which decreases in the same direction for various reasons. In consequence the isopleths of thickness show a ridge lying over the position of the occlusion. An example of the relation between the 1000–500 mb. thickness lines and the position of the fronts on the surface chart is shown in Figure 2.2. It should be noted that the axis of the thickness ridge does not necessarily lie exactly over the position of the occlusion on the surface chart.

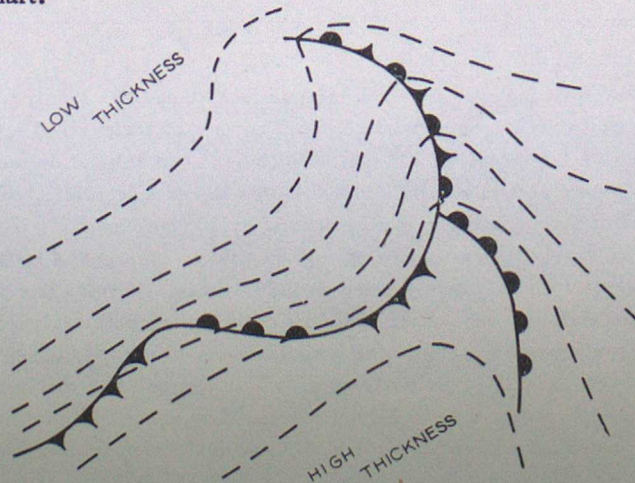


FIGURE 2.2 Relation of thickness lines to a frontal surface

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The 1000–500 mb. thickness chart is often used as a direct link between the surface and the 500 mb. level. It is also the layer of the atmosphere most concerned with the weather and indicates the major thermal distribution of the part of the troposphere which is frequently regarded as being below the level of non-divergence (see Chapter 5). The configurations shown on this particular thickness chart are much used in the forecasting of future developments of depressions and anticyclones (see Chapters 5 and 6).

2.4. THE CALCULATION OF HEIGHTS

2.4.1. *General*

The heights above mean sea level of the various standard-pressure levels are reported in geopotential metres* in the radio-sonde messages, having been calculated by the staff of the radio-sonde station. The methods used for these calculations follow a step-by-step procedure since this is the easiest way of taking account of the vertical change in temperature (see equation (5)).

The required height of any selected standard-pressure level is obtained as the total of the height of the station above mean sea level, the height of the 1000 mb. level above the station (negative if station level pressure is less than 1000 mb.) and the various thicknesses between successive pairs of the standard levels 1000, 700, 500, 300 mb. etc. due allowance being made for the humidity in the air at some stage during the calculation. It should be noted that if an error is made in the calculation of these values, the progressive addition carries the error upwards to affect the heights of all higher levels. In general, it is not necessary to recalculate the reported heights but occasionally a check on a height reported is necessary when either the message is mutilated or an error seems likely. In such cases the tephigram (dry-bulb temperatures and dew-points) is plotted on Form 2810A (or 2810B) and the following procedure adopted.

2.4.2. *Height of 1000 mb. level above mean sea level*

This is the algebraic sum of the height of the radio-sonde station above mean sea level and the height of the 1000 mb. surface above the station. The latter may be found from the reported temperature and surface pressure at station level by means of the nomogram printed on Form 2810A (or 2810B). The height is positive or negative according as the station pressure is greater or less than 1000 mb. respectively.

*The work done in lifting unit mass from the surface (mean sea level) to a height z is $\int_0^z g \cdot dz$ and this is equal to the geopotential. The c.g.s. unit of potential (1 erg per gm.) is small and so a larger unit of 10^5 c.g.s. units has been defined as the dynamic metre (= 0.01 joule per gm.). The vertical height interval separating two surfaces whose geopotentials differ by one dynamic metre, that is, by $10^5 \text{ cm.}^2 \text{ sec.}^{-2}$, is thus $10^5/980 \text{ cm.}$ or 1.02 m. approximately. Another unit of geopotential is more useful for practical purposes; it is the *geopotential metre* and is defined as 0.98 dynamic metres. The vertical height interval separating two surfaces whose potentials differ by one geopotential metre is therefore almost the same as one geometric metre. The actual difference between the height interval of one geopotential metre and 100 centimetres varies with latitude and with height and is less than 0.5 per cent at all latitudes up to 20,000 metres. The above definitions of dynamic metre and geopotential metre are as defined by W.M.O. Commission for Aerology.

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When the surface pressure is greater than 1000 mb. the appropriate temperature to use should be the mean virtual temperature between station and 1000 mb., where the average is with respect to the logarithm of pressure. This is done at most radio-sonde stations. However, the mean temperature between station and 1000 mb. is less than 2°C . different from the station temperature and use of the latter alone would give rise to an error of 1 per cent of the height (normally positive) at the most, that is, a maximum of about 3 metres. The error arising from neglect of the humidity is greatest at high temperatures and high humidities, but even for saturated air at 30°C . it only amounts to 2 per cent of the height interval. In general, this error is less than 5 metres and can be neglected for practical purposes in chart analysis. The surface temperature is again used when the surface pressure is less than 1000 mb., the layer in this case being assumed isothermal. This assumption does not affect the height calculated for any standard-pressure surface other than that for the 1000 mb. surface, because any error introduced is automatically cancelled in using the thickness from 1000 mb. upwards.

2.4.3. Thickness between standard levels

It will be seen from Form 2810A (and 2810B) that there are height scales inserted between the following levels – 1000, 900, 800, 300, 250, 150 and 100 mb. These scales give the values of the thickness of each layer for dry air having an isothermal temperature at the point of reading of the scale. This thickness is unchanged for any layer of dry air having the same mean temperature, the mean temperature being conveniently found by a graphical method, the equal area method using isothermals. On a tephigram the thickness of an isobaric layer is represented by the area between the two isobars bounding the layer, the virtual temperature curve and the entropy axis (that is, the area between the two isobars to the left of the virtual temperature curve as plotted on Forms 2810A or 2810B assuming that the diagram extended to zero absolute temperature). If the air is assumed dry the virtual temperature curve becomes the same as the temperature curve. Since the thickness depends on the size and not the shape of the area, the temperature curve can be replaced by any other line provided the size of the area is preserved. In particular, an isothermal line may be used. In Figure 2.3 is shown part of a tephigram with the temperature curve also drawn. The isothermal DBE is so chosen that the area ABE = area DBC. Then the thickness of the layer from 900 to 800 mb. is read from the intersection of the isothermal DE with the height scale (890 metres in the figure).

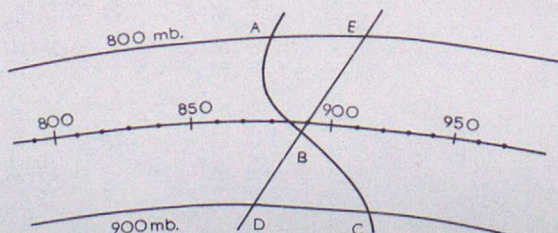


FIGURE 2.3 *Equal area (isothermal) method of obtaining thickness*

It is necessary to correct this thickness to take into account the fact that the air is moist. This correction is usually obtained from tables which give the correction in terms of dry-air thickness and average relative humidity (see Tables 2.1(a)–(b)). Relative humidity is not reported but can be rapidly estimated for each layer by inspection of the tephigram.

TABLE 2.1(a) Correction of 1000-900 mb. layer thickness in metres for relative humidity

Layer thickness of dry air	correction to be added (metres)												
	0	3	6	9	12	15	18	21	24	27	30	33	
metres													
840	0-77	>77	-	-	-	-	-	-	-	-	-	-	
860	0-47	>47	-	-	-	-	-	-	-	-	-	-	
870	0-38	>38	-	-	-	-	-	-	-	-	-	-	
880	0-30	31-90	>90	-	-	-	-	-	-	-	-	-	
890	0-24	25-72	>72	-	-	-	-	-	-	-	-	-	
900	0-19	20-58	59-97	>97	-	-	-	-	-	-	-	-	
905	0-17	18-52	53-87	>87	-	-	-	-	-	-	-	-	
910	0-15	16-47	48-78	>78	-	-	-	-	-	-	-	-	
915	0-13	14-42	43-70	71-98	>98	-	-	-	-	-	-	-	
920	0-12	13-37	38-63	64-89	>89	-	-	-	-	-	-	-	
925	0-11	12-34	35-57	58-80	>80	-	-	-	-	-	-	-	
930	0-10	11-30	31-51	52-72	73-93	>93	-	-	-	-	-	-	
935	0-9	10-27	28-46	47-65	66-84	>84	-	-	-	-	-	-	
940	0-8	9-25	26-42	43-59	60-76	77-94	>94	-	-	-	-	-	
942	0-7	8-24	25-40	41-56	57-73	74-90	>90	-	-	-	-	-	
944	0-7	8-23	24-38	39-54	55-70	71-86	>86	-	-	-	-	-	

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TABLE 2.1(a) (contd.) Correction of 1000-900 mb. layer thickness in metres for relative humidity

Layer thickness of dry air	correction to be added (metres)												33
	0	3	6	9	12	15	18	21	24	27	30	33	
metres													
946	0-7	8-22	23-37	38-52	53-67	68-83	84-98	>98	-	-	-	-	-
948	0-6	7-21	22-35	36-50	51-65	66-79	80-94	>94	-	-	-	-	-
950	0-6	7-20	21-34	35-48	49-62	63-76	77-90	>90	-	-	-	-	-
952	0-6	7-19	20-33	34-46	47-59	60-73	74-87	>87	-	-	-	-	-
954	0-6	7-19	20-31	32-44	45-57	58-70	71-83	84-97	>97	-	-	-	-
956	0-6	7-18	19-30	31-42	43-55	56-67	68-80	81-93	>93	-	-	-	-
958	0-5	6-17	18-29	30-41	42-53	54-65	66-77	78-90	>90	-	-	-	-
960	0-5	6-16	17-28	29-39	40-51	52-62	63-74	75-86	87-98	>98	-	-	-
962	0-5	6-16	17-27	28-37	38-49	50-60	61-71	72-83	84-94	>94	-	-	-
964	0-5	6-15	16-26	27-36	37-47	48-57	58-68	69-80	81-91	>91	-	-	-
966	0-4	5-14	15-25	26-35	36-45	46-55	56-66	67-76	77-87	88-98	>98	-	-
968	0-4	5-14	15-24	25-33	34-43	44-53	54-63	64-73	74-84	85-94	>94	-	-
970	0-4	5-13	14-23	24-32	33-41	42-51	52-61	62-71	72-81	82-91	>91	-	-
972	0-4	5-13	14-22	23-31	32-40	41-49	50-58	59-68	69-77	78-87	88-97	>97	-
974	0-4	5-12	13-21	22-29	30-38	39-47	48-56	57-65	66-74	75-84	85-93	>93	-
975	0-4	5-12	13-20	21-28	29-37	38-45	46-54	55-62	63-71	72-80	81-89	90-98	-

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TABLE 2.1(b) Correction of 900–850 mb. layer thickness in metres for relative humidity

Layer thickness of dry air	correction to be added (metres)									
	0	3	6	9	12	15	18	21		
metres										
470	0-70	>70	—	—	—	—	—	—	—	—
480	0-46	>46	—	—	—	—	—	—	—	—
490	0-30	31-92	>92	—	—	—	—	—	—	—
495	0-25	26-75	>75	—	—	—	—	—	—	—
500	0-20	21-62	>62	—	—	—	—	—	—	—
502	0-19	20-57	58-96	>96	—	—	—	—	—	—
504	0-17	18-55	56-89	>89	—	—	—	—	—	—
506	0-16	17-49	50-83	>83	—	—	—	—	—	—
508	0-15	16-45	46-77	>78	—	—	—	—	—	—
510	0-14	15-42	43-71	>71	—	—	—	—	—	—
512	0-12	13-39	40-66	67-93	>93	—	—	—	—	—
514	0-12	13-36	37-61	62-86	>86	—	—	—	—	—
516	0-11	12-34	35-57	58-80	>80	—	—	—	—	—
518	0-10	11-31	32-53	54-75	76-97	>97	—	—	—	—
520	0-9	10-29	30-49	50-69	70-90	>90	—	—	—	—
522	0-8	9-27	28-46	47-65	66-84	>84	—	—	—	—
524	0-8	9-25	26-42	43-60	61-78	79-97	>97	—	—	—
526	0-7	8-23	24-39	40-56	57-73	74-90	>90	—	—	—
528	0-7	8-21	22-37	38-52	53-68	69-84	>84	—	—	—
530	0-6	7-20	21-34	35-48	49-63	64-78	79-93	>93	—	—

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TABLE 2.1(c) Correction of 850-800 mb. layer thickness in metres for relative humidity

		corrections to be added (metres)					
Layer thickness of dry air	metres	0	3	6	9	12	15
		relative humidity (per cent)					
	490	0-89	> 89	-	-	-	-
	500	0-59	> 59	-	-	-	-
	510	0-39	> 39	-	-	-	-
	515	0-32	33-98	> 98	-	-	-
	520	0-26	27-81	> 81	-	-	-
	525	0-22	23-67	> 67	-	-	-
	530	0-18	19-55	56-92	> 92	-	-
	532	0-17	18-51	52-86	> 86	-	-
	534	0-16	17-48	49-80	> 80	-	-
	536	0-14	15-44	45-75	> 75	-	-
	538	0-13	14-41	42-70	71-98	> 98	-
	540	0-12	13-39	40-65	66-92	> 92	-
	542	0-12	13-36	37-60	61-85	> 85	-
	544	0-11	12-33	34-56	57-80	> 80	-
	546	0-10	11-31	32-52	53-74	75-96	> 96
	548	0-9	10-29	30-49	50-69	70-90	> 90
	550	0-9	10-27	29-45	46-64	65-83	> 83

TABLE 2.1(d) Correction of 800-700 mb. layer thickness in metres for relative humidity

Layer thickness of dry air	correction to be added (metres)									
	0	3	6	9	12	15	18	21	24	
metres										relative humidity (per cent)
1040	0-80	>80	-	-	-	-	-	-	-	-
1060	0-53	>53	-	-	-	-	-	-	-	-
1080	0-36	>36	-	-	-	-	-	-	-	-
1090	0-29	30-89	>89	-	-	-	-	-	-	-
1100	0-24	25-74	>74	-	-	-	-	-	-	-
1110	0-20	21-61	>61	-	-	-	-	-	-	-
1120	0-17	18-51	52-86	>86	-	-	-	-	-	-
1130	0-14	15-43	44-72	>72	-	-	-	-	-	-
1140	0-12	13-36	37-61	62-85	>85	-	-	-	-	-
1145	0-11	12-33	34-56	57-78	>78	-	-	-	-	-
1150	0-10	11-30	31-51	52-72	73-93	>93	-	-	-	-
1155	0-9	10-28	29-47	48-66	67-85	>85	-	-	-	-
1160	0-8	9-25	26-43	44-60	61-78	79-96	>96	-	-	-
1165	0-7	8-23	24-39	40-56	57-72	73-88	>88	-	-	-
1170	0-7	8-21	22-36	37-51	52-66	67-81	82-96	>96	-	-
1175	0-6	7-20	21-33	34-47	48-61	62-74	75-88	>88	-	-
1180	0-6	7-18	19-30	31-43	44-53	54-68	69-81	82-94	>94	-

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TABLE 2.1(e) Correction of 700–600 mb. layer thickness in metres for relative humidity

Layer thickness of dry air	correction to be added (metres)									
	0	3	6	9	12	15	18	21		
<i>metres</i>					<i>relative humidity (per cent)</i>					
1180	0-87	>87	—	—	—	—	—	—	—	—
1200	0-61	>61	—	—	—	—	—	—	—	—
1220	0-42	>42	—	—	—	—	—	—	—	—
1230	0-35	>35	—	—	—	—	—	—	—	—
1240	0-30	31-91	>91	—	—	—	—	—	—	—
1250	0-25	26-77	>77	—	—	—	—	—	—	—
1260	0-21	22-65	>65	—	—	—	—	—	—	—
1270	0-18	19-55	56-93	>93	—	—	—	—	—	—
1280	0-15	16-47	48-79	>79	—	—	—	—	—	—
1290	0-13	14-40	41-67	68-95	>95	—	—	—	—	—
1295	0-12	13-37	38-62	63-88	>88	—	—	—	—	—
1300	0-11	12-34	35-57	58-81	>81	—	—	—	—	—
1305	0-10	11-31	32-53	54-75	76-97	>97	—	—	—	—
1310	0-9	10-29	30-49	50-70	71-91	>91	—	—	—	—
1315	0-9	10-27	28-46	47-65	66-84	>84	—	—	—	—
1320	0-8	9-25	26-42	43-60	61-78	79-95	>95	—	—	—
1325	0-7	8-23	24-39	40-56	57-73	74-88	>88	—	—	—
1330	0-7	8-22	23-37	38-51	52-67	68-82	83-97	>97	—	—

*Handbook of Weather Forecasting*TABLE 2.1(f) *Correction of 600–500 mb. layer thickness in metres for relative humidity*

Layer thickness of dry air	correction to be added (metres)				
	0	3	6	9	12
<i>metres</i>	<i>relative humidity (per cent)</i>				
1380	0–80	> 80	—	—	—
1400	0–58	> 58	—	—	—
1420	0–43	> 43	—	—	—
1440	0–31	32–95	> 95	—	—
1460	0–23	24–71	> 71	—	—
1470	0–20	21–62	> 62	—	—
1480	0–17	18–53	54–90	> 90	—
1490	0–15	16–46	47–78	> 78	—
1500	0–13	14–40	41–68	69–96	> 96
1510	0–11	12–35	36–59	60–84	> 84

TABLE 2.1(g) *Correction of 500–400 mb. layer thickness in metres for relative humidity*

Layer thickness of dry air	correction to be added (metres)			
	0	3	6	9
<i>metres</i>	<i>relative humidity (per cent)</i>			
1660	0–79	> 79	—	—
1700	0–46	> 46	—	—
1720	0–35	> 35	—	—
1740	0–27	28–84	> 84	—
1760	0–21	22–66	> 66	—
1770	0–19	20–58	59–97	> 97
1780	0–17	18–51	52–86	> 86

TABLE 2.1(b) *Correction of 400–300 mb. layer thickness in metres for relative humidity*

Layer thickness of dry air	correction to be added (metres)	
	0	3
<i>metres</i>	<i>relative humidity (per cent)</i>	
2080	0–93	> 93
2120	0–59	> 59
2160	0–38	> 38

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An alternative way of correcting for the humidity of the air is to draw on Form 2810A (or 2810B) the curve of virtual temperature. The difference between the reported temperature and the virtual temperature can be obtained from tables.^{1*} The equal area method is then applied to the virtual temperature curve and the corrected height obtained directly.

It should be noted that when the thickness scales for the equal area (isothermal) method described above are printed on the mean pressure isobars (as on the present Forms 2810A and 2810B and as portrayed in Figure 2.3), they do not give exactly correct results if used with any other straight line cutting off areas of equal value. If the thickness scales were printed geometrically mid-way between the boundary isobars of the layer, then the use of straight lines other than isotherms would not introduce errors of appreciable magnitude because the curvature of the isobars is slight.

In an upper air unit it is almost always the thicknesses between the standard levels used for chart work which are required, and it is possible to obtain such thicknesses by a quicker method which is sufficiently accurate for the purpose in hand. When the equal area isothermal method is extended to the interval between the standard-pressure levels, large areas have to be equalized and the method becomes inaccurate. However, it is possible to use the saturated adiabatics as the boundary of the area and, since in the free atmosphere the temperature curve tends to follow a saturated adiabatic in the troposphere, more convenient areas of small size are obtained for equalization in this manner. The method thus reduces to identifying a saturated adiabatic so that, together with the temperature curve, it produces equal areas between the two isobars. The saturated adiabatic is identified from the corresponding value of the scale of wet-bulb potential temperatures and the layer thickness obtained from Table 2.2. Alternatively, saturated adiabatics are drawn on a transparent overlay and the thickness read off directly from a scale engraved in conformity with Table 2.2. The thickness so obtained must then be corrected for the effect of humidity. For general synoptic analysis the correction is worth-while calculating only for the layer 1000–700 mb. and the following simple calculation suffices. From the tephigram, estimate the mean humidity mixing ratio over the level in gm./kg. Multiply this figure by 2 and this is approximately the correction in metres to be added to the height. (In high temperatures, as in tropical air, it is sometimes worth-while correcting for humidity – when known – over the layer 700–500 mb. For such a layer the simple rule is : correction in metres is equal to $\frac{2}{3} \times$ mean humidity mixing ratio in gm./kg.).

2.4.4. Thermal winds

Thermal winds are needed for entry on the thickness charts. For each sounding, the wind shear across the layer can be obtained by plotting the reported winds for the standard levels as vectors on a hodograph and drawing the vector differences (see Chapter 3). The wind shear thus found is not exactly the thermal wind but, except when the curvature of the air flow varies rapidly along the vertical, the observed wind shear is a fair approximation to the thermal wind. In cases where the vertical change of curvature is rapid there will be an appreciable angle between the actual wind shear and the thickness lines. The sense of the angle can be deduced by remembering that the thermal wind is the shear between the two

*The superscript figures refer to the bibliography at the end of this chapter.

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geostrophic winds and that the geostrophic wind is greater than the real wind in cyclonic flow but less in anticyclonic flow. (It should be noted that the practice of reporting wind directions to the nearest 10 degrees can result, when the observed winds are large and similar (for example, 276° 60 knots and 264° 70 knots), in apparent shears of appreciable strength at large angles to the thermal wind.)

In obtaining the 1000–700 mb. wind shear, it is customary to use the reported 900 metre wind for the 1000 mb. wind. This wind is nearly always reported, is the lowest regularly available and approximates to the "surface" geostrophic wind quite closely. When no low-level wind is available an estimate is made from the surface pressure gradient.

TABLE 2.2 *Layer thickness in geopotential decametres obtained by the saturated adiabatic method*

Wet-bulb potential temperature	millibar layer				
	1000–700	700–500	500–300	1000–500	1000–300
$^{\circ}\text{C}$	<i>geopotential decametres</i>				
–6	268	232	—	500	—
–4	271	234	—	505	—
–2	273	237	—	510	—
0	275	239	—	515	—
2	278	242	—	520	—
4	280	245	—	525	—
6	283	247	336	530	866
8	285	250	341	535	877
10	287	253	347	541	887
12	290	256	352	546	898
14	292	259	357	552	910
16	295	262	363	557	921
18	297	265	369	562	932
20	299	268	375	567	943
22	301	271	381	573	954
24	304	274	388	578	965
26	306	277	394	583	976
28	309	279	400	588	987
30	311	282	405	593	998
32	313	—	—	—	—
34	315	—	—	—	—

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2.5. GRAPHICAL TECHNIQUES

2.5.1. *Addition of charts*

The technique often referred to as "gridding" is that of graphical addition (or subtraction) of two sets of isopleths to give a third set. This may be represented by the equation

$$S = F_1 + F_2,$$

where the quantities F_1 , F_2 and S can all be represented by sets of isopleths on the same basic chart, and at every point the value of S is the sum of the values F_1 and F_2 at that point.

If we differentiate this equation (in the plane of the chart) we get:

$$\nabla S = \nabla F_1 + \nabla F_2. \quad \dots \quad (7)$$

Thus the vector gradient of the sum S is the vector sum of the gradients of each of the two quantities F_1 and F_2 .

The graphical process saves time because it obviates doing separate additions for a large number of points and, if the original data for F_1 and F_2 contain errors, best-fit isopleths for F_1 and F_2 will produce best-fit isopleths for S . If there is doubt about the best fit of the isopleths for F_1 and F_2 they can be adjusted whilst obtaining the isopleths for S according to the operator's judgement. All sets of isopleths may be drawn on the same chart or, if a light-table is used, the isopleths may be on different charts which are superimposed in register on the light-table. In meteorology this technique is much used for differential analysis of heights of pressure surfaces and so the examples here given will be for the construction of contour charts for one level by the use of a contour chart for a lower level and the thickness chart for the intervening layer.

An example of the graphical addition of two sets of isopleths is shown in Figure 2.4. At each point of intersection A, B and C, the sum of the 1000 mb. height and the 1000–500 mb. thickness is 5340 metres, and at no other point of intersection of the isopleths drawn in the figure is the sum equal to this value. The 500 mb. contour for 5340 metres therefore passes through A, B and C and through no other point of intersection. The shape of the contour at intermediate points can be obtained by drawing in additional isopleths of height and thickness but this is rarely necessary in actual practice. It is, however, important to realize that the upper contour is defined at all points and the temptation to draw it midway between the lower contour and the thickness line must be resisted. It should be noticed that, since from equation (7) above the gradients are added, the direction of the third isopleth at any point of intersection can be obtained rapidly, since the vector geostrophic wind for the upper level is the resultant of the vector geostrophic wind of the lower layer and the thermal wind (see Figure 2.5), and in direction lies between the other two vectors. This fact is of assistance in ensuring that the isopleth produced in the addition passes through the intersection in the correct way, and allows the operator to start easily at any point of intersection.

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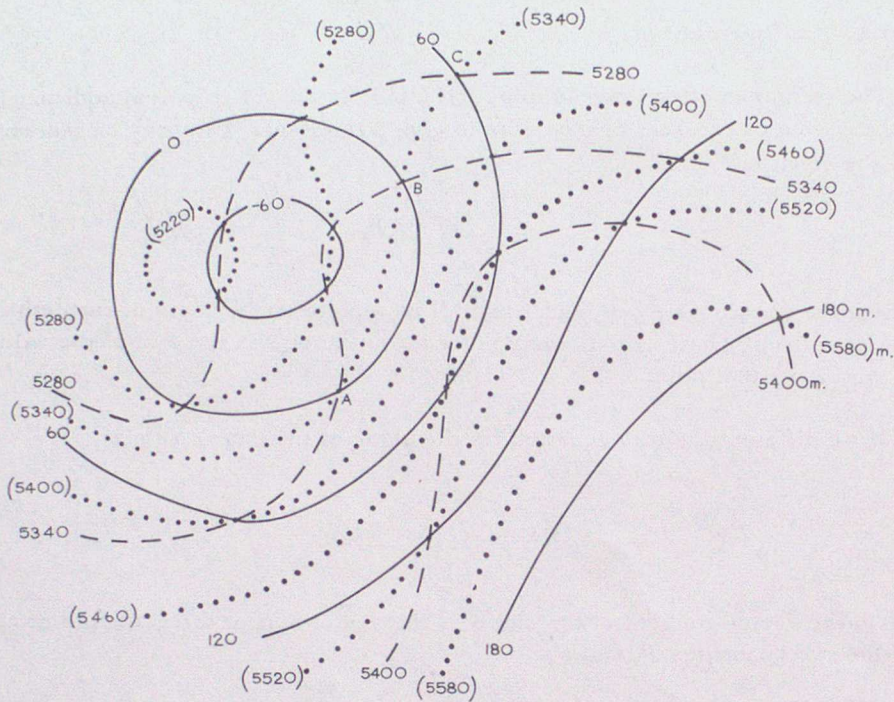


FIGURE 2.4 Gridding of 1000 mb. contours (—) with the 1000–500 mb. thickness lines (---) to obtain 500 mb. contours (.....)

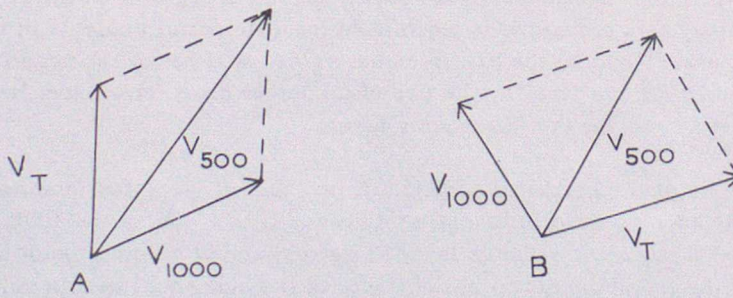
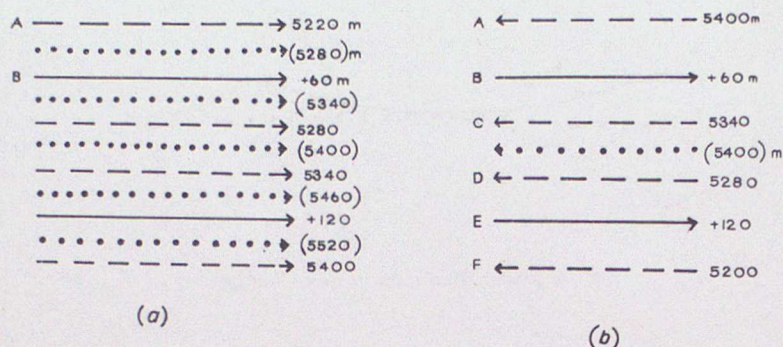


FIGURE 2.5 Addition of vectors at points A and B in Figure 2.4 (V_{1000} , V_{500} are geostrophic winds at 1000 and 500 mb., V_T is 1000–500 mb. thermal wind)

The case of the two families of isopleths not intersecting but lying between each other needs careful drawing. In Figure 2.6(a) the lower geostrophic wind and the thermal wind are approximately in the same direction, and in Figure 2.6(b) they are opposed (that is, gradient in opposite directions). (On actual charts the lines are unlikely to be straight as in these diagrams but the argument is the same.)

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FIGURE 2.6 *Isopleths not intersecting*

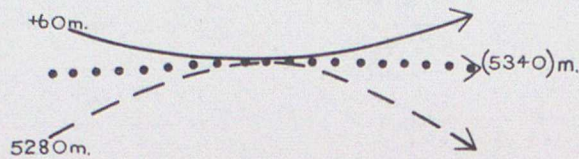
- 1000 mb. contours
- - - 1000-500 mb. thickness lines
- 500 mb. contours (arrow-heads indicate wind flow)

In Figure 2.6(a) along line A the thickness is 5220 and the 1000 mb. height is less than 60 metres but greater than 0, so that the 500 mb. height is less than 5280 but greater than 5220. Similarly along line B the 500 mb. height is less than 5340 but greater than 5280. Consequently between these two lines there must be a 500 mb. height contour of 5280. Continuing the argument in this way, it is easily seen that there is always a 500 mb. contour between every pair of isopleths of the two patterns being added whether the pair belong to the same set or not.

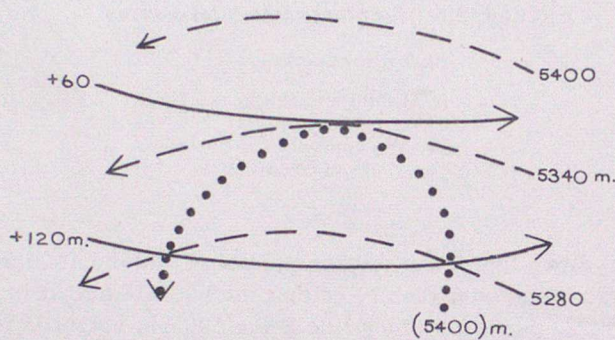
Similarly in Figure 2.6(b) it may be shown that for each of the lines A, B and C the 500 mb. height is less than 5460 but greater than 5400 and that for each of the lines D, E and F the height is less than 5400 but greater than 5340. There is thus no 500 mb. contour between the lines A, B and C, nor between the lines D, E and F, but there is between the lines C and D. The pairs of lines AB, BC, DE and EF contain one member from a set corresponding to decreasing height up the page and one corresponding to an opposed slope. Hence in interlaced isopleth patterns corresponding to opposed slopes there is usually no isopleth of the third series in between. (The qualification "usually" is required because cases can occur where instead of no isopleth there are in fact two isopleths of the third set of the same value, as in the case of a col or closed contour.) The lines C and D belong to the same set and correspond to a slope in the same direction; they come under the rule of Figure 2.6(a).

The special cases where one of the lower contours touches but does not cross one of the thickness lines can be dealt with as a special case of the non-intersecting lines shown in Figures 2.6(a) and (b) where the lines are bent towards one another until one line of each set just touch. The results are shown in Figures 2.7(a) and (b) respectively.

In Figure 2.7(a) the 1000 mb. geostrophic and the thermal winds run in the same sense and the 500 mb. geostrophic wind lies likewise between them. In Figure 2.7(b) the 1000 mb. geostrophic and thermal winds are opposed and the 500 mb. geostrophic wind is in the direction of the stronger of the two and the contour at the point of osculation does not cross the 1000 mb. contour or the thickness line. In the exceptional case of the 1000 mb. wind being exactly equal and opposite to the thermal wind, the 500 mb. contours would show a flat area whose size and shape would be dependent on the surrounding contours.

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(a) gradient direction in same sense



(b) gradient directions opposed

FIGURE 2.7 *Isopleths touching but not intersecting*2.5.2. *Subtraction of charts*

The reverse process of subtraction by graphical methods may be necessary on occasions, for example, to find the thickness between two layers p_1 and p_2 whose contours are given. Then to use the graphical process for $z' = z_2 - z_1$ it is necessary to note that

$$\nabla z' = \nabla z_2 + (-\nabla z_1)$$

so that to draw the contours through the intersection it is necessary only to imagine the direction of the geostrophic wind vector (∇z_1) everywhere reversed and, using the reversed direction, proceed as in addition.

2.6. ROUTINE ANALYSIS

The analysis of the state of the atmosphere at any given time calls for three-dimensional treatment but unfortunately must be carried out on two-dimensional charts. Each individual chart deals with a surface or layer and in order to ensure that the various charts are mutually consistent it is necessary to carry out the analysis in a methodical and well-planned sequence. The sequence used by the Meteorological Office is sometimes referred to as the differential method of analysis. In general, the number and accuracy of upper air temperature, pressure, humidity and wind observations decrease with height and so it is logical to expect that, if the three-dimensional synoptic analysis is commenced at the lowest layers and

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gradually extended upwards, greater consistency and accuracy will be attained than in any other way. Furthermore, from the sea-level analysis, the frontal structure and general history of the air masses are known so that the principal features of the temperature distribution may be directly assessed on the thickness charts. Conservation of the mean temperature of these fairly deep layers of air from one chart to another means that the thickness patterns must show continuity in time. The sequence of operations for the three-dimensional analysis largely followed by upper air units in this country is as follows:

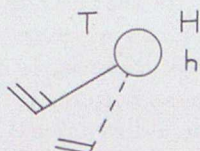
- (i) construction of a chart for 1000 mb.,
- (ii) construction of the various thickness charts 1000–700 mb.,
700–500 mb. etc.,
- (iii) adding the 1000–700 mb. thickness pattern to the 1000 mb. contour
pattern to obtain the 700 mb. contours,
- (iv) adding the 700–500 mb. thickness pattern to the 700 mb. contours
to obtain the 500 mb. contours,
- (v) continuing in this manner to 200 mb.,
- (vi) drawing contours of higher levels in accordance with the reported
winds and heights. (Some forecasters prefer to draw the 100 mb.
charts at an early stage as an aid to the detection of errors in the
heights reported.)

At each stage it will be necessary to regard the thickness chart to some extent as provisional and to adjust and smooth both the thickness chart in use and the contours being produced. Sometimes it is necessary to go back to the lower charts and adjust them to ensure consistency. At all levels the evolution of the situation must be considered so that a logical sequence of charts is obtained.

The addition of a thickness chart to a contour chart to produce another contour chart is performed by the method of "gridding" or graphical addition described in Section 2.5.1. above.

2.6.1. Plotting models

In general, the upper air plotting-model resembles the surface plotting-model in that temperature is plotted to the upper left-hand of the station circle, heights (or thicknesses) to the upper right-hand and winds by arrow shafts with 10-knot feathers leading from the wind direction into the station circle. However, whilst each thickness chart and each contour chart may be plotted and drawn up on individual charts (which must then be thin so that three layers can be used on a light-table), this is not necessary and may actually be quite inconvenient especially if space is limited. A most useful alternative is to plot thickness data for the layer and contour data for the top of the layer on the same chart (for example, 700–500 mb. data and 500 mb. data). In such a case the plotting model is as shown in Figure 2.8. The thickness of the isobaric layer is here plotted below the height above mean sea level of the upper isobaric surface and the thermal wind is distinguished from the wind at the top of the layer by being either pecked or in a colour. If in colour, h can also be in the same colour.

Handbook of Weather ForecastingFIGURE 2.8 *Plotting model*

H = height of isobaric surface above mean sea level

h = thickness of layer below

T = temperature at height H

Wind at H is drawn as a solid line.
Thermal wind is plotted as a pecked line or in red.

The amount of paper can be further reduced by drawing the 1000 mb. contours in a coloured ink on the same chart as the data for 1000–700 mb. thickness and the 700 mb. level.

Because much reliance in analysis is placed on the wind data and plotters frequently have difficulty in placing the wind direction line accurately, it is customary at many stations to write the tens figure of the wind direction by the side of the wind arrow. Alternatively, in the case of fixed stations, a ring of dots at 10° or 30° intervals is printed around and outside the station circles.

Additional items are often plotted for specific purposes, such as 700 mb. dew-point on the 700 mb. chart or the tropopause pressure on the 200 mb. chart. Also, it is often customary to plot in another colour any wind observations made up to six hours after the chart time (for example, 0600h winds are put on the 0000h chart).

2.6.2. *The 1000 mb. chart*

Because the 1000 mb. level is close to mean sea level it is usual to make use of the mean-sea-level chart to produce the 1000 mb. chart. This is done by placing the new chart on top of the surface chart over a light-table and then drawing the contours of the 1000 mb. surface, making use of the relation between temperature, pressure and height given in Table 2.3. When mean-sea-level pressure is below 1000 mb. the height is negative. The contours are at intervals of 60 metres and positions of centres of depressions and anticyclones are also marked and the height indicated. The frontal positions are also inserted on this chart. Since the height of the 1000 mb. surface depends only slightly on the temperature, the contours of the 1000 mb. surface can easily be drawn following the run of the appropriate isobars on the surface charts. It is profitable to plot the 1000 mb. heights reported both to aid the drawing of the contours and to serve as a check on errors.

It is obvious that using this method the 1000 mb. chart can only be drawn if the surface chart is completed first. When pressure of time does not allow this to be done, the 1000 mb. chart has to be based partly on synoptic surface analysis and

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TABLE 2.3. Surface pressure in millibars for tabulated values of temperature and the height of the 1000 mb. surface

1000 mb. surface heights (geopotential metres)													
Temperature	-360	-300	-240	-180	-120	-60	0	+60	+120	+180	+240	+300	+360
°C	millibars												
+40	961.5	967.8	974.2	980.6	987.0	993.5	1000	1006.6	1013.2	1019.8	1026.5	1033.3	1040.0
+30	960.3	966.8	973.3	979.9	986.6	993.3	1000	1006.8	1013.6	1020.5	1027.4	1034.4	1041.4
+20	958.9	965.7	972.4	979.3	986.1	993.0	1000	1007.0	1014.1	1021.2	1028.3	1035.6	1042.8
+10	957.4	964.4	971.4	978.5	985.4	992.8	1000	1007.3	1014.6	1022.0	1029.4	1036.9	1044.4
0	956.0	963.2	970.4	977.7	985.1	992.5	1000	1007.5	1015.1	1022.8	1030.5	1038.2	1046.0
-10	954.4	961.8	969.3	976.9	984.5	992.2	1000	1007.8	1015.7	1023.6	1031.6	1039.7	1047.8
-20	952.6	960.3	968.2	976.0	983.9	991.9	1000	1008.1	1016.3	1024.6	1032.9	1041.3	1049.8
-30	950.7	958.8	966.9	975.0	983.3	991.6	1000	1008.5	1017.0	1025.6	1034.3	1043.0	1051.9
-40	948.6	955.5	965.5	974.0	982.6	991.3	1000	1008.8	1017.7	1026.7	1035.8	1044.9	1054.1

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partly on forecast surface analysis. In this case it may be necessary to adjust the chart at a later stage before completing too many of the upper layers.

2.6.3. *The 1000–700 mb. thickness chart and 700 mb. contour chart*

The thickness isopleths are first put in lightly as pecked lines in accordance with the plotted thicknesses, the shear vectors and the surface frontal analysis. In a sequence of charts, the previous pattern of isopleths will be carried forward making allowance for development and the diurnal heating and cooling to which the layer is subjected. This is conveniently done with the new chart on top of the old 700 mb. chart on a light-table. When this has been done, the 700 mb. contours are drawn by graphical addition of the thickness lines and the contours of the 1000 mb. surface. The production of these contours must not be done mechanically for they are to be in reasonable agreement with the 700 mb. plotted winds and heights. The thickness lines and the contours are to be mutually adjusted so as to give the maximum of agreement with all observations, and the contours themselves must show reasonable development from previous charts. If the 1000 mb. contours have been constructed from an incomplete surface chart it might be necessary to revise these at this stage.

2.6.4. *Higher levels*

The next stage is the construction of the 700–500 mb. thicknesses and the 500 mb. contours. This is carried out in an exactly similar manner by comparison with the previous 500 mb. chart on a light-table followed by gridding, with these newly plotted charts placed on top of the 700 mb. contours. It is helpful in placing the thickness lines in this case to indicate, with the aid of the tephigram, the position of the 500 mb. fronts. At this stage the mutual adjustment is made mainly to the new thickness lines and the 500 mb. contours, but occasionally it may be necessary to adjust the 700 mb. contours (and thence the 1000–700 mb. thickness lines) in order to get the best fit with all observations and a consistent and reasonable analysis.

In a similar way, the 500–300 mb. thickness lines and the 300 mb. contours are next constructed, and the process can then be repeated to the 200 mb. level. However there are certain differences to be noted in proceeding to these highest levels. In general, the tropopause will be reached and above this the character of the wind flow reverses in the sense that the strength falls off with height, the thermal distribution being a reflection of that below the level of the maximum wind. The 300–200 mb. thickness pattern produces rather different problems from those at other levels. Only a small range of thickness is included in any one chart, and also strong winds and wind shears are encountered in the 300 mb. chart with which it is to be "gridded". Continuity in time for the thickness patterns appears to be poor. Any strong thickness gradients which do occur are usually above the jet axis in the 300 mb. surface and their effect is to move the jet axis on the 200 mb. surface a hundred miles or so to the high contour side of the 300 mb. axis. In the subtropics, on the other hand, in air with a tropopause above 200 mb. the thickness gradient may cause the wind to increase upwards.

The accuracy of the reported heights decreases with increasing height and errors become noticeably larger at 300 mb. and beyond (in some part due to isolation), whilst the accuracy of the reported winds shows little falling off with height (see Section 2.7.1.). Consequently it becomes increasingly important to fit the

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winds and carry out considerable smoothing of the heights when dealing with the 200 mb. level.

If this process were to be continued to the 100 mb. level using the 200–100 mb. thickness pattern, considerable difficulty would be found in fitting the height observations and in obtaining the fairly smooth flow which the wind observations tell us is characteristic of this level. The difficulty in using the gridding technique at this level is that one attempts to determine a small gradient by the subtraction of two larger gradients. The errors in the observations then result in an error in the derived gradient which is often large compared with the gradient itself. The differential method of analysis is therefore usually discontinued at the 200 mb. level. Even at 200 mb. there is some variation in opinion as to the advantages of applying the differential method of analysis.

2.7. ADDITIONAL REMARKS

2.7.1. *General considerations*

The number of upper air stations is considerably less than the number of synoptic surface stations but fortunately the flow patterns of the upper air are smoother than those at the surface. Nevertheless, it is of considerable importance to make the most of the data which are available. In general, over well populated areas in North America and Europe the density of upper air stations is satisfactory for general analysis, but over the other land areas and over the oceans in particular this is far from the case. Each observation in these areas is so isolated that it is essential to make use of all the facts reported by every station. On the other hand, it is equally important to realize that in such circumstances an error in one station's report can cause major errors in the analysis for many hundreds of miles and consequent errors in forecasting over even wider areas. It is thus very important to look critically at all observations and during the analysis it is essential to make use of all possible aids, such as continuity in time and space and reasonableness of the results. Criteria for the latter are comparison with climatological limits and conformity with known patterns. The following paragraphs are in amplification of some of these ideas.

A single observation of height and wind on a pressure surface will allow the placing of two contours since they will be (locally) parallel to the wind direction and their spacing apart (assuming geostrophic wind approximation) will be given by a geostrophic wind scale, whilst the reported height places them relative to the station. A single report cannot indicate whether the isobars are curved or not, but if this can be inferred from earlier or other data, a rough correction can be made to the spacing of the contours according to the expected departure of the wind from geostrophic. A relatively simple method of deriving this contour gradient has been proposed by Boyden². Using the reported speed, visualize on the chart the circular path along which the air is moving and note the number of degrees of wind-direction change if this movement were continued for a number of hours (t) depending only on the latitude (ϕ). t and ϕ are related thus:

ϕ degrees	t hours	ϕ degrees	t hours
72	3½	42	5
56	4	37	5½
48	4½	33	6

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Then the number of degrees (backing is counted as positive and veering as negative) is the percentage adjustment required to convert the reported wind to an equivalent geostrophic value which may be used with the geostrophic scale to space out the contours.

Where there are a number of reporting stations near together as in Europe, a compromise fitting the majority of winds and heights is not difficult to draw and any erroneous data can be detected easily but over the sea, and in other areas where observations are far apart, each station's report must be looked at very critically and full use made of it. If a choice has to be made between believing the wind or height reported by the station, it is preferable (other things being equal) to believe the reported wind. There are two reasons for this. The error of temperature measurement increases with height and, particularly with some kinds of radio-sonde at heights above 300 mb., large errors are possible partly because of solar insolation effects; on the other hand the accuracy of the winds falls off only slowly with height, the highest winds being almost as accurate as the lower ones. Secondly, the variation in the wind in the vertical is relatively smaller than the variation in temperature (in general) so that errors arising from pressure errors are smaller for winds than they are for heights.

In quasi-uniform air masses, the thickness lines will be wide apart, the thermal wind consequently small and the contour patterns very similar at all heights. In regions where the thickness pattern is similar to the contour pattern, the wind direction is approximately constant with height but the wind speed increases. The wind backs with height where it blows from cold to warm and veers with height where it blows from warm to cold, because the thermal wind introduces a backing component in the former case and a veering component in the latter case.

The centre of a depression or an anticyclone is rarely in the same place at all pressure levels. A general rule is that the centre of a depression is displaced with height towards the cold air but that if the depression is elongated this displacement is deviated somewhat toward the direction of the longer axis. An anticyclone is displaced with height towards the warmer air. Similarly, troughs are displaced with height towards the cold air and ridges towards the warm air.

In the initial state of a developing wave depression the circulation appears first at surface level and then builds upwards, gradually modifying the thickness pattern, and hence the contour pattern, to greater and greater heights. A thermal trough to the rear and a thermal ridge ahead is associated in the typical thickness pattern with the developing wave. The surface cold-front trough becomes displaced with height towards the cold air whilst the warm-front trough disappears with height because of the overlying anticyclonic thermal shear and the anticyclonic curvature of the thermal flow, the surface pre-frontal ridge being displaced towards the depression (and the warm air) in the process. (See also Chapter 5 for examples of idealized contours.)

2.7.2. Errors

Errors in the radio-sonde tend to be cumulative with height and a considerable part of the error at great heights is due to solar radiation effects. The effect of these errors is such that by the time 100 mb. is reached there is considerable random and systematic error in the calculated height. The random errors cannot be spotted unless there is a fairly close network of stations. Systematic errors would not greatly affect analysis if all sondes had the same systematic error.

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This, however, is not so and it is only too obvious to the analyst of the 100 mb. charts that allowance must be made for the various kinds of sonde and methods of working up the results (for example, whether or not a solar radiation correction has been applied before transmission). It is possible to determine, on a rough basis, corrections to be applied to the various groups of sondes to bring their heights into better agreement. To do this it is necessary to choose one group of sondes as standard and select charts when, according to the reported winds, the air flow is simple with slack gradient. It is then possible to calculate the gradients from the wind reports and to establish contour heights over the chart in terms of the standard sonde heights. The systematic errors of sondes in the various geographical groups (mainly national) according to the solar elevation can then be determined. A considerable number of occasions are required in order to eliminate random errors. The "systematic" errors thus found can then be applied as corrections to future reports during analysis (or by additional plotting).

These "corrections" are best found at 100 mb. but they also apply to some extent to 200 and 300 mb. Hawson and Caton³ have suggested that the following proportions should be applied to the lower-level charts (expressed as percentages of the "corrections" at 100 mb.):

200 mb. — 60 per cent 300 mb. — 35 per cent 500 mb. — 10 per cent.

(These same percentages can also be applied as rough corrections to individual anomalous soundings if it is believed that the abnormality increases progressively with height.) It will be appreciated that any change of radio-sonde type, or method of working up results, will affect these corrections so that any table of them may become obsolete without warning at any time. They thus need to be kept up to date and no table is published in this handbook.

The most frequent quantitative use of contours is to determine winds. The accuracy with which contour charts can be used to represent the upper wind fields has been investigated by Murray.⁴ Following on the work by Sheppard⁵, who showed that the estimated casual standard-height errors for British radio-sondes are about 7, 10, 20 and 30 metres at 700, 500, 300 and 200 mb. respectively, Murray went on to consider the effects of these height errors on the geostrophic wind and dealt also with errors due to inaccurate estimation, personal element in chart construction, small-scale fluctuations and apparent geostrophic departures. He showed that the height errors and the apparent geostrophic departures were the most important, the former increasing with height. His results are tabulated in Section 13.10. where the effect on forecasting upper winds is considered in detail.

2.7.3. Direct construction of high-level charts

In this age of jet aircraft, the requirement arises at times for the supply of upper wind and temperature data predominantly at levels above 30,000 ft. For such purposes use is made of the fact already noted in Section 2.6.4. that the advantage of gridding up progressively from lower levels is lost by the time the 100 mb. and possibly the 200 mb. level is reached. (Alternatively, staff limitations may not allow complete differential analysis from the surface upwards.) It is quite possible to draw charts for the levels of 200 mb. and upwards and even 300 mb. direct from the winds and heights reported for each level, without reference to wind shears and thicknesses except as a check on doubtful observations. The contours are drawn on each chart independently having due regard to the reported winds and

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height at that level, though the winds are more important at the highest level. It is most necessary to keep a careful watch on continuity in space and time to make a success of the direct drawing of charts. For aviation purposes, temperatures at operating heights are also required and on these charts isotherms can be drawn quickly at 5°C. intervals. It is of importance to remember the normal connection between the wind and the temperature fields and that in the lower stratosphere these relations are the reverse of those occurring in the troposphere. Thus in the lower stratosphere, warm pools are associated with troughs and cold pools with ridges. Where the flow is blocked, there will be a warm pool in the low areas and a cold pool in the high areas. With 5°C. isotherms, there is usually one closed isotherm at 200 mb. in pronounced ridges and troughs. The centre of the warm pool is usually to the left of the line of maximum wind through the trough, whilst the centre of a cold pool is nearer or slightly to the right of the line of maximum wind through the ridge. Since the advection of a warm pool out of a trough is rare, these relationships can be used to assist in planning the isotherms and contours in areas with sparse observations. Because the isotherms and contour patterns are linked, it follows that at stratospheric levels the air descends into troughs (ascending out of them) and ascends to a ridge (descending away from the ridge). The amount of vertical movement is less at 100 mb. than at the tropopause. Care must be taken not to enforce these "rules" on every occasion because situations do occur from time to time when cooling or warming of the air may occur without any obvious connection with the contour pattern.

2.7.4. Jet-stream analysis

No set of upper air charts for middle latitudes and extending to the tropopause can be considered complete unless some attention is given to the jet streams. A jet stream is defined by the World Meteorological Organization as a strong narrow current concentrated along a quasi-horizontal axis in the upper atmosphere, characterized by strong vertical and lateral wind shears and featuring one or more velocity maxima. The vertical wind shear is of the order of 10–20 knots per thousand metres, the lateral shear about 18 knots per hundred nautical miles and an arbitrary lower limit of 60 knots is assigned to the speed of the wind at the core. A full account of jet streams and their features is given in Chapter 7 and the present section is restricted to their representation on the constant-pressure charts considered in this chapter.

On such a chart, the presence of a jet stream is indicated by a belt of more or less closely packed contours lying along the belt of strong winds. The belt may be hundreds or thousands of miles long; it is usually curved and may have a few simple branches. In middle latitudes, the jet streams are often at about 300–250 mb. so that the standard level at which these jets are most marked is usually 300 mb. In the case of subtropical jet streams, the 200 mb. chart is more useful since the cores of these jets are mainly at about 200 mb.; however, these jets are well marked at 300 mb. as well. It is therefore usual to mark the jet streams on the 300 mb. chart first and to proceed upwards and downwards afterwards. Usually, jets are not found below 500 mb. or above 150 mb. The core of a jet is, of course, rarely coincident with a standard level so that in general no chart will portray the maximum winds. Another point to remember is that, as may be seen in Chapter 7 Figures 2 and 3, the axis of the various isobaric cross-sections of a jet are not vertically above one another but both above and below the core are often progressively displaced towards the tropospheric warm air.

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The remarkable wind shears of the jet streams are perhaps best shown in vertical cross-sections perpendicular to the line of the core. On contour charts, the close packing of the contours along the quasi-horizontal section of the jet does not indicate directly to the eye either the location of the jet axis or the wind strengths and shears. These latter features are brought out in a much more prominent manner if isotachs are drawn on the chart (that is, lines of equal wind strength). (See Chapter 13 Section 13.11.1.) For such purposes, the isotachs can be drawn at intervals of 20 knots and where possible to fit the actual winds reported. On such charts, the jet axis is usually indicated by a double or thick line with the actual values of the velocity maxima along it inserted at appropriate places. Over the continents of Europe and North America, the network of upper air observations is sufficient to allow a fairly accurate placing of the jet axis and isotachs on each chart almost on wind reports alone. Over the oceans, the paucity of data makes such recognition impossible and recourse must be made to more indirect methods of analysing the chart. Once again continuity in time and space becomes of the utmost importance and every observation must be given full weight unless there is very definite evidence against it.

In the placing of jet streams over the oceans, the relation of the jets to the surface frontal systems should be borne in mind. In middle latitudes, the jet streams usually exist in close association with the strong thermal gradients of well marked fronts and, although the core of the jet will lie in the warm air a little below the tropopause, the slope of the frontal surface is such that the core actually lies well to the cold side of the surface front position. In fact, an approximate rule is that the core lies vertically above the position of the frontal surface at 500 mb. Further examples of the relative position of the jet core and the surface fronts are given in Chapter 7 Section 7.3.2.7. It should be noted, however, that the subtropical jets are not so related to frontal features and that, when their meanderings are sufficiently large to bring them or branches of them northward, no attempt should be made to tie them to surface fronts. Similarly, branches of middle latitude jets sometimes occur which cross surface cold fronts in the rear of depressions.

Although there are material differences between one jet stream and another in middle latitudes, it has been noticed by several workers in this field that there is a strong family resemblance and over considerable areas of the world the horizontal velocity profiles perpendicular to the core conform to a pattern. There is some difference in the mean velocity profiles found by meteorologists on the two sides of the Atlantic, but as a general rule one can assume that the wind speed drops to 75 per cent of the axis value at 100 nautical miles from the axis on the tropospheric cold side and at about 150 nautical miles from the axis on the warm tropospheric side. According to Johnson⁶ this rate of fall continues to about where 50 per cent of the axis value is reached, but Endlich and McLean⁷ found a very considerable decrease in the horizontal wind shear, especially on the cold side, beyond the wind speed of 70 per cent of the axis value. In the absence of other more definite information, the analyst can make use of this mean profile in the placing of the contours and isotachs about a jet stream. The winds on the axis of a jet stream vary along its length having one or more maximum values. When the wind is accelerating along the axis, the air stream can be expected to cross the contours towards the low side and vice versa. Simla's⁸ approximate calculations show the order of magnitude of the cross-contour angles. At about 50°N. the inclination to the contours is about 10° when the speed changes by 40 knots in 600 miles (measured along the jet axis), 20° when the 40-knot change occurs in 250 miles and 30° when it occurs in about 150 miles. At 60°N. the

Chapter 2

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angles are about 10 per cent smaller; at 30°N. they are nearly 50 per cent larger. Since, in general, the axis of a jet can be assumed to be a streamline, this means that the jet axis will cross the contours in like manner (see Section 13.11.1.). Occasions will be found, however, when the axis of maximum wind is not completely coincident with any streamline and then the jet axis may not cross the contours in the manner just described.

In Figures 2.9 and 2.10 are examples of a 300 mb. contour analysis and the corresponding jet stream and isotach analysis (at 300 mb.).

Analysis of Upper Air Charts

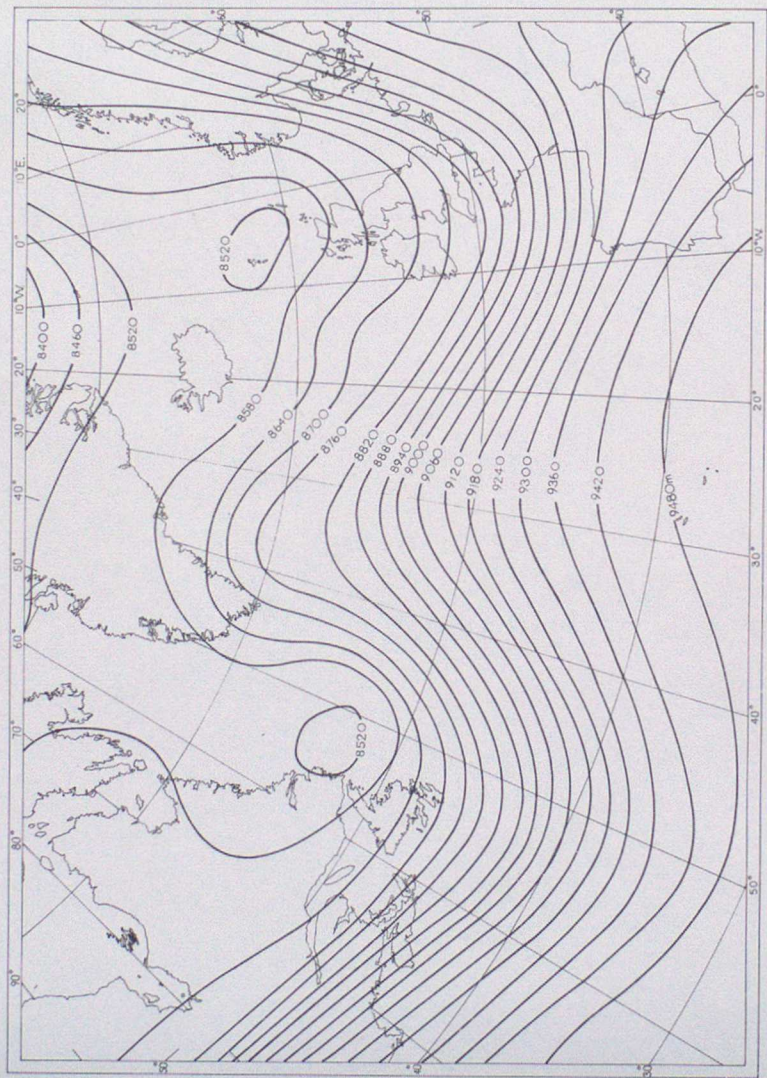


FIGURE 2.9 300 mb. contours, 0001 G.M.T., 18 December 1959

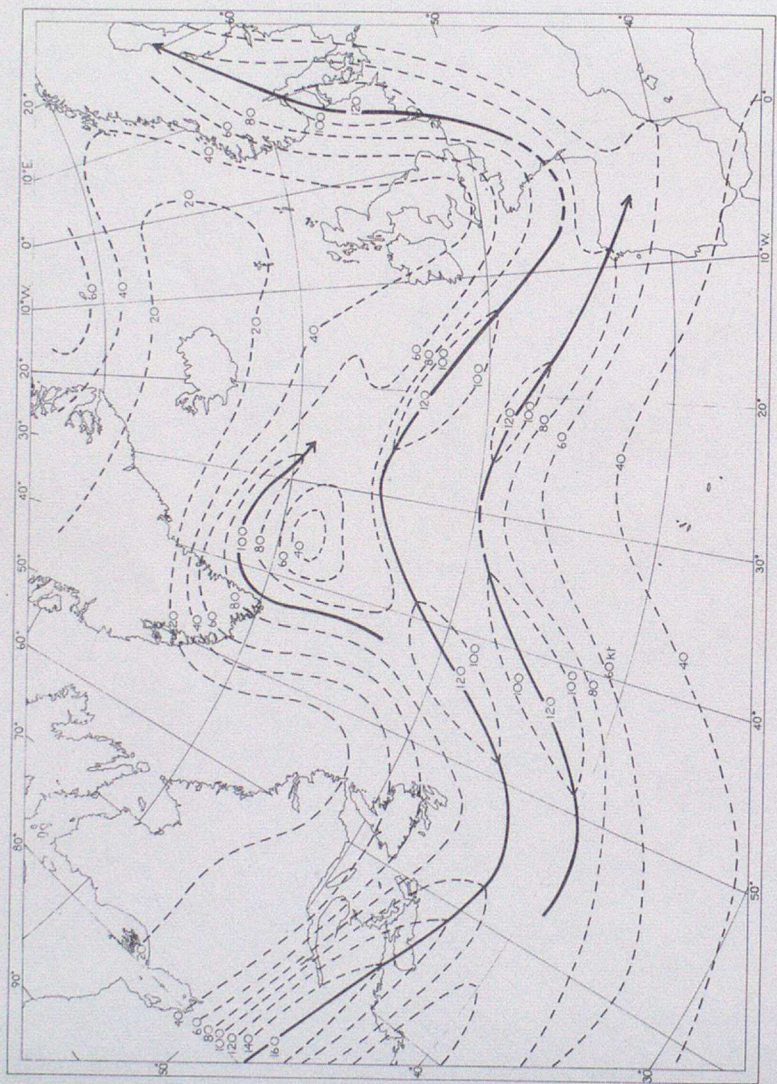


FIGURE 2.10 Jet streams and isotachs at 300 mb., 0001 G.M.T., 18 December 1959

Analysis of Upper Air Charts

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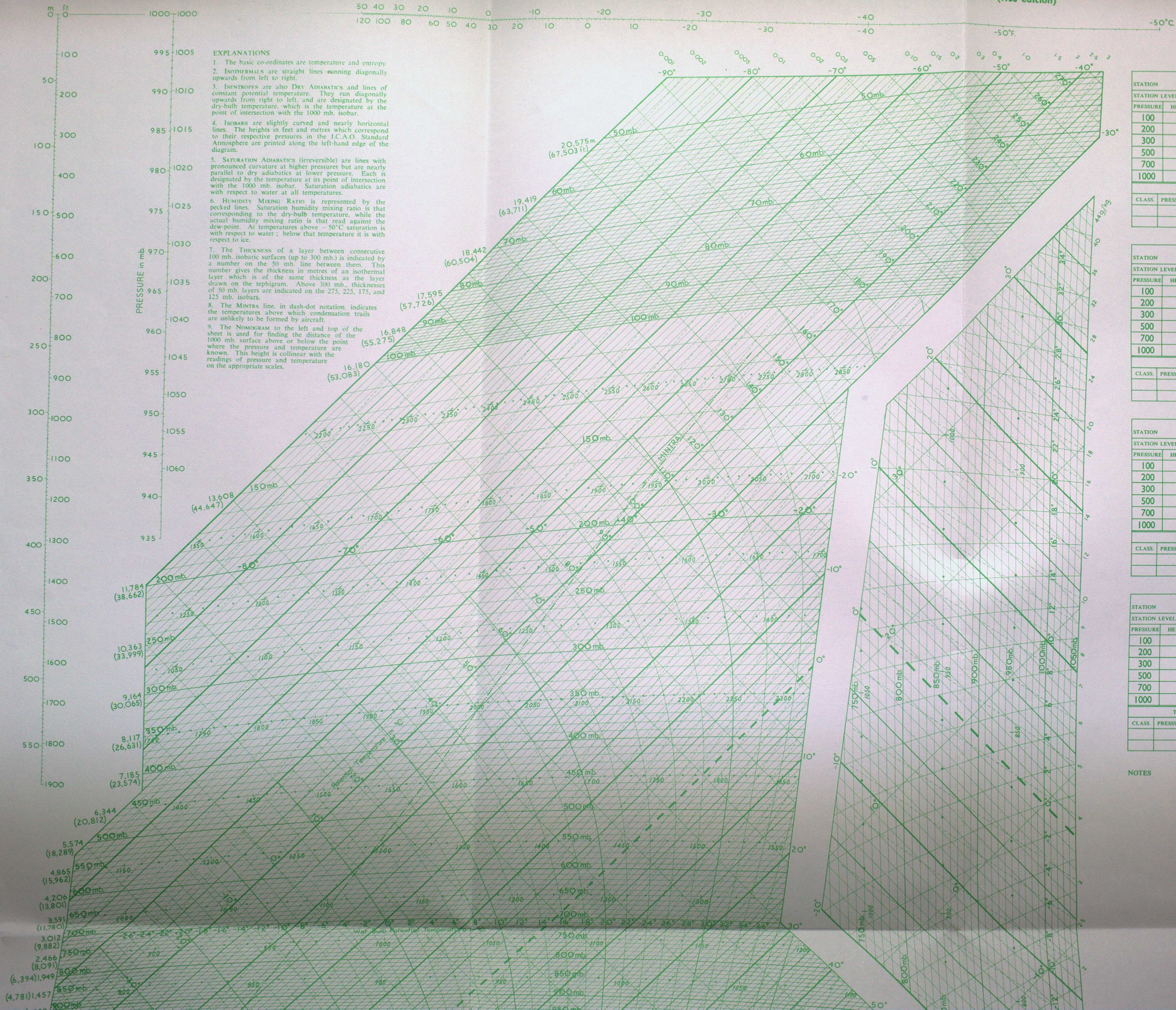
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TEPHIGRAM

AIR MINISTRY METEOROLOGICAL OFFICE

Form 2810A (1956 edition)

Date 19



EXPLANATIONS

- The basic co-ordinates are temperature and entropy.
- ISOOTHERMS are straight lines running diagonally upwards from left to right.
- ISENTROPES are also DRY ADIABATS and lines of constant potential temperature. They run diagonally upwards from right to left, and are designated by the dry-bulb temperature, which is the temperature at the point of intersection with the 1000 mb. isobar.
- ISOBARS are slightly curved and nearly horizontal lines. The heights in feet and metres which correspond to their respective pressures in the I.C.A.O. Standard Atmosphere are printed along the left-hand edge of the diagram.
- SATURATION ADIABATS (irreversible) are lines with pronounced curvature at higher pressures but are nearly parallel to dry adiabats at lower pressure. Each is designated by the temperature at its point of intersection with the 1000 mb. isobar. Saturation adiabats are with respect to water at all temperatures.
- HUMIDITY MIXING RATIO is represented by the pecked lines. Saturation humidity mixing ratio is that corresponding to the dry-bulb temperature, while the actual humidity mixing ratio is that read against the dew-point. At temperatures above -50°C saturation is with respect to water; below that temperature it is with respect to ice.
- The THICKNESS of a layer between consecutive 100 mb. isobaric surfaces (up to 300 mb.) is indicated by a number on the 50 mb. line between them. This number gives the thickness in metres of an isothermal layer which is of the same thickness as the layer drawn on the tephigram. Above 300 mb., thicknesses of 50 mb. layers are indicated on the 275, 225, 175, and 125 mb. isobars.
- The MINTRA line, in dash-dot notation, indicates the temperatures above which condensation trails are unlikely to be formed by aircraft.
- The NOMOGRAM to the left and top of the sheet is used for finding the distance of the 1000 mb. surface above or below the point where the pressure and temperature are known. This height is collinear with the readings of pressure and temperature on the appropriate scales.

STATION				TIME G.M.T.	
STATION LEVEL PRESSURE				M.S.L. PRESSURE	
PRESSURE	HEIGHT	THICKNESS	TEMP.	PRESSURE	WIND
100		1/2		100	
200		2/3		200	
300		3/5		300	
500		5/7		500	
700		7/10		700	
1000		10/10		1000	
TROPOPAUSE				FREEZING LEVEL	
CLASS	PRESSURE	HEIGHT	TEMP.	PRESSURE	HEIGHT

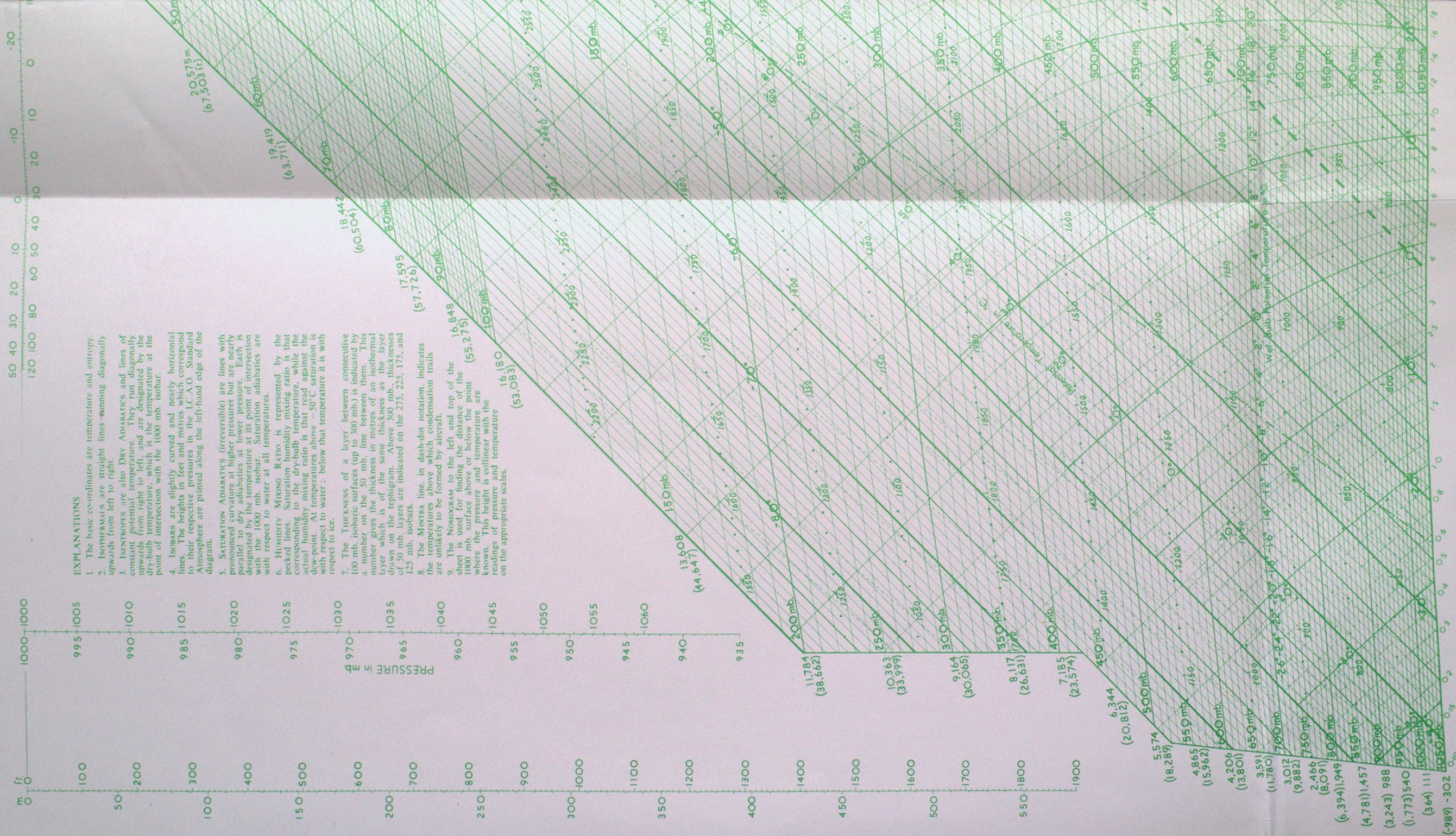
STATION				TIME G.M.T.	
STATION LEVEL PRESSURE				M.S.L. PRESSURE	
PRESSURE	HEIGHT	THICKNESS	TEMP.	PRESSURE	WIND
100		1/2		100	
200		2/3		200	
300		3/5		300	
500		5/7		500	
700		7/10		700	
1000		10/10		1000	
TROPOPAUSE				FREEZING LEVEL	
CLASS	PRESSURE	HEIGHT	TEMP.	PRESSURE	HEIGHT

STATION				TIME G.M.T.	
STATION LEVEL PRESSURE				M.S.L. PRESSURE	
PRESSURE	HEIGHT	THICKNESS	TEMP.	PRESSURE	WIND
100		1/2		100	
200		2/3		200	
300		3/5		300	
500		5/7		500	
700		7/10		700	
1000		10/10		1000	
TROPOPAUSE				FREEZING LEVEL	
CLASS	PRESSURE	HEIGHT	TEMP.	PRESSURE	HEIGHT

STATION				TIME G.M.T.	
STATION LEVEL PRESSURE				M.S.L. PRESSURE	
PRESSURE	HEIGHT	THICKNESS	TEMP.	PRESSURE	WIND
100		1/2		100	
200		2/3		200	
300		3/5		300	
500		5/7		500	
700		7/10		700	
1000		10/10		1000	
TROPOPAUSE				FREEZING LEVEL	
CLASS	PRESSURE	HEIGHT	TEMP.	PRESSURE	HEIGHT

NOTES

TEPHIGRAM



EXPLANATIONS

- The basic co-ordinates are temperature and entropy.
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- The NOMOGRAM to the left and top of the sheet is used for finding the distance of the 1000 mb. surface above or below the point where the pressure and temperature are known. This height is collinear with the readings of pressure and temperature on the appropriate scales.

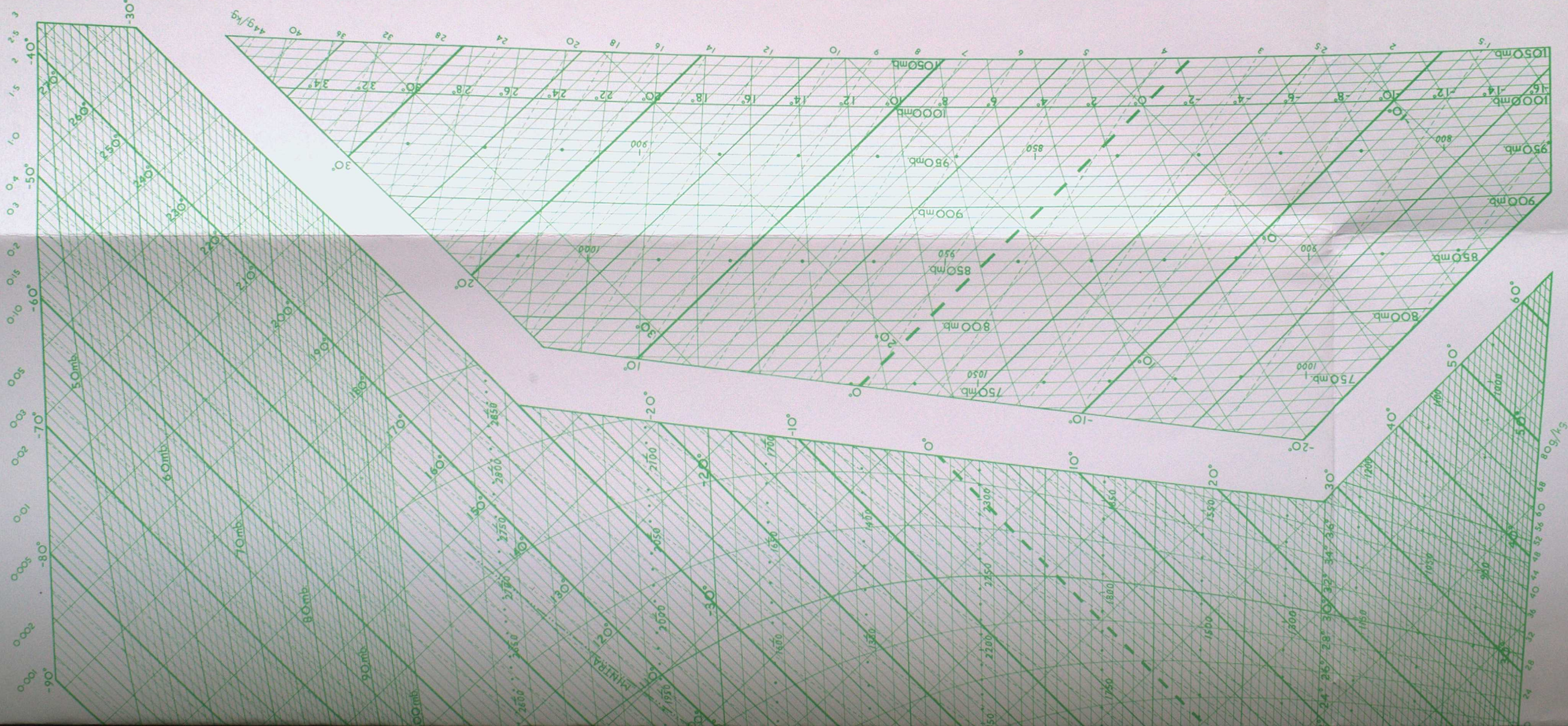
-50°C

-50°F

-40

-30

-20



STATION				TIME		G. M. T.
STATION LEVEL PRESSURE				M. S. L. PRESSURE		
PRESSURE	HEIGHT	THICKNESS	TEMP.	PRESSURE	WIND	
100		1/2		100		
200		2/3		200		
300		3/5		300		
500		5/7		500		
700		7/10		700		
1000		5/10		1000		
TROPOPAUSE				FREEZING LEVEL		
CLASS.	PRESSURE	HEIGHT	TEMP.	PRESSURE	HEIGHT	

STATION				TIME		G.M.T.
STATION LEVEL PRESSURE				M.S.L. PRESSURE		
PRESSURE	HEIGHT	THICKNESS	TEMP.	PRESSURE	WIND	
100		1/2		100		
200		2/3		200		
300		3/5		300		
500		5/7		500		
700		7/10		700		
1000		5/10		1000		
TROPOPAUSE				FREEZING LEVEL		
CLASS.	PRESSURE	HEIGHT	TEMP.	PRESSURE	HEIGHT	

STATION				TIME		G.M.T.
STATION LEVEL PRESSURE				M.S.L. PRESSURE		
PRESSURE	HEIGHT	THICKNESS	TEMP.	PRESSURE	WIND	
100		1/2		100		
200		2/3		200		
300		3/5		300		
500		5/7		500		
700		7/10		700		
1000		5/10		1000		
TROPOPAUSE				FREEZING LEVEL		
CLASS.	PRESSURE	HEIGHT	TEMP.	PRESSURE	HEIGHT	

STATION				TIME		G.M.T.
STATION LEVEL PRESSURE				M.S.L. PRESSURE		
PRESSURE	HEIGHT	THICKNESS	TEMP.	PRESSURE	WIND	
100		1/2		100		
200		2/3		200		
300		3/5		300		
500		5/7		500		
700		7/10		700		
1000		5/10		1000		
TROPOPAUSE				FREEZING LEVEL		
CLASS.	PRESSURE	HEIGHT	TEMP.	PRESSURE	HEIGHT	

NOTES